Influence of rapid glacial retreat on the rate of erosion by tidewater glaciers

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ABSTRACT

Glacial erosion rates inferred from total sediment budgets in recently deglaciated fjords, which are the highest reported erosion rates worldwide, have received considerable attention in fields as diverse as tectonics, glacial sedimentation, and climate. These record rates, however, are representative only of tidewater glaciers during their extensive retreat of the post–Little Ice Age period; erosion rates averaged over glacial-interglacial cycles and longer periods are likely to be substantially smaller. We examine the influence of retreat rate on sediment yields from tidewater glaciers by reconstructing the history of sediment output from retreating glaciers necessary to produce sediment packages observed in contemporary fjords. Using a simple numerical model of proglacial sedimentation in front of a retreating glacier, seismic profiles of proglacial sediments, and the history of terminus retreat of Muir Glacier, Glacier Bay, Alaska, we calculate the sediment flux as a function of time from this glacier between 1900 and 1979, and conclude that sediment flux scales with retreat rate. The corresponding basin-wide erosion rate during this 79 yr period averages 37 mm/yr, and exceeds long-term erosion rates by a factor of 5 ± 1. For Muir Glacier and, by inference, for other calving glaciers, the general drastic retreat and the marked regional drawdown of ice since the Little Ice Age are both linked to unusually rapid calving and fast ice motion, which is conducive to rapid erosion.

Keywords: tidewater glaciers, glaciomarine sedimentation, erosion rates, sediment yield, Glacier Bay, Alaska.

INTRODUCTION

Modern glaciomarine environments provide stratigraphic data useful in unraveling both Earth's climatic record and the role of glaciers in landscape development and sediment delivery to ocean margins. Fjords are efficient traps for sediment produced by tidewater glaciers. The sediments, once deposited within the basins behind moraines and transverse shoals, have little opportunity to be removed, except by glacial readvance. Fjords therefore contain complete sequences of glacial debris (Anderson and Ashley, 1991), from which we can assess the relationship of sediment production by glaciers to the extent of glacial cover, glacier mass balance, and history of retreat.

Recent studies have speculated on the relationship between regional tectonics and climate, and the role that erosion, in particular glacial erosion, may play in the coupling of tectonics and climate through its influence on topography (e.g., Raymo et al., 1988; Molnar and England, 1990). Modern glaciomarine sedimentary sequences can elucidate links between topography and climate by improving our understanding of the efficiency of glaciers in denuding the landscape, particularly tidewater glaciers, which include some of the largest and fastest moving glaciers on Earth.

Hallet et al. (1996) reported that the rates of erosion of tidewater glaciers in Alaska, derived from glaciomarine sediments deposited in the southeast Alaskan fjords, were as much as centimeters per year for periods ranging from years to nearly one century, an order of magnitude higher than the highest rates of erosion elsewhere in the world. Rapid erosion is not surprising, considering the ample precipitation and the dramatic relief of the southeast Alaska region, including the highest coastal mountains on Earth (e.g., Mount St. Elias rises 5000 m within 18 km of the Pacific). However, in view of the maximum estimated rates of tectonic uplift of ~7 mm for the region (Bird, 1996), these erosion rates do not seem to be sustainable in the long term. Erosion would quickly outpace uplift, eliminating the exceptionally high ranges and relief that characterize the area and sustain the large tidewater glaciers that have persisted in the region for 5.5 m.y. (Lagoe et al., 1993).

We believe that the solution to this conundrum is that the sediment yields are high because they have all been measured during the rapid retreat of coastal Alaskan glaciers from their Little Ice Age maximum extents. Ice loss, primarily by calving, must have exceeded ice accumulation in the basins since the Little Ice Age to account for the regional drawdown of hundreds of meters of ice during the past century (Brown et al., 1982). Rapid calving is associated with high ice flux and rapid basal ice motion, conducive to high sediment flux (Humphrey and Raymond, 1994). Thus, recent sediment yields are not representative of the long-term rates of erosion averaged over the glacial cycle, but reflect a short-term (10–l00 yr) acceleration in glacier sliding.

In order to quantify this relationship, we present a simple numerical model of proglacial sedimentation. The model enables us to reconstruct the past sediment output from a retreating tidewater glacier necessary to produce the sediment packages observed in its fjord. Thus, we can examine the relationship between the time-varying sediment output, glacier dynamics, and retreat rate, and study how the stratigraphic record reflects both short- and long-term erosion rates. Here we apply the model to the Muir Glacier in Glacier Bay, Alaska.

Our work is founded on a substantial body of research on modern glaciomarine sedimentation. Several studies (e.g., Powell, 1991; Hunter, 1994; Stravers and Syvitski, 1991; Hallet et al., 1996) have divided sediment yields in fjords determined from sediment thickness profiles by the drainage area of the glacier to calculate basinwide erosion rates averaged over the retreat period, assuming that all sediment was excavated out of the fjords during the prior advance. Previously, this erosion rate, typically representing decades of sediment accumulation, has been taken to reflect the basinwide rate of erosion for the entire glacial-interglacial cycle and longer term. However, most of these studies have not sought to extract high temporal resolution from the glaciomarine record. Comparisons of fjord bathymetries from annual surveys (e.g., Hunter, 1994; Powell, 1991) and analysis of sediment traps and cores collected in fjords (e.g., Cowan and Powell, 1991; Jaeger and Nittrouer, 1999) have occasionally been used to examine short-term rates of sediment accumulation, but they are costly and impractical, and sediment cores to date have penetrated at most only the top 10 m of sediment, whereas typical sedimentary sequences in fjords are as much as 100 m thick. Thus, our goal is to develop a model that enables us to extract temporal information about sediment yields from sediment sequences in fjords, and in so doing greatly expand the global database on erosion rates.

MODEL OF TIMING OF GLACIOMARINE SEDIMENTATION

The thickness of a proglacial sedimentary sequence at any location in a fjord reflects a

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combination of the rates of two glacially modulated processes: sediment delivery to the glacier front and frontal retreat. Thick sediment sequences in fjords often constitute prominent shoals or moraine embankments formed during times of rapid sediment delivery to the glacier front, slow retreat of the front, or both. The objective of our model is to deconvolve the accumulation rate histories both from measured sediment thickness profiles and from the known history of glacial retreat. We stress that because of its modest objective our model can be quite simple; it merely aims to represent the essence of primary sedimentation and subsequent reworking by gravity flows and other processes.

In our model, sediment accumulates in a zone of active deposition near the glacier front. The sediment thickness, $S(x)$, in a reach of the fjord is dictated by the sedimentation rate, $\dot{S}(x, t)$, which has been noted to decrease with distance from the terminus (e.g., Cowan and Powell, 1991; Hunter, 1994; Jaeger and Nittrouer, 1999), so that

$$S = \int_0^t \dot{S}\, dt. \qquad (1)$$

To illustrate the dependence of S on both $\dot{S}$ and the retreat rate, $\dot{R}(t)$, we assume an exponential decrease in sedimentation rate with distance from the terminus: $\dot{S} = \dot{S}_0 e^{-x/x^*}$, where $\dot{S}_0(t)$ is the sedimentation rate at the ice front, x is the distance between the terminus and fjord reach at time t, and x^* characterizes the distance over which the sedimentation rate decreases by $1/e$. The distance x is the product of the retreat rate, $\dot{R}$, and time. Substituting this exponential function into equation 1 yields

$$S = \int_0^t \dot{S}_0 e^{-\dot{R}t/x^*}\, dt. \qquad (2)$$

Integration of equation 2 with a constant $\dot{R}$ for long times ($t \rightarrow \infty$) yields

$$S = x^* \dot{S}_0 / \dot{R}. \qquad (3)$$

For example, given a rate of sedimentation at the ice front $\dot{S}_0$, the sediment thickness decreases with increasing retreat rate, as the fjord reach spends less time in the zone of active sedimentation, and any given sediment volume is deposited over a broader area. In general, however, both $\dot{S}_0$ and $\dot{R}$ vary in time. The model enables one to calculate one of these parameters if the other is known, and the total proglacial sediment thickness (S) has been measured. In most cases, $\dot{S}_0$ is unknown but of considerable interest because it reflects the sediment flux from the glacier, which is difficult to measure; $\dot{R}$ can often be reconstructed from maps and photographs.

Because sediment storage in fjord waters is insignificant, the integral of the sedimentation rates over the entire fjord bottom must equal the total flux of sediment from the glacier for that time,

$$Q(t) = \int_0^\infty \dot{S}(x, t) W(x)\, dx, \qquad (4)$$

where $W(x)$ is the width of the sediment sequence. For Glacier Bay, analysis of seismic profiles indicates that the vertical average of $W(x)$ is 32% of the width of the fjord at sea level. If the retreat rate, $\dot{R}$, of a particular glacier and the thickness of its proglacial sediment sequence, $S(x)$, are known, the model can then be used to compute the time variation in the sediment yield, $Q(t)$, of the glacier during its retreat phase.

These equations pertain to the glaciofluvial and ice-rafted debris, which composes ~95%–98% of total sediment delivery to the glacier front (Syvitski, 1989); these deposits thin with distance from the terminus. The glaciofluvial system is assumed to be dynamic, major outlet streams switching positions frequently across the ice front, so that sedimentation rates are uniform across the width of the fjord bottom over annual and longer time scales. The remaining 2%–5% (Syvitski, 1989; Hunter et al., 1996) is dumped directly to the fjord bottom at the ice front by calving ice and ice-cliff melt out. Because this fraction represents such a small percentage of the total sediment delivery, and so little is currently known about ice-cliff melt-out processes, we assume it to be constant in time.

In addition to direct glacial input of sediment, the model simulates in a simple way other factors affecting the sediment record, including sediment transfers due to submarine failures of unstable moraine embankments and gravity flows off submarine bedrock highs. The fjord bathymetry is averaged into discrete reaches, and sediment is allowed to build up in each reach; if the slope between two adjacent reaches at any time step exceeds a critical slope angle, the sediment is remobilized into the adjacent fjord reach by gravity flow until the critical angle is achieved. The critical angle is assumed to be that of the steepest slope currently observed in the fjord bottom, commonly between 5° and 20°.

We assume that, during its advance phase, the glacier evacuated the entire sediment sequence previously deposited in the fjord and, therefore, that the entire seismically imaged sediment record in the fjord was deposited proglacially during the current retreat cycle. We have confidence in this assumption because there is no evidence in the seismic records of temperate fjords of hard reflectors within the transparent and layered sediment sequence; such reflectors would be expected if the glacier overrode and consolidated glacial sediments before retreating and depositing additional, unconsolidated sediments.

APPLICATION OF THE MODEL TO MUIR INLET

To explore the potential interactions between ice motion, ice retreat, and sediment accumulation, and to develop a sense of time and length scales represented in sediment thickness profiles, $S(x)$, we analyzed the sediment package in Muir Inlet, Glacier Bay, Alaska, in which Muir Glacier and its tributaries have been retreating for the past century (Fig. 1). Muir Inlet is ideal because there is a good historical record of the rates of glacier retreat over the past century (Powell, 1991; A. Post, 1999, personal commun.), bathymetric and seismic surveys have been conducted in the fjord (Molnia et al., 1984), we can determine terminus positions and fjord widths for the past half century from air photos, and empirical studies of contemporary sediment fluxes and glaciomarine sedimentation rates have been conducted in Muir Inlet (Powell, 1991; Cowan and Powell, 1991; Hunter, 1994; Hunter et al., 1996).

We measured the thickness of the proglacial sediment sequence for Muir Glacier for the period from 1900, when the glacier first retreated from its terminal shoal at the mouth of the inlet, until 1979, from seismic reflection profiles collected by the U.S. Geological Survey in 1979 (Molnia et al., 1984). Sediment thicknesses along the deepest part of the fjord bottom were calculated by using an acoustic velocity of 1500 m/s and assumed to be uniform across $W(x)$, the width of the sediment sequence. The integrated annual retreat rates were calculated by reconstructing midsummer terminus positions from available maps (A. Post, 1999, personal commun.) and aerial photos, and applying a piecewise spline function to estimate positions during years in which no record was available. Fjord widths were determined from nautical charts and aerial photos.

Empirical studies of sedimentation rates with distance from the ice front in Muir Inlet (e.g., Powell, 1991; Cowan and Powell, 1991; Hunter, 1994) have shown that the rate of sedimentation with distance from the ice front is better described as a power-law decay; thus, in this application of the numerical model we use the following equation instead of an exponential:

$$\dot{S} = \dot{C} x^{-k}, \qquad (5)$$

where k now characterizes the length scale of significant sedimentation (i.e., as k increases,

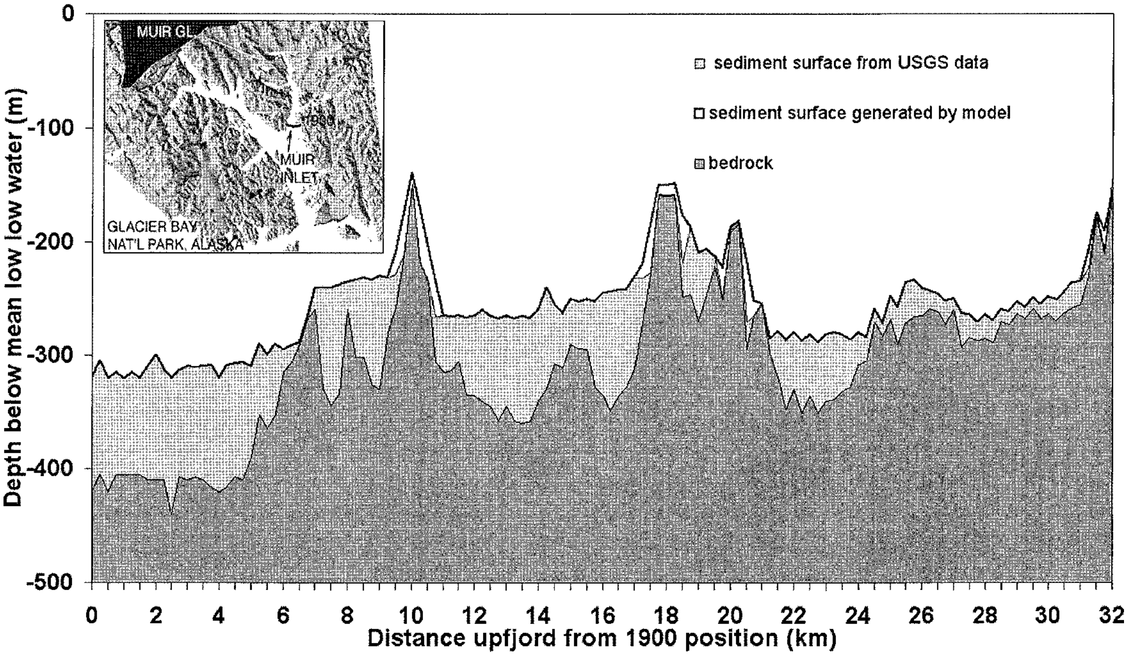

Figure 1. Modeled sediment surface and input data used in model. Bedrock depth profile and sediment surface in center of Muir Inlet were obtained from U.S. Geological Survey (USGS) seismic profiles. Model perfectly simulates sediment surface everywhere except around prominent bedrock highs. Inset: Location of Muir Inlet within Glacier Bay, Alaska.

the extent of the zone of active sedimentation in front of the glacier decreases), and $\dot{C}$ is now a parameter representing the sedimentation rate at the ice front, the units being m^{k+1}/yr. The use of an inverse power-law function implies that $\dot{S}$, and therefore $Q(t)$, approach infinity as x vanishes; however, this singularity is avoided by considering sedimentation averaged over a finite reach (250 m).

The parameter $\dot{C}$ is highly dependent upon the selected value of the exponent k. In our model, values of k of 0.7 and 1 were used, as empirically documented in Muir Inlet by Cowan and Powell (1991) and Hunter (1994) and in nearby Icy Bay by Jaeger and Nittrouer (1999); they represent significant sedimentation (i.e., >80% of total sedimentation) within 5 km of the ice front, when k equals 0.7, and within 1 km, when k equals 1. The model was run using critical slope angles from 5° to 20°; the maximum slope observed in Muir Inlet is 12°.

In addition, we maintain a direct sediment flux of 1.1×10^6 m^3/yr to the bin closest to the ice front, which is the average recent measurement by Hunter et al. (1996) of direct glacial debris flux from Muir Glacier.

MODEL RESULTS

The total volume of the proglacial sedimentary package in Muir Inlet, reconstructed from seismic profiles and recalculated using the model, is 1.3×10^9 m^3, corresponding to an average sediment flux of 1.6×10^7 m^3/yr for the period 1900–1979. If averaged over the entire 683 km^2 glacierized basin (the estimated drainage area in 1900, and therefore the maximum basin area), it yields an underestimation of the basinwide effective erosion rate of 18 mm/yr during the retreat (assuming a density of 2100 kg/m^3 for glaciomarine sediments, and 2700 kg/m^3 for eroded bedrock), consistent with the sediment fluxes and erosion rates inferred by others for Muir Glacier (Stravers and Syvitski, 1991; Hunter, 1994). Taking into account the large decrease in drainage area with time, the average basinwide erosion rate for the glacier during this period is 37 mm/yr.

Our model yielded a highly variable sediment flux that accurately reproduced the observed sediment thicknesses, with the exception of the major bedrock highs devoid of sediment (see Fig. 1). The calculated sediment accumulation history did not appear to be sensitive to the choice of the critical slope angle for submarine mass wasting, or of the length scale of deposition, k. Dividing the sediment flux by its contributing area at each time step yields the annually resolved erosion-rate history of Muir Glacier (Fig. 2A). In general, the erosion rate systematically parallels both the timing and magnitude of variations in retreat rate.

ICE DRAWDOWN AND SEDIMENT FLUX

Rates of erosion and retreat of Muir Glacier are correlated because changes in volume of the retreating glacier must be related to changes in ice dynamics. From the retreat history of the glacier, we can compute the reduction in glacier volume per unit time. Because calving vastly overwhelms ablation in reducing the glacier volume and ice must reach sea level to calve, this ice must be lost by calving at the ice front and drawdown of the glacier surface as it adjusts its longitudinal profile to its decreasing glacier length. We refer to this loss as the excess ice flux. Excess ice flux increases with the retreat rate, and vanishes when the total volume of ice added to the glacier from precipitation is exactly removed every year through calving and ablation, at which point retreat ceases.

Following Brown et al. (1982), a longitudinal profile can be reconstructed at every time step by assuming a parabolic profile for the glacier and constant ice-cliff height (60 m), basal shear stress (10^5 Pa), and valley shape factor (0.8). In the model, the volume of ice lost is the change in the product of glacier thickness, length, and width. The sediment flux from Muir Glacier closely parallels the ice flux, which is the sum of the excess flux related to this volume loss and balance flux dictated by the basin area and precipitation rate, assumed to be 3 m/yr (Hunter et al., 1994).

Our model results indicating a strong correlation between rapid retreat and high sediment yields enable us to reexamine the dichotomy between inferred erosion rates for tidewater glaciers in southeast Alaska and rates of tectonic uplift in the region. An average effective erosion rate of 37 mm/yr would lower the mean landscape at a rate of ~6 km/m.y. (~1/6 of 37 mm/yr, if local isostatic balance is maintained), quickly eliminating the relief we see today. The drastic retreat of large ice masses in temperate fjords and the concomitant increase in ice flux as they have retreated since the Little Ice Age are likely responsible for rapid erosion in the short term. Extrapolating the calculated erosion rates to periods of vanishing retreat yields rates of 7.5 ± 1.5 mm/yr, 5 ± 1 times lower than the average over the past century.

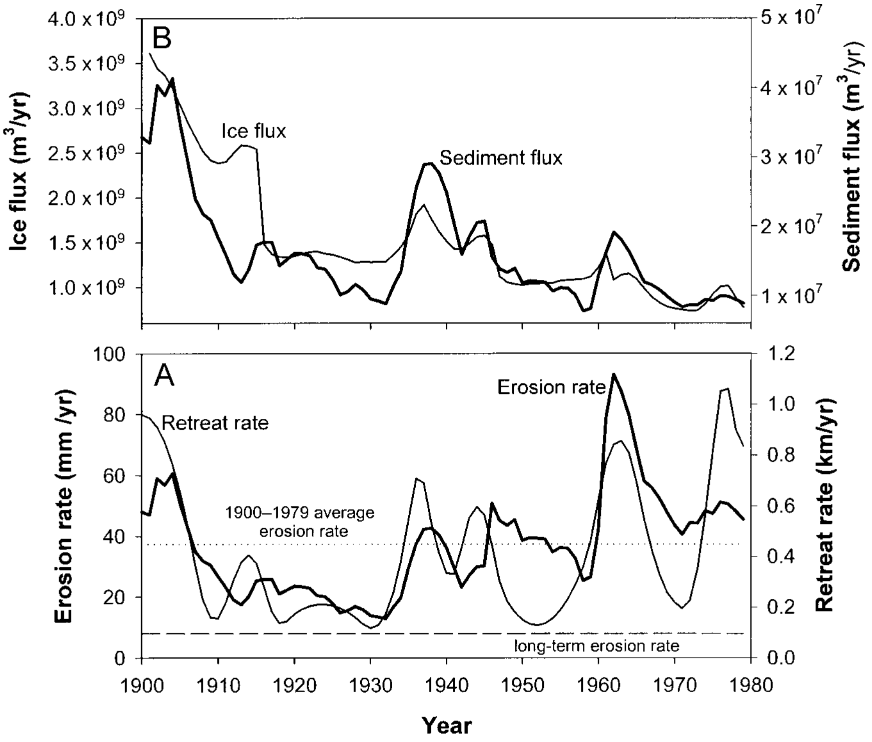

Figure 2. A: Basin-averaged erosion rate and retreat rate as functions of time. Three-point moving average for rates of erosion is used to reduce numerical noise inherent in averaging sediment thicknesses for discrete terminus positions. Over 79 yr period, erosion rate averages 37 mm/yr, but this is strongly biased by rapid glacial retreat since Little Ice Age; long-term rates are expected to be closer to ~7 mm/yr. B: Comparison of sediment flux from Muir Glacier and ice flux (see text).

SEDIMENT FLUX REFLECTS EROSION RATE

The correlation between the calculated sediment flux and measured retreat rate for Muir Glacier is not surprising if ice velocity is proportional to retreat rate, as it was found to be for Columbia Glacier (Van der Veen, 1996). Increases in ice velocity can lead to increases in glaciofluvial sediment flux to the terminus, either through enhanced fluvial evacuation of subglacial sediments that decrease the storage of sediments under the glaciers, or through enhanced subglacial erosion (Humphrey and Raymond, 1994). The former is unlikely to account for much of the proglacial sediment in the fjords because it requires an exceedingly large amount of sediment storage under the ice. To sustain the inferred sediment flux for the past century would require the evacuation of a debris layer almost 2 m thick over the entire basin. If the vast majority of sediment evacuation is transported by means of a well-developed subglacial hydraulic system that flushes the entire ablation zone, which typically comprises ~10% of total area of Alaskan tidewater glaciers (Hunter, 1994), the initial thickness of debris in the ablation zone would need to exceed 20 m. This is not likely, considering that there is no significant debris being stored subaerially, and the few basal core samples taken from other coastal glaciers in the region suggest that the debris layer is generally decimeters in thickness (Humphrey et al., 1993). More plausibly, the rapid sliding that accompanies rapid terminus retreat accelerates erosion of bedrock.

CONCLUSIONS

Total sediment budgets in recently deglaciated fjords can be used to calculate contemporary erosion rates of glaciers, but these rates are substantially larger than long-term rates because deglaciation is a period of anomalously high ice flux and rapid basal ice motion. Extrapolating the model results for Muir Glacier suggests that the 37 mm/yr average basinwide erosion rate obtained for the 1900–1979 period is about five times the long-term rate. The strong correlation we observed between sediment flux and ice flux suggests that, for land-based temperate glaciers as well as other tidewater glaciers, erosion rates increase with ice flux and much of the erosion is likely to occur during periods of rapid basal motion.

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