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SUBGLACIAL EROSION AND THE FATE OF COARSE MATERIAL IN THE SUBGLACIAL DRAINAGE SYSTEM OF THE MATANUSKA GLACIER, ALASKA

presented by

NICHOLAS J. WATERSON

has been accepted towards fulfillment
of the requirements for the

Master's degree in Geological Sciences

Grahame J. Larson
Major Professor's Signature

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SUBGLACIAL EROSION AND THE FATE OF COARSE MATERIAL IN THE SUBGLACIAL DRAINAGE SYSTEM OF THE MATANUSKA GLACIER, ALASKA

By

Nicholas J. Waterson

A THESIS

Submitted to
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ABSTRACT

SUBGLACIAL EROSION AND THE FATE OF COARSE MATERIAL IN THE SUBGLACIAL DRAINAGE SYSTEM OF THE MATANUSKA GLACIER, ALASKA

By
Nicholas J. Waterson

Melt-water streams draining temperate glaciers are known to transport considerable sediment via suspended and bed load. However, recent studies of sediment in melt-water streams discharging from vents along the margin of the Matanuska Glacier in south-central Alaska show bed load to be <1% of the total load despite the availability of coarse material at and near the glacier bed. A possible explanation for this is that much of the coarse material is being trapped within the subglacial drainage system due to an adverse slope of the glacier bed near the terminus. An estimate of the mass of coarse material potentially being trapped was calculated by determining the grain-size distribution of the debris-rich basal ice and subglacial sediment at the Matanuska and measuring the suspended sediment flux in melt-water streams and calculating an average minimum effective erosion rate for six consecutive ablation seasons. The results show that 2.85E+08kg to 8.61E+08kg of coarse material could by trapped at the glacier bed each year. If deposited within $5km^2$ of the glacier terminus this would be equivalent to a layer 2.9 to 9.3 cm thick. How the coarse sediment might be distributed, however, would depend on the geometry of the adverse(s) and the type and pattern of the subglacial drainage system. The average minimum effective erosion rate for the six consecutive ablation seasons of 1997-2002 is 1.13 mm/yr.

ACKNOWLEDGEMENTS

Like any type of research, one person can seldom do it alone. I would like to take this opportunity to thank the people that made this research possible. First, I would like to thank my advisor, Grahame J. Larson for passing on his knowledge and for his patience and guidance with my many revisions. The knowledge that I have learned has been invaluable from subjects to glacial geology, writing, and surficial mapping. Secondly, I would like to thank my committee members, David T. Long and Gary S. Weissmann, for taking time to critique the thesis and suggest the proper changes. Third, I would like to thank the Matanuska Mafia for the opportunity to work in Alaska at the Matanuska Glacier and for the experience of working with so many great scientist in the field. Forth, I would like to thank the Camp Crew, including, John Linker, Michiel Kramer, James Cassionne, for help setting up camp and collecting samples throughout the summer. Lastly, I would like to thank my family for their support during my time here at MSU.

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Introduction

Melt-water streams draining mountain glaciers are characterized by large and rapid discharge fluctuations that transport major amounts of sediment and with analysis of the sediment yield, an erosion rate for the glacierised basin can be determined (Ostrem, 1973; Hammer and Smith, 1983; Gurnell, 1987; Bezinge, et al. 1989; Hallet et al., 1996; Collins, 1998; Linker, 2001). For example, Hallet et al., (1996) studied sediment yields from melt-water streams draining the Nigardsbreen Glacier, Norway, from the past 25 years and calculated an erosion rate of 0.15 mm $year^{-1}$. In this study, he also complied erosion rates calculated by Benzinge (1987), Andrews et al., (1994), and Hunter (1994) for different glaciers. These ranged from 0.01 mm $year^{-1}$ for polar glaciers (Andrews et al., 1994) to 1.0 mm $year^{-1}$ for small temperate glaciers in the Swiss Alps (Benzinge, 1987), and 10 to 100 mm $year^{-1}$ for large temperate valley glaciers in southeast Alaska (Hunter, 1994). Subsequently, Collins (1998) studied the sediment yield from melt-water streams draining the Batura Glacier, India during the melt season of 1990 and calculated erosion rate 7.7 mm $year^{-1}$. More recently, Linker (2001) studied the sediment yield from melt-water streams draining the Matanuska Glacier, Alaska for the years of 1997 to 2000 and calculated an average erosion rate of 1.6 mm $year^{-1}$, a value that is in the middle of the rates compiled by Hallet et al., (1996).

Many difficulties exist, however, when calculating erosion rates for glacierised basins. One difficulty is obtaining representative samples of sediment from melt-water streams (Fenn et al., 1985; Collins, 1998; Linker, 2001). Another difficulty is approximating the influx of sediment from subaerial erosion of adjacent nonglacierized areas (Fenn et al., 1985; Collins, 1998; Linker 2001). Still another problem is the collection of long-term, annual data sets of sediment yield, which is needed because of the annual variability of sediment production caused by temporary storage of sediment within and beneath the subsole of the glacier and changes within the subglacial plumbing (Ostrem, 1975; Hammer and Smith, 1983; Gurnell, 1987; Bezinge et al., 1989; Hallet et al., 1996; Collins, 1998; Linker, 2001). Lastly, and probably the greatest difficulty, is estimating the bedload component of the total sediment output for the melt-water streams because of the 1) logistical problems associated with monitoring bed load in remote, high energy, melt-water streams and 2) because of the great disparity between published values of bed load ranging from <1% of the total clastic load at the Matanuska Glacier (Pierce et al., 2003) to >75% of the total clastic load for glaciers in southeast Alaska (Ostrem, 1975; Hammer and Smith, 1983; Hallet et al.,1996; Linker, 2001).

The objective of this research is to calculate the average minimum effective erosion rate for the Matanuska Glacier during six consecutive ablation seasons and to determine the fate of coarse material at the glacier bed by analyzing the grain-size characteristics of the available sediment supply.

Methods of Bed Load Estimation

There have been only a few studies that attempt to deal with bed load transport in glacial melt-water streams (Ostrem, 1975; Hammer and Smith, 1983; Gurnell, 1988; Hallet et al., 1996; Pierce et al., 2003). Ostrem (1975) studied the suspended sediment yield from several Norwegian glaciers, but at the Nigardsbreen Glacier, he estimated the bed load component by building a steel mesh fence across a stream draining the glacier that trapped bed load. After several weeks, he estimated the bed load to be about 25% of the total load. Hammer and Smith (1983) also studied bed load in a melt-water stream draining a small cirque glacier in northern Banff National Park, Alberta during the melt season of 1977 and 1978. They measured bed load by using a steel mesh fence extended across the melt-water stream that trapped bed load. Periodically, they excavated and measured the accumulated bed load and estimated bed load to be about 57% of the total load in 1977 and 54% in 1978.

At two small glaciers in the Swiss Alps, Gurnell et al., (1988) studied bed load in melt-water streams draining Glacier de Tsijiore Nouve and Bas Glacier d' Arolla. They measured bed load from these melt-water streams using accumulation traps in hydroelectric power adduction structures. For each glacier, Gurnell et al., (1988) estimated that the bed load to be about 60% of the total load.

At the Nigardbreen Glacier, Hallet et al., (1996) estimated bed load from annual measurements of deltaic growth in a lake close to the terminus of the glacier. He estimated bed load to be about 41% of the total load.

Other studies have also attempted to estimate bed load from measurements done at other glaciers. For example, Collins (1998) referred to ratios determined by Ostrem (1975) for the Nigarsbreen Glacier (75/25), by Gurnell et al. (1988) for Glacier de Tsijiore Nouve (60/40), and for Bas Glacier d' Arolla (60/40) to estimate bed load in streams draining the Batura Glacier, India. He estimated bed load in those streams to be about 50 % of the total load.

However, Pierce et al., (2003) studied bed load from melt-water streams discharging from vents along the margin of the Matanuska Glacier and found bed load to be < 1% of the total load despite the availability of coarse material at and near the glacier bed. They sampled bed load by using two Helly-Smith hand-sampling devices of different sizes and sampled the same location throughout the 2002 ablation season.

Study Area

The Matanuska Glacier is a large valley glacier that flows north from ice fields of the Chugach Mountains and terminates in the upper Matanuska Valley in south-central, Alaska (61^{o} 47'N, 147^{o} 45'W) (Figure 1). The regional bedrock of the basin consists of sedimentary and low to mid grade meta-sedimentary rocks such as phyllites, slates, and argillites (Winkler, 1992). The glacier is approximately 45 km long and ranges in width from approximately 2.5 km near the equilibrium line to about 5 km at the terminus and occupies approximately 57% of an elongate drainage basin that covers an area of 665

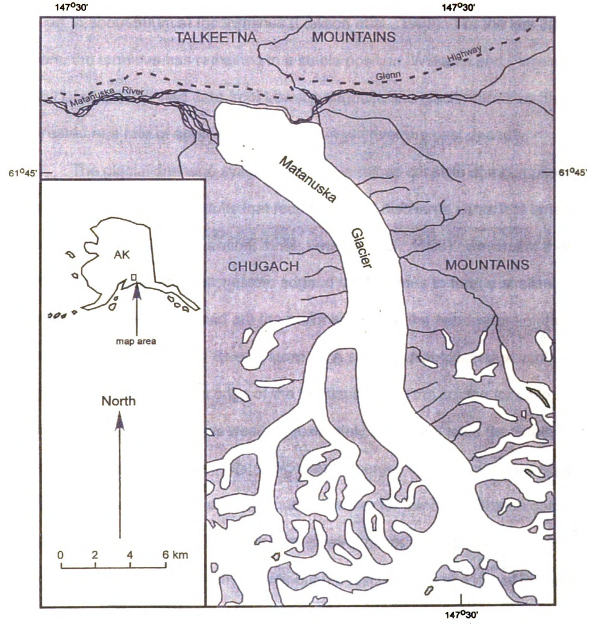


Figure 1. Location map for the Matanuska Glacier, Alaska (modified from Lawson, 1979).

km^2 (Lawson et al., 1998; Strasser et al., 1996). The glacier ranges in elevation from approximately 3500 m at the highest source on Mount Marcus Baker to about 500m at the terminus (Lawson et al., 1998). For the last 200 years, the terminus has remained in a stable position (Williams and Ferrains, 1961), but unpublished data from Lawson suggests the glacier terminus has retreated at a rate of approximately 10-30 m yr^{-1} over the past decade.

The glacial drainage system near the terminus consists of a complex network of subglacial conduits that feed individual discharge vents that emerge from the glacier margin (Lawson, 1993; Lawson et al., 1998). Several of these vents occur along the southwestern edge of the terminus to form a shallow perennial proglacial lake and are the major source for the headwaters of the South Branch, Matanuska River (Figure 2). A second main discharge vent emerges from the western edge of the terminus and is the source for Little River (Figure 2), which flows west approximately 500m and joins the South Branch, Matanuska River. A third large vent emerges from the northern edge of the terminus and is the primary source of water for the North Branch of the Matanuska River (Figure 2). There are several minor vents occurring on the north-northeastern edge of the glacier but the discharges are <1 % of the total discharge and are insignificant (Denner, personal communication).

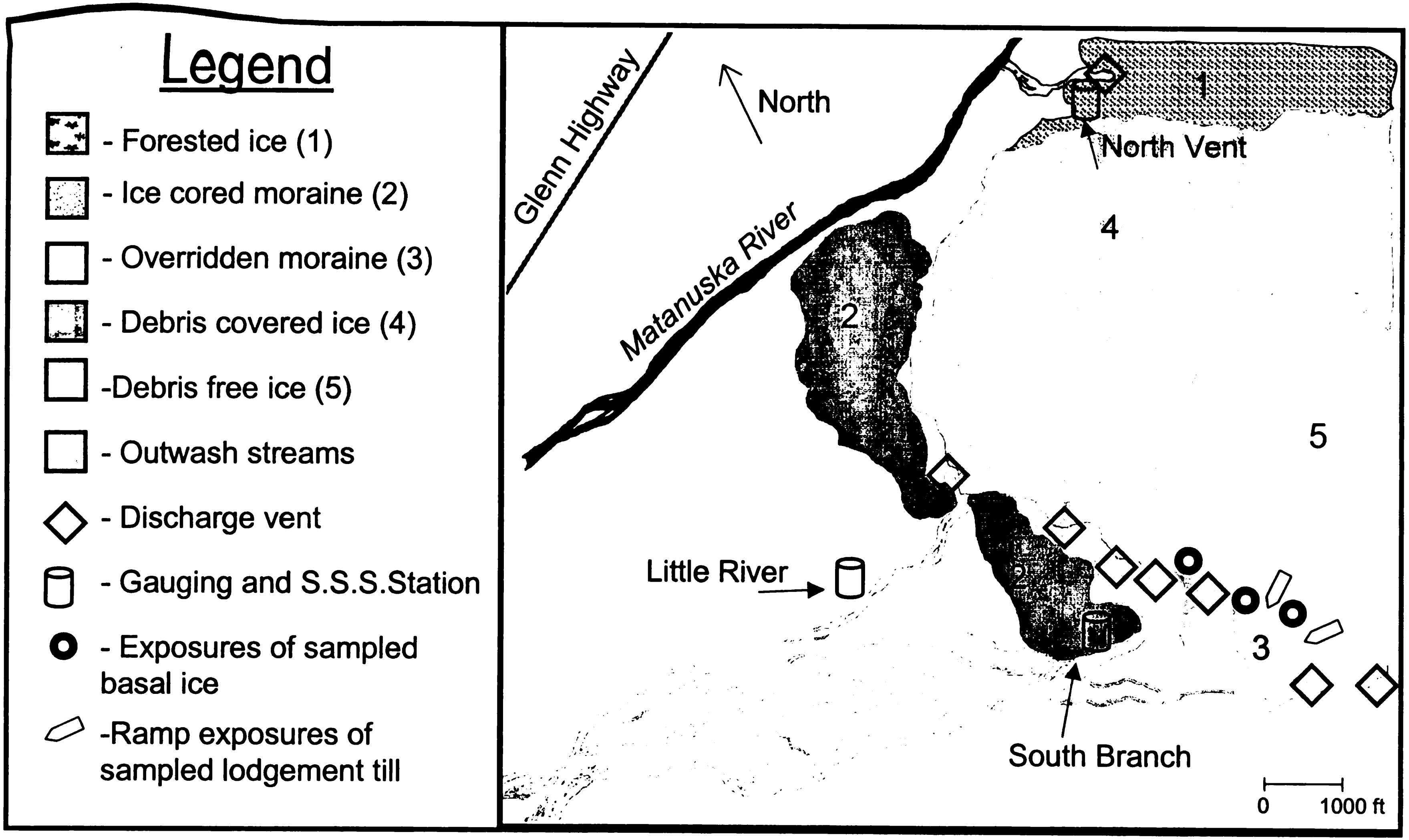


Figure 2: Map showing margin of the Matanuska Glacier with sample locations

Methodology

Located on each of the three main meltwater streams (South Branch, North Branch, Little River) draining the Matanuska Glacier are a suspended sediment sampling (SSS) station and a gauging station. At South Branch, the SSS station is located approximately 200m from the western terminus of the glacier and is adjacent to the gauging station (Figure 2). The SSS station at North Branch is located approximately 25 m upstream from the gauging station at the large vent that forms the headwaters for the North Branch stream (Figure 2). At Little River the SSS station is located approximately 150m from the edge of the glacier terminus and adjacent to the gauging station (Figure 2).

Discharge Measurements

During the ablation seasons of 1995-2001, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) maintained the gauging station on the South Branch and the North Branch, Matanuska River and generated stage/discharge rating curves for both streams. CRREL also maintained the Little River gauging station during the ablations seasons of 2000-2001 and generated a rating curve for that stream. At each station is a datalogger and a nitrogen gas bubbler system, which continuously collects stage data throughout most of the year and allows for hourly calculation of discharge through the entire melt season with a measurement accuracy of approximately 93% (Linker, 2001: Denner, personal communication).

Suspended Sediment

Suspended sediment samples of 1000 ml were obtained at two-hour intervals at each of the SSS stations, using an automated water sampler (ISCO 3700). At SSS station at South Branch, samples were continuously collected from early June through late August, 1997-2000. At the SSS station along North Branch, samples were continuously collected from late July through late August, 1999, and early June through late August, 2000-20001. Little River was not sampled during 1997-1999 melt seasons because it was not a significant meltwater stream but became a significant melt-water stream from early June though late August, 2000-20001, samples were collected continuously (Denner, personnel communication).

Each ISCO water sampler was equipped with an intake connected to approximately 15 m of 1.5 cm diameter latex tubing. The intake was anchored 10-30 cm above the channel bed or in the case of North Branch, within the opening of the large vent. Each sample was processed by vacuum filtration through individually pre-weighed numbered 90mm borosilicate microfiber filter circles. Sediment filled filter circles were then dried in an oven at 110°C and gravimetrically weighed to a precision of $\pm$ 1 mg. Suspended sediment concentrations in terms of g/L (equivalent to kg/m^3) were calculated by dividing the mass of the dried samples by the volume of the water sample. Concentrations of suspended sediment recorded at South Branch, North Branch, and Bridge Stream ranged from about .3g/L to 32g/L.

Potential Sediment Sources

Sediment supplied to the three main melt-water streams draining the Matanuska Glacier is derived from four principal sources: 1) subglacial sediment, 2) debris within basal ice, 3) superglacial debris, and 4) proglacial sediment. Each source has a characteristic grainsize distribution.

Subglacial Sediment

Subglacial sediment is composed mainly of melt-out till, some lodgement till, and some interstratified material composed of debris flows, and fluvial lacustrine sediments that have been overridden by ice (Lawson, 1979; Lawson, 1982). Melt-out till is locally exposed along the terminus of the glacier, generally below debris flow deposits (Figure 3). Where as lodgement till is exposed sporadically along the western part of the terminus along active shear planes associated with the override of stagnant ice (Figure 4) (Lawson, 1979). Interstratified debris flows and fluvial and lacustrine sediments are visible along the western part of the terminus where ice is overriding what appears to be a former moraine (Figure 5).

Lawson (1981) characterized three types of melt-out till at the Matanusaka Glacier, which vary from 1) structureless pebbly silts to 2) pebbly sandy silt containing disturbed, discontinuous laminae to 3) lenses of sorted and stratified sediment of variable grain size or composition. In melt-out till, subangular to rounded clasts of pebble to cobbles are randomly dispersed in a loose matrix. Depostis of melt-out till occur as sheets to discontinuous sheets with a variable thickness of one to three meters (Lawson, 1979). Lawson

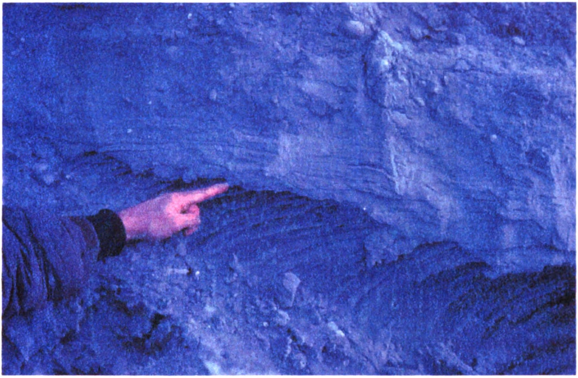


Figure 3. Melt-out till exposure approximately 0.5km from the terminus. Pointing to contact between buried basal ice on bottom and melt-out till on top.

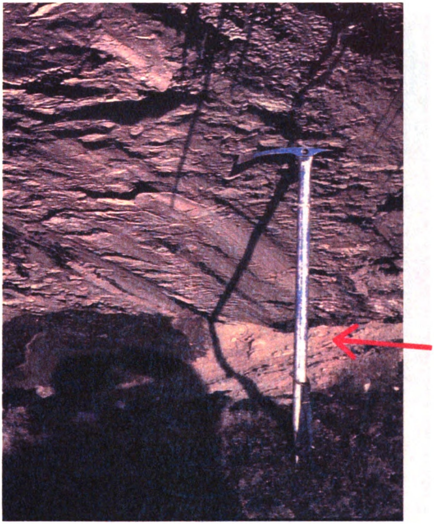


Figure 4. Lodgement Till exposure under an ice ramp along the active terminus. The pick of the ice axe (1m) is resting on the ramp of ice and the sediment hanging down are till curls. The red arrow is pointing to the lodgement till.

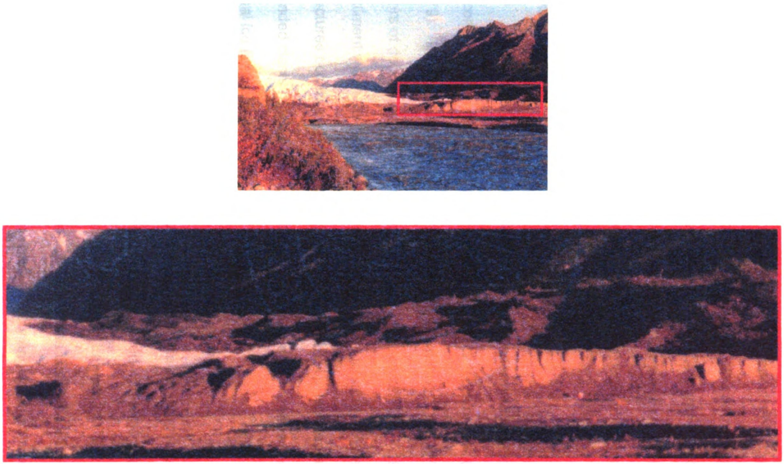


Figure 5. Exposure of an overridden moraine along the active terminus.

(1979) also characterized lodgment till at the Matanuska Glacier as a mixture of gravel-sand-silt with mostly subrounded clasts of pebble to cobbles randomly dispersed to clustered in a dense matrix. Deposits of lodgement till generally occur as discontinuous pockets or sheets (Lawson, 1979). Observations beneath ramps of overriding ice near the Matanuska Glacier terminus during the winter of 98 show deposits of lodgement till up to 10-20cm thick. No information, however, exists about the thickness of lodgement till beneath active ice further up glacier.

Basal Ice

Basal ice is exposed along the active western terminus and occurs as a discontinual layer ranging in thickness from about 0.2 to 15 meters (Lawson, 1979). It is stratified, with debris distributed in alternating .01 to 1.7m thick layers of debris rich and debris poor ice (Figure 6)(Lawson, 1979; 1981). Sediment within the debris rich layer consists of clay to sand with sedimentary structures occasionally preserved (Lawson, 1979; 1981). Isolated angular to rounded clasts ranging from gravel to cobbles also occur randomly within the basal ice (Lawson, 1979).

Supraglacial Debris

Supraglacial debris is exposed all along the glacier margin but mainly on the eastern part of the terminus where it is associated with a medial moraine and ranges in thickness from <1cm to > 3 meters (Lawson, 1979; 1981). Along the western part of the terminus it consists as isolated cobbles and boulders (Figure 2). It is composed chiefly of very angular to angular, sandy

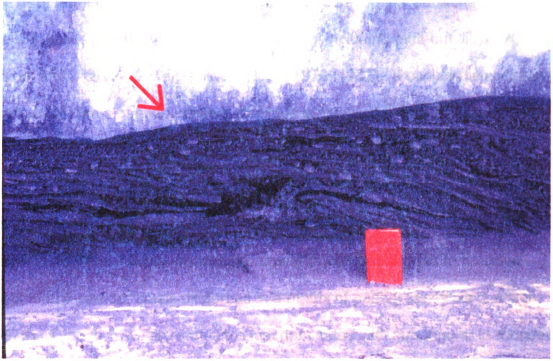


Figure 6. Exposure of basal ice along the active terminus. The field notebook is sitting at the base of stratified basal ice and the red arrow is pointing to the contact between englacial ice and basal ice.

gravel and more than half is composed of cobbles and boulders (Lawson, 1979).

Proglacial Sediment

Proglacial sediment is exposed mainly in an ice-cored zone along the western terminus of the glacier and is composed mainly of subaerial gravity flow deposits and some interstratified material including melt-out till, spall, fluvial and lacustrine sediments (Lawson, 1979; 1982). It occurs mainly in an ice-cored zone along the western terminus of the glacier (Figure 2) (Lawson, 1982). Lawson (1979; 1981; and 1982) has classified the subaerial flow deposits into four types, primarily as a function of water content. These flows range in thickness from .01 to approximately 2 meters (Lawson, 1979; 1982). Type I and Type II flows are matrix dominated with subangular to rounded cobble and boulder clasts dispersed in a matrix of pebbly sandy silt (Lawson, 1979). Type III flows are matrix to clast dominated with subangular to rounded cobble and boulder clasts in a matrix of gravelly sand to sandy silt (Lawson, 1979). Type IV flows are relatively fine grained with a homogenous texture of sandy silt or a coarse silty sand with coarse subangular to rounded clasts in traction at the bed of the flow (Lawson, 1979).

Grain-Size Analysis of Suspended Sediment and Potential Sediment Sources

Samples of supraglacial debris (n=10) were collected for grain-size analysis from debris-covered ice along the western margin. Also, samples of subglacial debris (n=10) were collected from an exposure located along the active western terminus of the glacier, and samples of basal-ice debris (n=10) and melt-out till (n=10) were collected from an exposure of buried, stagnant basal-ice approximately 0.5 km from the western terminus. Samples of lodgement till (n=10) were collected from an exposure located along the active western terminus. Proglacial lacustrine sediment (n=10) was sampled along a transect in front of the western terminus and suspended sediment was sampled from a discharge vent (Mega Vent) at the western terminus and also from the Matanuska River at the South Branch S.S.S. station. All samples were analyzed by dry sieving at 1/2 phi intervals for the grain-size range of -2.0 to 4.0 phi (4mm to .063mm). A Micromeritics Sedigraph 5100 was used for the grain-size range of 4.25 to 10 phi (.053mm to .001mm).

The grain-size ternary diagram presented in figure 7 show that supraglacial, subglacial, and basal-ice debris, melt-out till, lacustrine sediment, and suspended sediment has different textural characteristics. Samples of supraglacial debris plot mainly in the gravel and sand region of the ternary diagram and have an average gravel, sand, silt/clay content of approximately 55%, 36%, and 9%. The samples of subglacial debris plot mainly in the middle region and have an average gravel, sand, silt/clay content of approximately 29%, 40%, and 31%. Basal-ice debris and melt-out till samples plot between the silt/clay and sand region and have an average gravel, sand, silt/clay content of 11%, 38%, and 51% and 11%, 35%, and 54%, respectively.

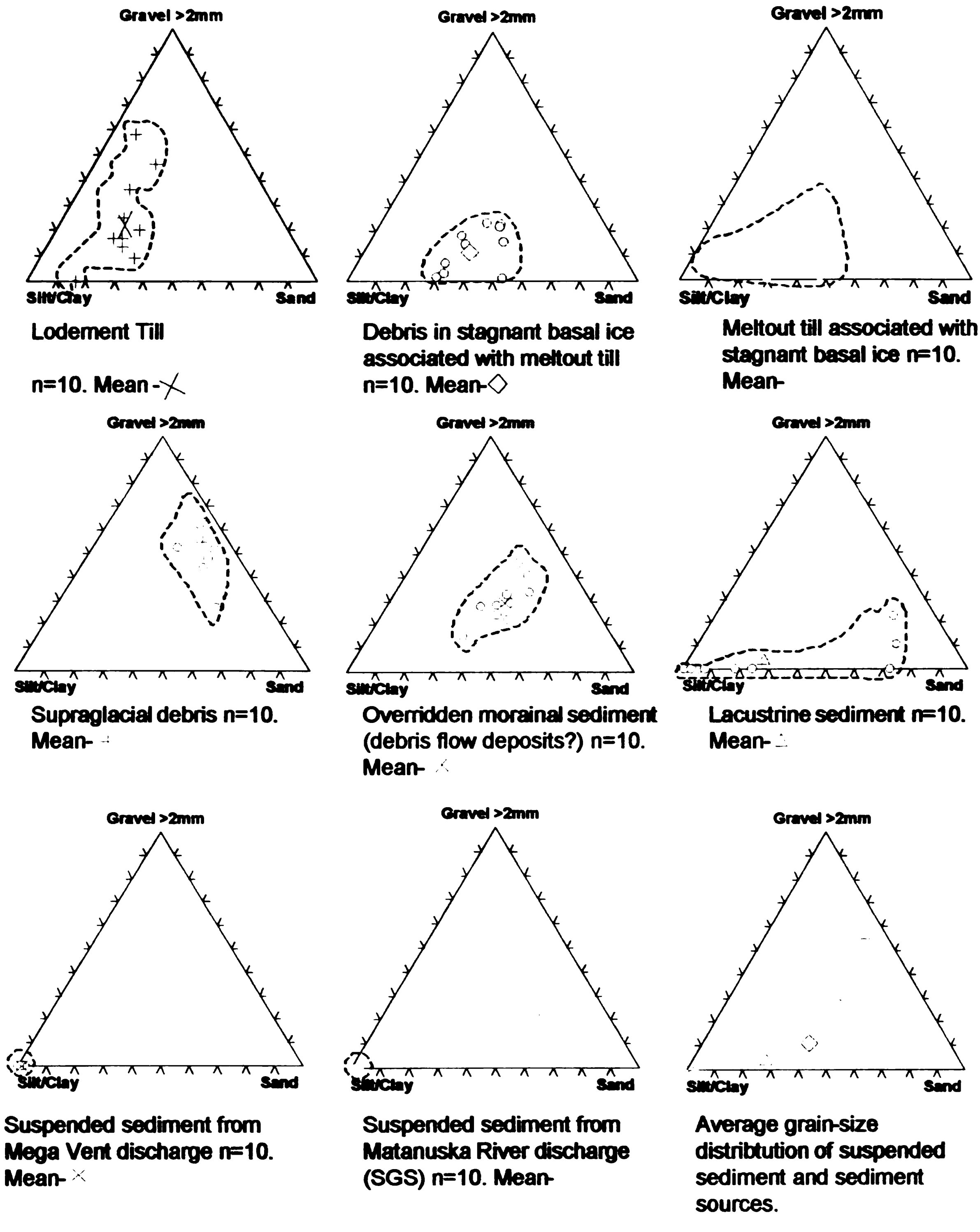


Figure 7. Ternary plots for the average grain-size distribution of suspended sediment and potential sediment sources.

Lodgement till samples plot between the silt/clay and sand region and have an average gravel, sand, and silt/clay content of approximately 24%, 21%, and 55%. Samples of lacustrine sediment plot mainly in the silt/clay region and have an average gravel, sand, silt/clay content of approximately 3%, 27%, and 70%. Samples of suspended sediment from the discharge vent and the Matanuska River plot mainly in the extreme silt/clay region. The samples are generally void of any gravel and sand and have an average silt/clay content of approximately 99%.

The average cumulative-percent curves of grain-size for supraglacial, subglacial, and basal-ice debris, melt-out till, lacustrine sediment, and suspended sediment presented in figure 8 also show that the samples have different textural characteristics distinct. The curve for supraglacial debris shows a grain-size distribution similar to that described by Lawson (1979) for supraglacial debris at the Matanuska Glacier which he attributes to material weathered from valley walls and nunataks and mass transported onto the glacier surface. The curve for subglacial debris is within the range of curves published by Lawson (1979) for recent debris-flow deposits at the Matanuska Glacier. The similarity suggests that the subglacial sediment originated as an assemblage of debris-flow deposits and was subsequently overridden by advancing ice. The curve for basal-ice debris is also comparable to curves published by Lawson' (1979) for basal-ice debris from the Matanuska Glacier. Strasser et al., (1996), Alley et al., (1998), Lawson et al., (1998), Evenson et al., (1998) attribute the origin of the basal-ice to "glaciohydraulic supercooling",

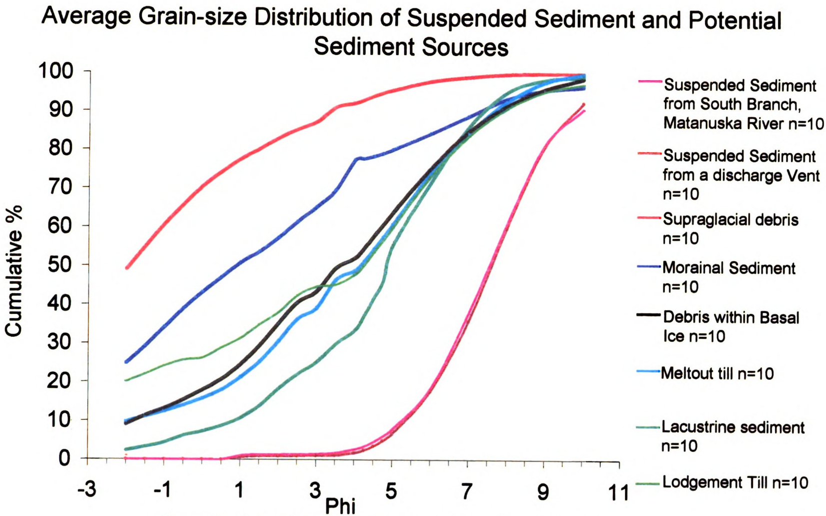


Figure 9. Cumulative percent curves of the average grain-size distribution of suspended sediment and potential sediment sources.

a mechanism creating debris rich basal-ice by entraining sediment during ice growth and accretion process at the basal zone of the glacier. The curve for melt-out till is similar to curve for basal-ice debris. This is to be expected since the melt-out till is derived from the *in situ* melting of buried basal ice (Boulton, 71; Lawson, 81). The curve for lacustrine sediment shows a lack of coarse sediment. The two curves for the suspended sediment show that the suspended sediment from the discharge vent is texturally equivalent to suspended sediment in the Matanuska River.

Discharge Characteristics

The discharge recorded for South Branch S.S.S. station during the 1997-2000 ablation seasons (Linker 2001) and during the 2001-2002 ablation seasons (this study) is presented in figure 9a., b., c. In general, the record shows increasing discharge between early to mid June, peak discharge occurring between mid to late July or early August, and decreasing discharge throughout the remainder of the melt season (Figure 9 a., b., c). Total discharge recorded for the period June through August 1997-2002 is approximately 6.54E+08 m^3, 5.06E+08 m^3, 6.42E+08 m^3, 4.39E+08 m^3, 5.01E+08m^3 and 4.97E+08m^3.

The record shows substantial variability in daily discharge that can be attributed to rainfall events (Linker, 2001), air temperature changes that effect rate of ice melt (Collins, 1998), rapid changes in ice-surface albedo due to snow fall (Lawson,1993) and periods of sunny cloudless weather where melt

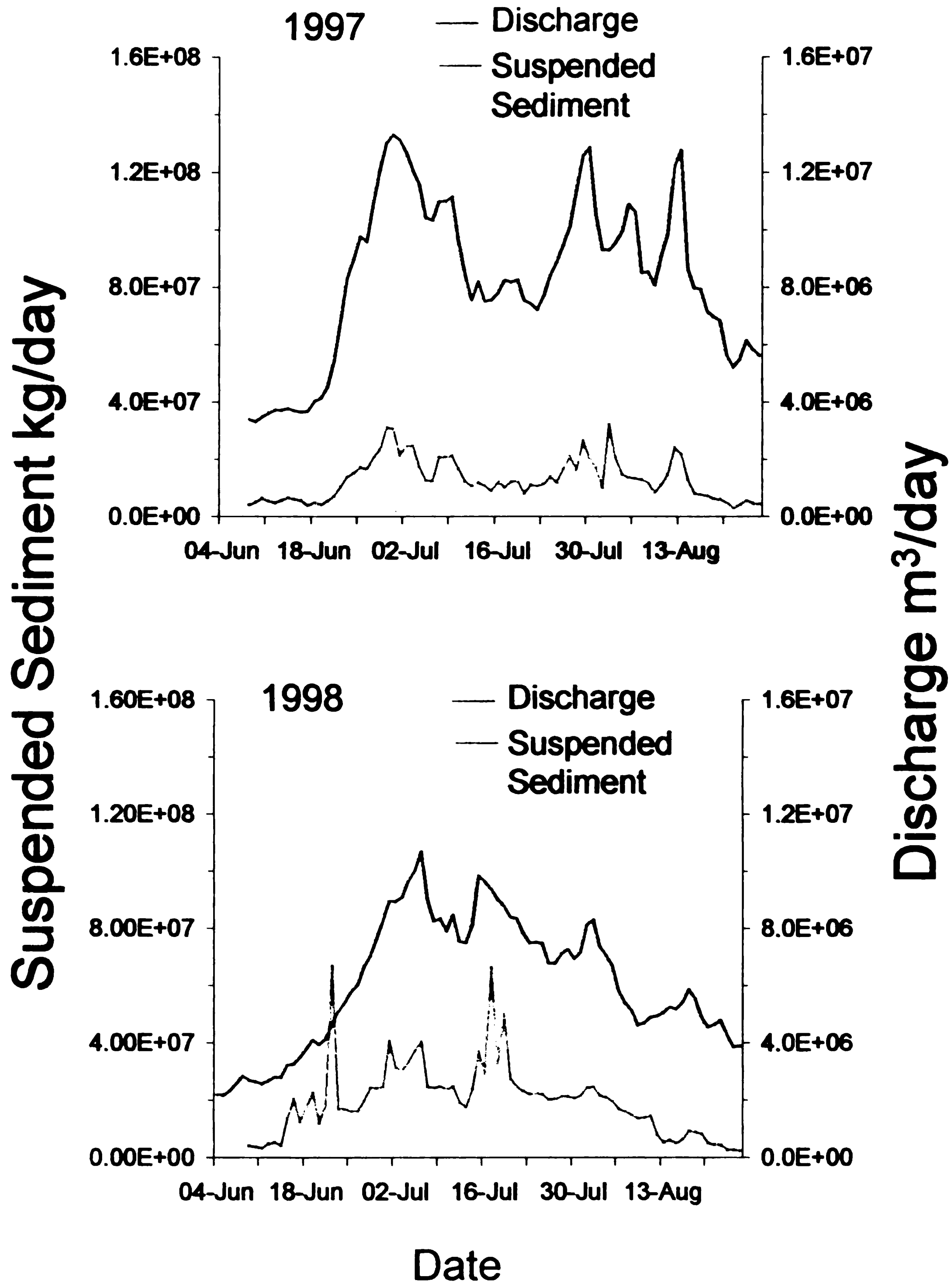


Figure 9. Plots showing suspended sediment and discharge recorded at South Branch, Matanuska River during the 1997 and 1998 ablation seasons.

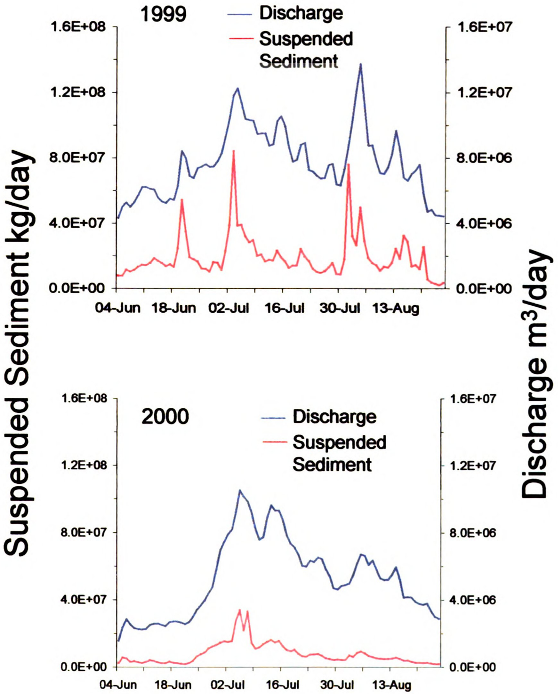


Figure 9 (continued). Plots showing suspended sediment and discharge recorded at South Branch, Matanuska River during the 1999 and 2000 ablation seasons.

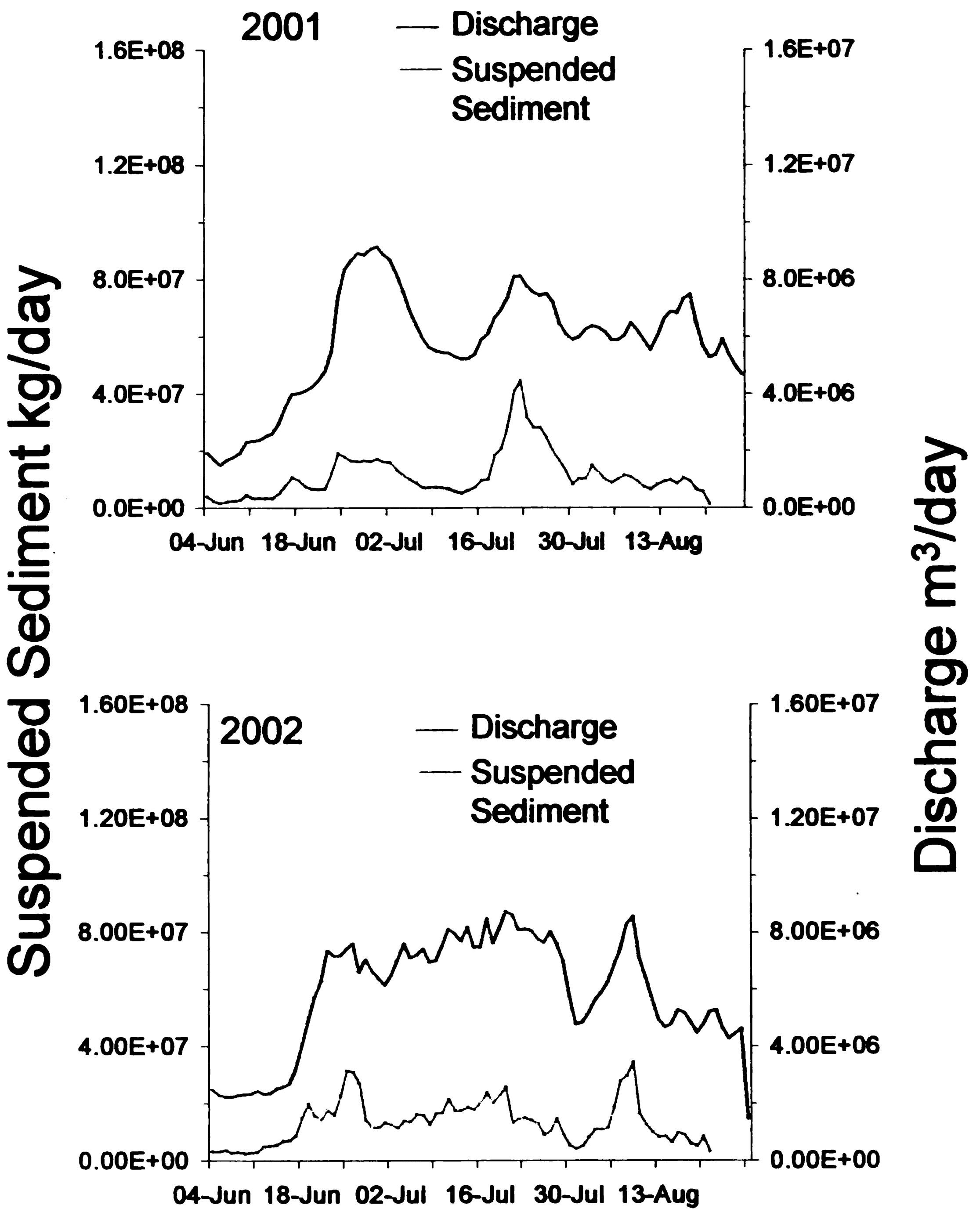


Figure 9 (continued). Plots showing suspended sediment and discharge recorded at South Branch, Matanuska River during the 2001 and 2002 ablation seasons.

from solar radiation is excessive. For example, Linker (2001) attributes peak discharges recorded 1 and 8 August and 12 and 20 August, 1999 to rainfall events. On the other hand, the high discharge recorded 24 June to 3 July, 2001 can be attributed to a period of high solar radiation receipts.

Suspended-Sediment Flux Characteristics

The suspended-sediment flux recorded for South Branch S.S.S. station during the 1997-2000 ablation seasons (Linker, 2001) and during the 2001-2002 ablation (this study) is also shown in figure 9a., b., c. The daily-suspended- sediment flux was calculated as a product of the measured suspended-sediment concentrations and the average discharge measured at the station summed over a 24-hour period (Linker, 2001). Total suspended-sediment concentration for the period June through August for 1997-2002 is approximately 9.82E+08 kg, 1.47E+09kg, 1.55E+09kg, 6.96E+08kg, 8.62E+08kg, and 1.04E+09kg.

The record in figure 9.a., b., c. also shows substantial variability in daily suspended-sediment flux. This variation can be attributed to meltwater outbursts that transport large volumes of suspended sediment and the migration of channels that erode unworked sources of sediment stored at the ice-bed interface (Gurnell, 1987). The variability can also be attributed to increasing discharge from rainfall events, which transport additional suspended sediment from inwash into the glacier basin, and due to increasing melt from high solar radiation receipts that increase subsequent erosion by subglacial streams. For example, Linker (2001) attributes peak suspended sediment flux recorded 1 and 8 August and 12 and 20 August, 1999 to rainfall events. On the other hand, the high suspended sediment recorded 24 June to 3 July, 2001 can be attributed to increase melt due to high solar radiation.

Minimum Effective Erosion Rate

The total suspended-sediment flux shown in figure 10 includes data from all three melt-water streams draining the Matanuska Glacier. According to Linker (2001), South Branch contributed approximately 96% of the total sediment flux during the 1997, 1998, and 1999 ablation seasons, whereas North Branch contributed approximately 4% of the total sediment flux for those years. He also found South Branch contributed approximately 95% of the total sediment flux during the 2000 ablation season, whereas North Branch contributed approximately 3.6% of the total sediment flux and Little River which developed that year, only about 1.4% of the total sediment flux for that year. In this study, it was found that South Branch contributed approximately 93% of the total sediment flux during the 2001 and 2002 ablation seasons while North Branch contributed approximately 5% of the total sediment flux and Little River only about 2% of the total sediment flux during those years.

In this study, the annual, minimum effective erosion rate is defined as the total annual suspended-sediment flux recorded in the three melt-water streams draining the glacier (difference between what is being eroded and deposited at the bed of the glacier) and assumes no change in sediment

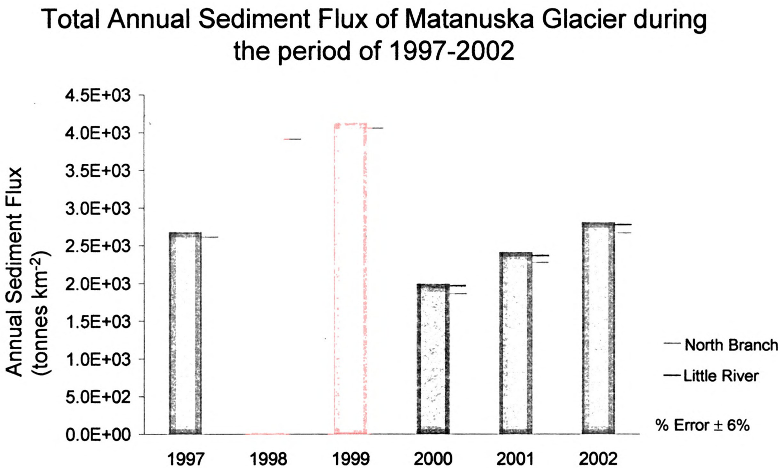


Figure 10. Total annual sediment flux of Matanuska Glacier during the period 1997-2002.

storage within the ice. It is also assumed that input of sediment by subaerial erosion from nonglacierized areas within the basin is minimal and does not significantly contribute to the total sediment flux. A third assumption is that the annual sediment flux recorded in the melt-water streams during the ablation season approximates the total annual sediment flux from the glacier, or at least the minimum, total annual sediment flux.

Annual, minimum effective erosion rates for the Matanuska Glacier were calculated for the period of 1997-2002 by dividing the minimum total annual suspended-sediment flux by the total area of the glacierized basin, approximately 380 km^2, and subsequently dividing by an estimated bedrock density of 2.65 g/cm^3. The calculated annual, minimum effective erosion rates are presented in figure 11 and show rates ranging from 0.75$mmyr^{-1}$ for 2000 ablation season to 1.56 $mmyr^{-1}$ for 1999 ablation season, or an average minimum effective erosion rate of approximately 1.13 $mm\ yr^{-1}$ over the six year period.

Discussion

Annual Suspended Sediment Flux vs. Discharge

A plot of suspended-sediment flux vs. discharge at South Branch for the 1997-2002 ablation seasons is presented in figure 12a and shows an unstable relationship between the two parameters. For example, the highest recorded suspended-sediment flux occurred in the 1999 ablation season, whereas the highest recorded discharge occurred in the 1997 ablation season. On the

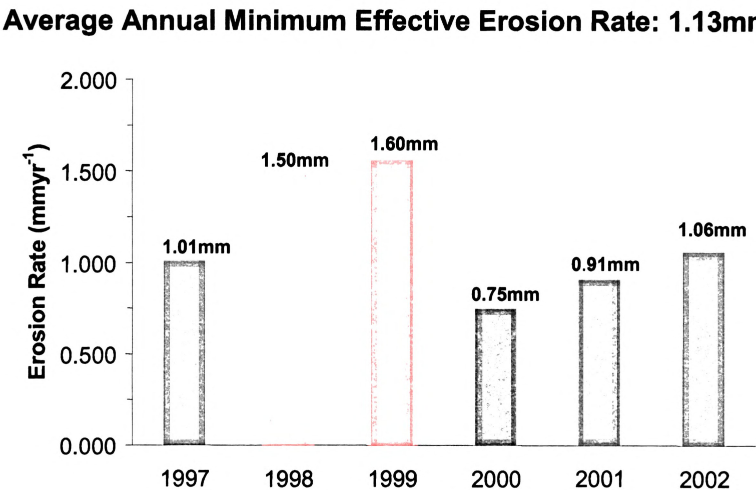
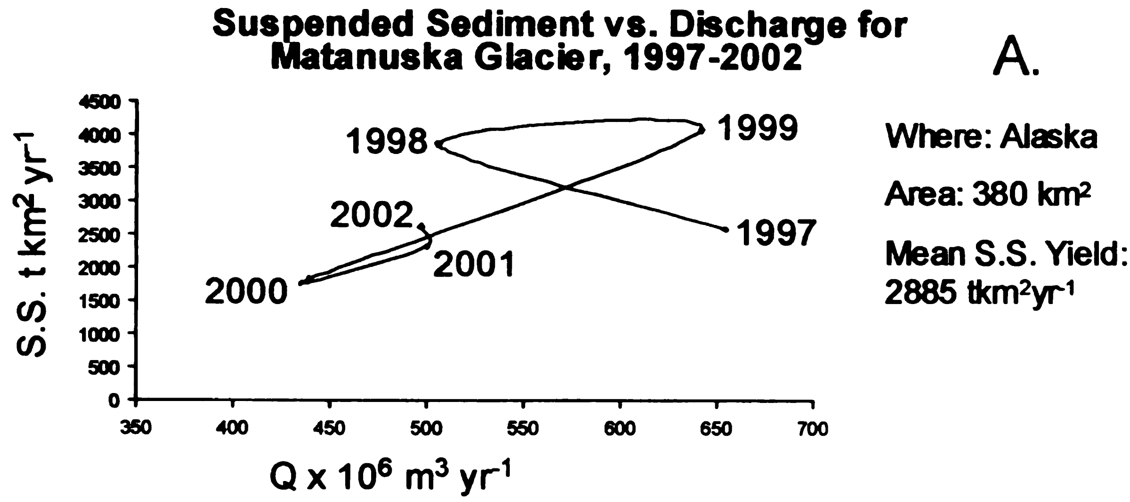


Figure 11: Average annual minimum erosion rate of the Matanuska Glacier



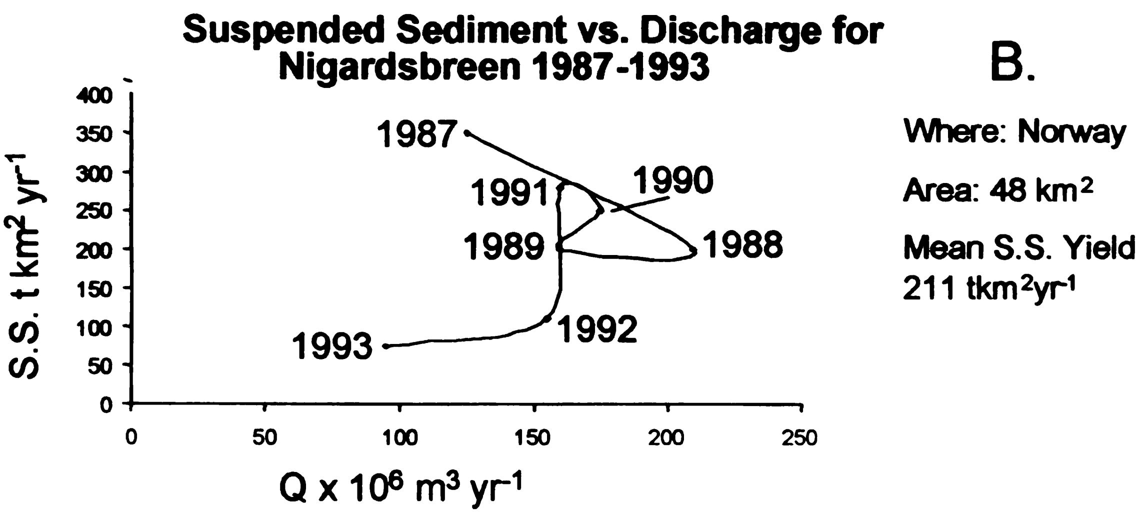
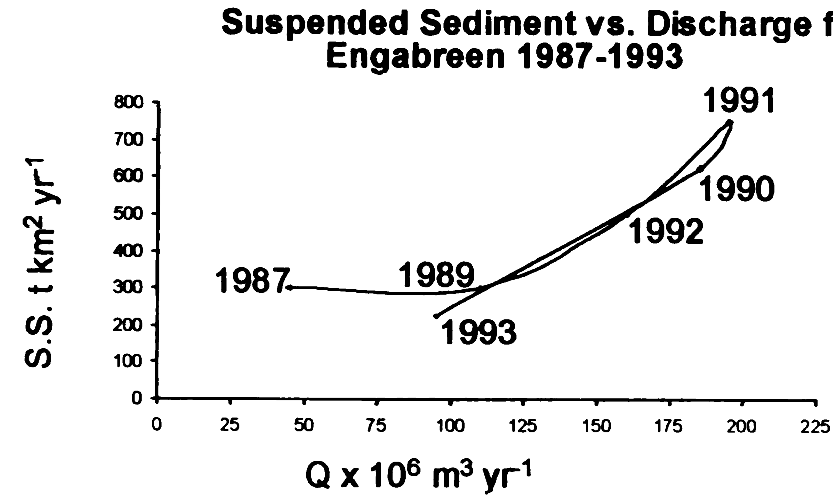


Figure 12. Plots of annual suspended sediment vs. discharge. (A) Plot of Matanuska Glacier 1997-2002. (B) Plot of Nigardsbreen Glacier, Norway, 1987-1993.

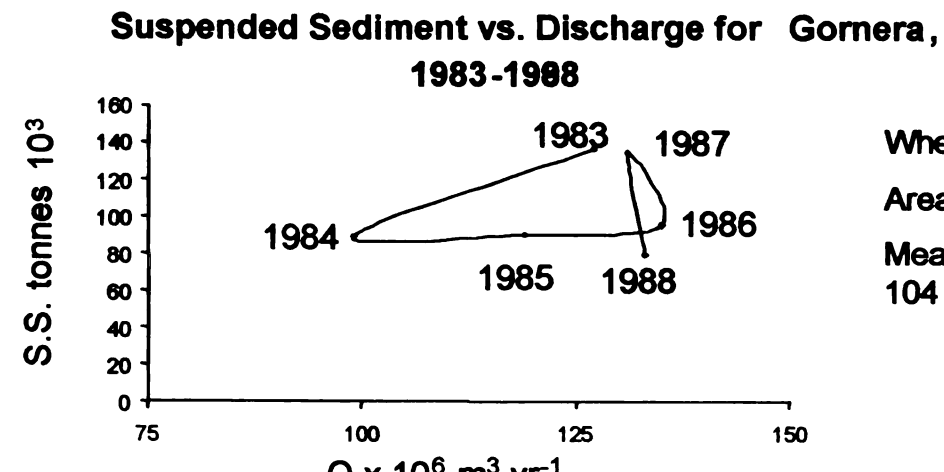


C.

Where: Norway

Area: 36 km²

Mean S.S. Yield:
456 tkm²yr⁻¹



D.

Where: Switzerland

Area: 82 km^2

Mean S.S. Yield:
104 tonnes 10^3

Figure 12 (continued). Plots of annual suspended sediment vs. discharge. (C) Plot of Engabreen Glacier, Norway 1987-1993. (B) Plot of Gornera Glacier, Switzerland, 1983-1988.

other hand, the lowest suspended-sediment flux and lowest melt-water discharge recorded occurred in the 2000 ablation season. The plot also shows that during the 1997-1999 ablation seasons, recorded annual suspended-sediment fluxes and melt-water discharges were relatively high, whereas that during the 2000-2002 ablation seasons, recorded annual suspended-sediment fluxes and melt-water discharges were relatively low. When compared to records of annual suspended sediment flux vs. discharge recorded for other glaciers of varying sizes from around the world (Collins, 1990; Bogen, 1996)(figure 12, b,c,d), the instability relationship observed at the Matanuska Glacier is not unusual and can be attributed to several factors: 1) seasonal development of the subglacial drainage system (Collins, 1989; 1998), 2) the scale and occurrence of seasonal discharge and suspended-sediment flux pulses (Collins, 1989; 1998), and 3) history of hydrological events (Collins, 1989) that all coincide with each other.

Rapid changes in suspended sediment flux can provide an indirect view into the development of the subglacial drainage system (Collins, 1998). For example, an increase in melt-water discharge can result in subglacial stream migration allowing water to invade unworked pockets of sediment stored at the ice-bedrock interface and provide a short lived supply of suspended sediment (Collins, 1998; 1991). At the Matanuska Glacier, the 1998 and 1999 ablation seasons have the highest recorded pulses of suspended sediment whereas the 2000, 2001, and 2002 ablation seasons have the smallest recorded pulses of suspended sediment. The scale and occurrence of the sediment pulses during the 1998 and 1999 ablation seasons could have evacuated most of the stored sediment leaving small amounts for the 2000, 2001, and 2002 ablation seasons to erode. According to Collins (1998), Hallet et al., (1996), and Collins (1991) the evacuation of suspended sediment into the suglacial drainage system is variably with time and depends on the erodibility of the bedrock and the amount of sediment stored at the ice-bedrock interface. The variation at the Matanuska suggests that the rate of supply and rate of sediment removal from storage are not equal over a period of six years and might explain the instability relationship between annual suspended-sediment flux vs. discharge.

Along with seasonal changes, scale, and occurrence of the discharge and sediment pulses, the hydrologic history may also explain the instability between annual suspended-sediment flux vs. discharge. Prior to 1997, a 100-year flood event occurred in September 1995 (Denner, et al., 1999) and could have flushed considerable sediment from the system, explaining the small amount of suspended sediment during 1997, which was the year for highest recorded discharge.

Comparison of Glacier Erosion Rates

The average annual minimum effective erosion rate of 1.13 mm yr^{-1} calculated for the Matanuska Glacier is intermediate to rates recorded for other glaciers around the world (Table 1). Compared to the Nigardsbreen Glacier, Norway, it is much greater, probably because the Matanuska Glacier 1) flows over meta-sedimentary bedrock that is weaker than the metamorphic bedrock

Glacier	Effective Erosion Rate mm yr^{-1}	Reference
Nigardsbreen, Norway	.15	Hallet et al. 1996
Engabreen, Norway	.41	Bogen, 1989
Tsidjore, Swiss Alps	.97-1.1	Bezinge, 1989
Matanuska, Alaska	**1.1**	**This Study**
Gorner, Swiss Alps	1.4	Bezinge,1987
Batura, Pakistan	7.7	Collins, 1998
Muir, Alaska	28.1	Hunter, 1994
Margerie, Alaska	60.0	Hunter, 1994

Table 1: Average effective erosion rate recorded for several glaciers around the world, including the rate for the Matanuska Glacier.

underlying the Nigardsbreen Glacier (Ostrem, 1975), 2) is located in a tectonically more active area (Hallet et al., 1996), and 3) possibly has a higher glacier mass balance. Compared to the Batura Glacier, Pakistan, however it is subsequently less, probably because the Matanuska Glacier 1) lies in a tectonically less active region than the Batura Glacier and 2) has a lower glacier mass balance than the Batura Glacier (Collins, 1998). In addition, compared to glaciers in southeastern Alaska, the average annual minimum effective erosion rate for the Matanuska Glacier is small, probably because it has a lower glacier mass balance, overrides harder bedrock, and lies in a region that is tectonically less active (Hunter et al., 1996).

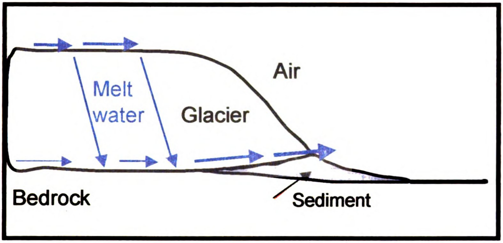
Role of an Overdeepening in Sediment Transport

Within ½ km of the terminus of the Matanuska Glacier lies a head of outwash that contains coarse sediment ranging from large pebbles to boulders. It indicates that sometime in the recent past the glacier terminus extended further north and melt-water emerging from the terminus was transporting considerable bed load. This is in contradiction to Pierce et al., 's (2003) observation that bed load currently in streams draining the Matanuska Glacier is <1% of the total clastic load and is strongly supply limited. A mechanism proposed by Alley et al., (in review) that might account for the apparent decrease in stream bed load is presented in figure 14 and involves two geometric conditions occurring just inside the ice margin.

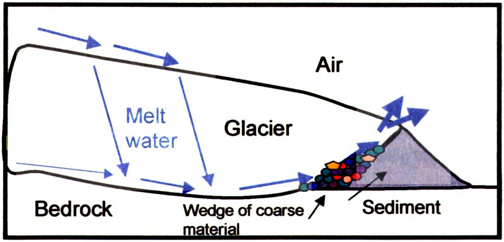
Condition A): The ice-bedrock adverse slope is ≤ 20% of ice-surface slope. The glacier is at or below the "supercooling threshold" and has a channelized drainage system that is under capacity which leads to erosion at the glacier bed.

Condition B): The ice-bedrock adverse slope is 20-70% steeper than the ice-surface slope. The glacier is above the "supercooling threshold", which leads to ice growth in channels causing them to decrease in size and close off. The channels evolve into a distributed subglacial drainage system, transport capacity drops off, and leads to deposition of course material at the glacier bed.

Today, the geometric condition of the Matanuska Glacier margin is similar to condition B. Recent geophysical data show that located just inside the margin is a significant overdeepening (Alley et al., 1999; Lawson et al., 1998; Baker, unpublished data). Observational evidence also shows that supercooling is occurring (Evenson et a., 1999; Lawson et al., 1999; Ensminger et al., 2002) and that the subglacial drainage system consists of a complex network of conduits that emerge at the ice margin as vents that turn on and off throughout the ablation season (Lawson et al., 1993,1998).



Condition A.



Condition B

Figure 13: Overdeepening model (modified from Alley et al., in review), Mechanism for trapping coarse meterial at the ice-bedrock interface. Condition A. Glacier lacking supercooling. Condition B. Glacier far into the supercooling phase.

If it is assumed that debris within basal ice and morainal sediment represents the main debris reservoir within the glacier and that it supplies most of the melt-water stream load, it may be possible to estimate the amount of coarse material being retained by the glacier in an overdeepening relative to what is leaving the glacier in the form of suspended load. For example, grain-size analysis of debris in basal ice and morainal sediment show that 57 to 72% of the debris has a grain-size diameter of > 0 phi and is capable of being placed in suspension by subglacial melt-water streams. The remaining 18 to 43% of the debris has a diameter of ≤ 0 phi and, on the other hand, is not capable of being placed in suspension and is subject to being trapped in an overdeepening. The O phi cutoff between debris in suspension and debris not in suspension was used because grain-size analysis of suspended sediment data show that the largest particle in suspension throughout the ablation season is 0.5 phi. Given the average yearly amount of suspended load leaving the glacier is 1.14E+09kg for the period of 1997 to 2002, it is logical to conclude that the average amount of coarse material being trapped is on the order of 2.85E+08 kg to 8.61E+08 kg for the same period using the Flux of bed load equation.

$$F_{BL} = F_{SS} *(M \geq \Phi / M \leq \Phi) \qquad \text{eq.(1)}$$

Where F_{BL} is the flux of bed load or the amount of material being trapped, the F_{SS} is the flux of suspended sediment or average yearly amount of suspended load leaving the glacier, and $(M \geq \Phi / M \leq \Phi)$ is the ratio between debris in suspension and debris not in suspension. This amount of coarse material trapped is applied to a Rate of Accretion equation

$$R_A = F_{BL} / (1\text{-}n)A \qquad \text{eq. (2)}$$

where R_A is the rate of accretion or thickness of coarse material trapped over a given area, F_{BL} is flux of bed load or amount of coarse material trapped, 1-n is the porosity, and A is the area. Using the assumed porosity for gravel of 30%(Fetter, 2001), the amount of coarse material trapped could deposit a layer of 2.9 to 9.3 cm a year over an area of $5km^2$ on the ice-bedrock adverse slope.

If the grain size cutoff between debris in suspension and debris not in suspension is shifted to include debris $\leq$ 3.5 phi because the grain-size analysis of suspended sediment from the discharge vent show that < 1% of sands is coming out of the vent, then the coarse material trapped may also include fine sands with the gravel. When the cutoff is shifted, the grain-size analysis of debris within basal ice and morainal sediment show that 30 to 51% of the debris has a grain-size analysis > 3.5 phi and is capable of being placed in suspension by subglacial melt-water streams. The remaining 49 to 70% of the debris has a diameter of $\leq$ 3.5 phi and is not capable of being placed in suspension is subject to being trapped in an overdeepening. Given the same variables for the same equations and period of time, it is logical to conclude that the average amount of coarse material being trapped is on the order of 1.10E+09 kg to 2.66E+09 kg. This amount of coarse material trapped, which assumes a porosity of 20% (Fetter, 2001), could deposit a layer 10.3 to 25.1 cm a year over an area of $5km^2$ on the ice-bedrock adverse slope.

The thickness of the coarse trapped material includes major assumptions. The first is that coarse material is being accreted as a thin sheet or layer along the entire adverse slope of the glacier. How the coarse material might be distributed however would depend on the geometry of the adverse slope(s) and the type and pattern of the subglacial system. The second is that the area in which coarse material is being accreted is limited to $5km^2$.

The third assumption is that the debris within basal ice and morainal sediment represent the main debris reservoir within the glacier. Compared to the supraglacial debris, the debris within basal ice and morainal sediment have the higher amount of sediment > 0 phi. The supraglacial debris does not have enough fines to supply the amount of suspended sediment coming out of the glacier. Also, the debris within basal ice and morainal sediment are of subglacial origin whereas the melt-out till and lacustrine sediment are located in the proglacial environment. Lodgement till is of subglacial origin but was not used because it fell within the grain-size range of debris within basal ice and morainal sediment. The exact composition of the material being trapped is unknown and further studies are needed to quantify the exact amount being retained by the overdeepening.

Conclusion

Knowledge of glacier erosion rates have become increasingly important in understanding the tectonic evolution of glaciated mountain belts (Alley et al., in review; Collins, 1998; Hallet et al., 1996). The Matanuska Glacier average, annual, minimum effective erosion rate of 1.13 $mmyr^{-1}$ for the period of 1997-2002 is intermediate to other rates recorded for glaciers around the world because of the amount of tectonic activity in the area, the amount of mass balance, and the erodibility of the bedrock. For the same period, the average, annual total sediment flux is 1.14E+09 kg. The amount of coarse material trapped due to the overdeepending is on the order of 2.85E+08 kg to 8.61E+08 kg for the same period. Finally, the fate of this coarse material could deposit a layer of 2.9 to 9.3 cm a year over an area of $5km^2$ on the ice-bedrock adverse slope.

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