Sediment accumulation rates in the West Arm of Glacier Bay, Alaska based on Lead-210 analysis

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Abstract

Unique climate, tectonics and temperate glacial dynamics make Glacier Bay one of the fastest eroding and rebounding landscapes in the world. Because Glacier Bay has one of the fastest sediment accumulation rates in the world, glacial fjord basins in the bay are a suitable way of observing rapid sedimentation that has occurred since the last ice age. The radioisotope $^{210}$Pb is a useful tool because it is adsorbed from the water onto settling sediment particles. In March of 2008, four Kasten cores from Glacier Bay were examined by the radiochemical $^{210}$Pb dating technique to calculate sediment accumulation rates from $^{210}$Pb decay profiles. Sediment accumulation rates from the four cores ranged from 2.7 cm yr$^{-1}$ to 0.97 cm yr$^{-1}$.

Introduction

Glacier Bay National Park and Preserve is located ∼ 100 km west of Juneau, Alaska. This area of Alaska is composed of actively tectonic mountains and glacier carved fjords that receive as much as 8 meters of precipitation/snowfall annually (Powell & Molnia, 1989). Extreme weathering coupled with high uplift rates of these mountains and high basal lubrication of these temperate glaciers amplify the erosion to the underlying substrate of shattered and altered rock comprised mostly of weakly lithified sediments of glacimarine origin (Hallet et al., 1996). In the late 19th century Glacier Bay was predominantly covered with glaciers from the Little Ice-Age period (Cai et al., 1997). In the following years, these glaciers have rapidly retreated, exposing numerous glacial-carved fjords. Variations in sediment input into the bay are directly linked to these retreats because the fjords are efficient sediment traps for sediment produced by tidewater glaciers (Koppes and Hallet, 2002). Complete sequences of glacial debris in the fjords allow assessment of the relationship between glacial sedimentation and the extent of glacier cover, glacier mass balance and history of retreat (Koppes & Hallet 2002). Hallet (1996) and others (e.g. Koppes and Hallet, 2002) have documented erosion rates of tidewater glaciers in Alaska on the order of cm yr$^{-1}$ for the last century, an order of magnitude higher than the highest erosion rates in the world. Glacier Bay also has one of the highest sedimentation rates in the world (Table 1).

Previous sediment trap and sediment core $^{210}$Pb data illustrate that sediment accumulation rates decrease away from the glacial termini of Tarr Inlet in three distinctive zones: Ice-proximal, Ice-berg and Ice-distal (Fig.1)(Cai et al., 1997).

In Tarr Inlet, the Ice-proximal zone is characterized by high and variable sediment accumulation rates ranging from tens of m yr$^{-1}$ to tens of
Table 1: Displays previous Glacier Bay sediment accumulation rates from $^{210}$Pb dating

<table>
<thead>
<tr>
<th>Location</th>
<th>Glacier terminus</th>
<th>(km) from terminus</th>
<th>Accum. rate (cm yr$^{-1}$)</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarr Inlet</td>
<td>Grand Pacific Glacier</td>
<td>3, 6.5, 8.8 &amp; 15</td>
<td>70, 40, 19 &amp; 2-3</td>
<td>Cai et al., 1995</td>
</tr>
<tr>
<td>Muir Inlet</td>
<td>Muir Glacier</td>
<td>1.5, 26, 38 &amp; 55</td>
<td>82, 0.5, 1.4 &amp; 0.5</td>
<td>Cai et al., 1996</td>
</tr>
<tr>
<td>Queen Inlet</td>
<td>Carroll Glacier proximal &amp; distal</td>
<td>9 &amp; 3</td>
<td>9 &amp; 3</td>
<td>Carlson et al., 1996</td>
</tr>
</tbody>
</table>

cm yr$^{-1}$, with an average of 3-4 m yr$^{-1}$. Sediment accumulation rates in the Ice-berg zone: upper (closer to glacier terminus), middle and lower (furthest away from glacier terminus), range from 100 cm yr$^{-1}$, 40 cm yr$^{-1}$, and 19 cm yr$^{-1}$, respectively. In contrast, rates in the upper and lower areas of the Ice-distal zone, range from 6 cm yr$^{-1}$ to 3.2 cm yr$^{-1}$ (Cai et al. 1997).

Interest in glacial erosion has recently broadened to a much wider community of earth scientists because of its role in the controversial and globally significant interplay between climate and topography that includes chemical weathering as an important sink of atmospheric CO$_2$ (Hallet et al., 1996).

Determination of sediment accumulation rates is critical to calculating sediment yields from glacial erosion. The radioisotope $^{210}$Pb can be used to measure sediment accumulation by the adsorption of excess $^{210}$Pb activity by sediment particles in the water column (Jaeger et al., 1998). Excess activity is any activity that exceeds the background activity of the parent $^{226}$Ra (Nittouer et al., 1984). $^{210}$Pb half-life
of 22.3 years makes it a valuable tool in dating sediment within the last century (Jaeger et al., 1998). “Due to analytical and environmental constraints, a radioisotope generally can be used to examine sedimentation for a period of about 4 to 5 times its half-life”(Nittrouer et al., 1984). Usually, the exponential decay profile of $^{210}\text{Pb}$ decreases with depth in the sediment (Jaeger et al., 1998). This study provides quantitative analyses of $^{210}\text{Pb}$ to examine sediment accumulation rates in various locations within Glacier Bay.

**Methods**

**Field Methods**

Kasten cores sampled from areas near previous sediment studies were used to augment information on accumulation rates and also to determine if sedimentation rates have changed with climate since the last studies of the 1990s. Four Kasten cores of various lengths were obtained near Glacier Bay National Park historical CTD stations (Hodgde and Hodge, 2002), Station #s KC-10, 16, 21 and 23 (Table 2).

These environments include Tarr and Muir Inlets and other inlet mouths in the West Arm, which are fed by the John Hopkins, Lamplugh, Reid and Geikie glaciers (Fig. 2).

**Seabed Sampling**

Sediment sampling in Glacier Bay was performed onboard the R/V Thomas G. Thompson during a cruise in March 2008. To broadly characterize layering in the sub-sea floor and sediment thicknesses, 3.5 kHz surveys were conducted. These data were important in determining optimal sampling sites. In addition, EM300 multi-beam surveys were co-located to provide additional information on bottom topography. Following preliminary survey studies, a Van Veen grab (Fig. 3) or Soutar core (Fig. 4) sample of the proposed site was conducted to determine the presence of boulders or areas of coarse-grained sediment accumulation that would prevent taking a Kasten Core (Fig. 5). Where sampling was permissible, a Kasten core was taken and recovered on deck.

The Kasten corer was assembled (See Appendix A) and deployed on board. Sediment cores recovered with the Kasten corer were measured, described and digitally imaged upon recovery. Kasten cores were sub-sampled immediately at 2 cm intervals and homogenized on board for geochemical studies. Two sediment samples from every 2 cm interval were bagged and labeled for archive and laboratory analyses back at the University of Washington Marine Science sediment lab. Sediment baggies were stored in a refrigerator on board.
<table>
<thead>
<tr>
<th>Core #</th>
<th>Date</th>
<th>Time</th>
<th>Location</th>
<th>Lat/Long</th>
<th>Water depth</th>
<th>Core length</th>
</tr>
</thead>
<tbody>
<tr>
<td>KC-10</td>
<td>3/20/2008</td>
<td>22:15</td>
<td>S. of Russell Island</td>
<td>58.89° N, 136.83° W</td>
<td>369 m</td>
<td>207 cm</td>
</tr>
<tr>
<td>KC-16</td>
<td>3/21/2008</td>
<td>21:02</td>
<td>E. of Hunter Cove</td>
<td>58.89° N, 136.09° W</td>
<td>294 m</td>
<td>68 cm</td>
</tr>
<tr>
<td>KC-21</td>
<td>3/20/2008</td>
<td>17:15</td>
<td>N. Tarr Inlet</td>
<td>59.04° N, 137.05° W</td>
<td>217 m</td>
<td>58 cm</td>
</tr>
<tr>
<td>KC-23</td>
<td>3/18/2008</td>
<td>16:58</td>
<td>W. Geikie Inlet</td>
<td>58.60° N, 136.47° W</td>
<td>99 m</td>
<td>93 cm</td>
</tr>
</tbody>
</table>

**Table 2:** Displays Cruise 217 Kasten core locations, dates and times taken, latitudes and longitudes, water depths and core lengths.

**Figure 4:** This is a picture of a Soutar Box core on the stern of the R/V *Thompson* (photo by Brandon Knox).

**Laboratory methods**

On shore, laboratory procedures include pre lab and ²¹⁰Pb lab procedures (T. Drexler, 2007)(See Appendix B). ²¹⁰Pb activities were determined by the ²¹⁰Po method (Benninger et al., 1979; Nittrouer et al. 1979). The ²¹⁰Po method is applicable because ²¹⁰Pb and its granddaughter ²¹⁰Po are in secular equilibrium within the seabed (Nittrouer et al., 1979). Five grams of dried sediment was spiked with ²⁰⁹Po as a yield determinant, chemically leached with hot concentrated HNO₃ and 6 N HCL, and ²¹⁰Po was autodeposited onto silver planchettes (Jaeger et al. 1998). The ²¹⁰Po activities were measured by alpha counting the planchettes with Ortec Plus and PC alpha spectrometers for 23-24 hours or until 80,000 seconds of counting was completed.

**Figure 5:** Picture of Kasten core being recovered on the stern of the R/V *Thompson* in North Tarr Inlet (photo by Eric Collins).
Analytical methods

Spread sheets provided by Tina Drexler were used for calculating $^{210}\text{Pb}$ activities from $^{210}\text{Po}$ activities and $^{209}\text{Po}$ Spike. These spreadsheets also calculated porosity, salt corrected porosity, bulk density, salt corrected sample mass and sediment accumulation rates.

Sediment accumulation rates of $^{210}\text{Pb}$ were measured in dpm g$^{-1}$ (disintegrations per minute per gram dry weight). “A characteristic profile of $^{210}\text{Pb}$ activity contains a nearly homogenous surface layer, below which activities decrease logarithmically to a constant low level (background). The background level represents $^{210}\text{Pb}$ supported by a $^{226}\text{Ra}$ in the sediment. Excess $^{210}\text{Pb}$ activity at each point in a core is determined by subtracting supported $^{210}\text{Pb}$ activity from total $^{210}\text{Pb}$ activity” (Nittrouer et al., 1984).

If the sediment and $^{210}\text{Pb}$ fluxes remain continuous, then a vertical profile of $^{210}\text{Pb}$ can be used to calculate an accumulation rate ($A$) using the following equation (Nittrouer et al., 1984):

Figure 2: Displays color-coded dots for Kasten core locations from Table 2. Red indicates KC-21, Yellow indicates KC-10, Blue indicates KC-23 and Green indicates KC-16 (Cai et al. 1997)
\[ A = \frac{\lambda_z}{\ln \frac{C_0}{C_z}} \]

where \( C_0 \) = activity of \(^{210}\)Pb at an upper level of the profile; \( C_z \) = the activity of \(^{210}\)Pb at a distance \( z \) below level of \( C_0 \); and \( \lambda \) = the decay constant of \(^{210}\)Pb = 0.031 yr\(^{-1}\) (Nittouer et al., 1984)

**Results**

**KC-23**

KC-23 was characterized by lighter brown colored mud at the top with a progressively darker grey mud towards the bottom (Fig 6). Total \(^{210}\)Pb activities varied from 3.6990 to 0.6489 dpm g\(^{-1}\). The resulting excess \(^{210}\)Pb activities ranged from 3.2718 to 0.2217 dpm g\(^{-1}\). The sediment accumulation rate was \( \sim 0.97 \) cm yr\(^{-1}\) (Fig. 7). Porosity ranged from 0.6936 to 0.4650 (Fig. 8).

**KC-21**

KC-21 was characterized with a muddy top 30 cm, sandier mud at 30- 40 cm depth and sandy with smaller cobbles at 40- 57 cm depth. Total \(^{210}\)Pb activities varied from 0.6891 to 0.2593 dpm g\(^{-1}\) (Fig. 9). No excess \(^{210}\)Pb was visible. KC-21 \(^{210}\)Pb total activity was averaged for a background level of 0.4272 dpm g\(^{-1}\). Porosity ranged from 0.5489 to 0.2964 (Fig. 10).

**KC-10**

KC-10 was characterized by very soupy mud all the way through the core(Fig. 11) Total \(^{210}\)Pb activities varied from 1.0497 to 0.3770 dpm g\(^{-1}\). The resulting excess \(^{210}\)Pb activities were 0.6225 to 0.0384 dpm g\(^{-1}\). The sediment accumulation rate was \( \sim 2.7 \) cm yr\(^{-1}\) (Fig 12). Porosity ranged from 0.6686 to 0.4762 (Fig. 13).

**Figure 6:** Picture of KC-23 from Geikie Inlet. The length of the core is \( \sim 92 \) cm (photo by Brandon Knox).

**Figure 7:** Displays KC-23 \(^{210}\)Pb activities logarithmically vs. depth. The red plots are total activities and the green plots are the excess activities. The Linear regression line of the green excess activity is a component of finding the accumulation rate \( A \). Using equation 1, the accumulation rate is 0.97 cm yr\(^{-1}\).
Figure 8: Displays Porosity of the sediment vs. depth for KC-23

Figure 9: Displays the $^{210}\text{Pb}$ activity logarithmically vs. depth of KC-21. The red dots indicate total activity. There is no excess activity. The vertical line represents the total activities averaged. The average of 0.4272 dpm g$^{-1}$ was used as a background activity for the other cores.

Figure 10: Displays Porosity of the sediment vs. depth for KC-21

Discussion

There was no grain size analysis conducted on any of the sediment. So all observations of grain size were based on sight and touch during wet and dry weighing and crushing.

KC-21 was poorly sorted, composed of sand, mud, pebbles and cobbles. This variability of the sediment makes sense because the core was recovered within 1 km of Grand Pacific and Margerie Glacier termini. This area is near the morainal bank of the glacier. It resides in the Ice-proximal zone, lying on the border of the bank core and bank front zones. Cai and others 1997 explain that evidence from many bottom grab samples and ROV submersible observations (Powell et al. 1991)(Dowdwell & Powell 1996) indicate that deposits of these bank core environments are mixtures of dicitons, gravel, rubble, sand and mud. The bank front environment was composed mostly of stratified sand interbedded with thin laminated mud (Cai et al., 1997). Ekman grab samples from this area also revealed mixtures of gravel sand and mud (Cai et al., 1997).

This core didn’t reveal an accumulation rate. This could have been because of the lack of fine particles for $^{210}\text{Pb}$ to attach to. Another theory is that gravity flows dumped the recently accumulated sediment on top of the sediment.
Figure 11: This is a picture of KC-10, recovered between Reid Inlet and Russell Island. The core was 207 cm long (Photo by Brandon Knox).

Figure 12: Displays the $^{210}$Pb activities logarithmically vs. depth of KC-10. The red plots are total activities and the green plots are the excess activities. The Linear regression line of the green excess activity is a component of finding the accumulation rate $A$. Using equation 1, the accumulation rate is 2.7 cm yr$^{-1}$. Displays KC-10.

Figure 13: Displays Porosity of the sediment vs. depth for KC-10.

Further down slope (Cai et al., 1995). Just when I thought this core was worthless, it proved to be a valuable tool. The low activity was averaged, revealing a background activity to subtract from the total activities of the other cores and leave us with excess activities, resulting in accumulation rates.

KC-23 was composed mostly of mud with very little sand. We were hoping to get closer to the head of Geikie Inlet, but ice prevented us from getting any closer than two thirds of the way in. We knew there was no tidewater glacier actively feeding this inlet, so the accumulation rate could not be that large. I was still impressed that this core revealed an accumulation rate of 0.97 cm yr$^{-1}$. On a geologic time scale this rate is still remarkable.

KC-10 was the largest core we obtained. It was composed of the soupiest of mud. This core revealed an accumulation rate of 2.7 cm yr$^{-1}$. I was not surprised that this core had a higher accumulation rate than the prior, because it wasn’t as compacted as the other cores. This core has Reid Glacier feeding it, which is a tidewater glacier. Tidewater glaciers offer the highest rates of sedimentation to fjords. Just northwest of KC-10 Lamplugh Glacier also feeds into the West Arm, which could only increase the chances of the area sampled to get even more sedimentation from an outside source.
The accumulation rates that I discovered were on the low end of the spectrum compared to previous studies. I have not come across other accumulation rates for these KC-23 and KC-10, maybe they will prove valuable for future studies.

Porosity describes the fraction of void space in the sediment, containing air or water. It is measured as a fraction between 0 and 1. Porosities of KC-23 and KC-10 were very similar, higher than KC-21 because of there muddy compositions. Muddy sediment also holds more water. The porosity was lower in KC-21 than the others cores, accounting for the poorly sorted sediment present. Poorly sorted material has lower porosity because water or air gaps are filled with random sized particles of rock.

KC-16 was composed mostly of mud, with dark bands. \(^{210}\text{Pb}\) analysis of this core has not been conducted yet. Therefore a sediment accumulation rate cannot be calculated. Future analysis will be included in later text.

**Conclusions**

In hindsight, I would have done many parts of this experiment differently. I would not have run so many samples for the \(^{210}\text{Pb}\) analysis. I was trying to get high definition results by analyzing every 2 cm of sediment. The down side was that I ran out of time to finish KC-16. It would have been better to conduct more coring in inlets with tidewater glaciers actively feeding the fjord with sediment to get higher accumulation rates. I might also use a different coring device so that cores could be split and x-rayed on board the research vessel. I would have also taken more detailed pictures of the cores that were level and flush with the plane of view. If time allowed, sediment grain size analysis could give a more accurate description of actual classification of the sediment. In hind site, I would have done many parts of this experiment differently. I would not have run so many samples for the \(^{210}\text{Pb}\) analysis. I was trying to get high definition results by analyzing every 2 cm of sediment. The down side was that I ran out of time to finish KC-16. It would have been better to conduct more coring in inlets with tidewater glaciers actively feeding the fjord with sediment to get higher accumulation rates. I might also use a different coring device so that cores could be split and x-rayed on board the research vessel. I would have also taken more detailed pictures of the cores that were level and flush with the plane of view. If time allowed, sediment grain size analysis could give a more accurate description of actual classification of the sediment.

**Conclusions**

- KC-21 revealed an averaged background \(^{210}\text{Pb}\) activity of 0.4272 dpm g\(^{-1}\)
• KC-23 revealed a sediment accumulation rate of 0.97 cm yr\(^{-1}\)
• KC-10 revealed a sediment accumulation rate of 2.7 cm yr\(^{-1}\)

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I appreciate the assistance provided by fellow scientists and students from the University of Washington School of Oceanography. Special thanks to Professor Chuck Nittrouer for his assistance and encouragement and for providing me all the gear and equipment for my research. Thanks to Professor Deb Kelley for all the adventure, guidance, knowledge, editing and for believing in me. Thanks to Professor Rick Keil for advice, knowledge, humorizing me, visualizing my potential and a once in a life-time opportunity to visit Glacier Bay Alaska. Thanks to my colleague Brandon Knox for being my partner in this whole project, getting extremely dirty, cold, tired, fatigued and humorizing me when I was starting to act a little goofy from sleep deprivation. I could have not done it without you Brandon. Thanks to Christina Biladeau for her help, advice and bag labeling. Thanks also to Joshua Hill for making the night shift run smooth as silk, for helping me lift that heavy Soular Corer repeatedly and for all the hands on help with Kasten core deployment. Thanks to Brittany Kimball for teaching me the ropes to all of the \(^{210}\)Pb lab procedures. Thanks to Eric Collins for the feedback, photographs, and making me laugh. Thanks also to all of the other professors and students on the trip for making this trip to Glacier Bay a success. The successful completion of this study was greatly facilitated by the crew of the R/V Thompson.

References
0.1 Appendix A

1. Place open barrel on blocks.
2. Barrel Assembly
3. Put lids on in Alpha-numeric order (starting at penetrating end), make sure they are flush.
4. Flip barrel 90°
5. Insert two short screws on one side of each plate all of the way down one side of the core barrel.
6. Flip barrel 180°
7. Insert all the short screws on the other side of the core barrel (make sure they are snug but not stripped).
8. Flip barrel 90°
9. Insert the rest of the short screws on the first side of the barrel.
10. Place trap door end on penetrating end (trap door end and penetrating end have matching letters)
11. Use a mallet to get it on snug (put a piece of wood in between mallet and trap door end cap to ensure no metal to metal contact)
12. Insert at least 5 of 8 of longer screws in on the cap (don’t force the screws or they will strip the holes)(screws don’t need to be flush, they are primarily for shear strength).
13. Wrap 3 layers of duct tape around the screws to hold them in the holes (make sure tape is stuck on tight).
14. Place sliding weight on top end of barrel before barrel insertion into weighted end.
15. Slide barrel into weight package assembly.
16. Insert 2 T-bars with pins, facing each other
17. Assembly complete
18. Make sure shackle is weight tested before deployment

Figure 15: Directions for Kasten Corer Assembly