The Subglacial Hydraulics of the Surge-Type Black Rapids Glacier, Alaska: A Schematic Model

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A

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ABSTRACT

The subglacial hydraulic system of the surge-type Black Rapids Glacier was studied in 1993 by comparing glacier velocity and seismicity with the stage, electrical conductivity, and turbidity of its proglacial streams. Brief events of increased velocity and seismicity occurred at the beginning and end of the measurement season. Five events coincided with drainages of supraglacial lakes and potholes. During events, water was stored englacially or subglacially and released subsequently, as indicated by a dye tracing experiment. Conductivity-stage-seismicity relationships suggest a model wherein daily storage and release of water depended on variations in subglacial pressure, which were reflected by daily variations in seismicity. Heavy precipitation and increases in stage preceded late-season pothole drainages. We hypothesize that precipitation triggered pothole drainages by enlarging drainage conduits, thus lowering subglacial pressure. Differences between the drainage systems in 1993 and 1986-89 may reflect mechanisms of surge evolution.

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CHAPTER 1: INTRODUCTION

Knowledge of subglacial hydraulics over several time scales is integral to understanding glacier motion. Surges, short-period increases in velocity and seismicity, and diurnal variations in velocity (Iken and Bindschadler, 1986) may all be triggered by pressure variations within the subglacial drainage system due to changes in drainage architecture, abrupt large water inputs, and daily fluctuations in water input. Changes in architecture may, in turn, be triggered by glacier motion. Increases in glacier velocity, for example, promote development of basal cavities, which can then fill with water and become part of the subglacial drainage system (Kamb, 1987).

We measured proglacial hydrology, glacier velocity, and glacier seismicity simultaneously to investigate the relationship between the subglacial hydraulics and motion of Black Rapids Glacier, a quiescent, surge-type glacier in Alaska. We also conducted a dye-tracing experiment. Such simultaneous measurements, which are easily made and can be automated, can offer insight into the subglacial drainage system as a whole and its evolution through time. Our measurements were accompanied by site-specific, active seismic and ice radar studies of the glacier bed, which will be discussed in future papers (M. Nolan and A. Gades, personal communication).

Black Rapids Glacier has a history of scientific study that began in 1937, the time of its most recent surge. Over the last 25 years, extensive field investigations and laboratory analyses have been conducted, many of which investigate the nature of a surge-type glacier in its quiescent phase. In a comparison study between Black Rapids Glacier and neighboring, non-surge-type Fels Glacier (Figure 1), Raymond and others (1995) conclude that differences in their hydrology and perceived bed structure may be due to differences in their lengths, not to surge versus non-surge characteristics. Their study, which covers 1986-1989, defines general, seasonal patterns in the hydrology of both glaciers and provides a base-line for the research on Black Rapids Glacier described here.

CHAPTER 2: BLACK RAPIDS GLACIER

Black Rapids Glacier is a temperate, surge-type glacier (Harrison and others, 1975). It is approximately 42 km long, has a total area of 246 km^2, and extends from 2580 m to 990 m elevation with a mean surface slope of 2.2 degrees (Heinrichs and others, 1995, and in press). It is located along the Denali Fault (right-lateral motion) and near West Fork and Susitna glaciers, which are also surge-type (Figure 1). The fault juxtaposes metamorphosed granite and sedimentary rocks to the north of the glacier with schist, amphibolite, and gneissose granite to the south (Nokleberg and others, 1992). The glacier itself could overlie some combination of these rocks or, possibly, fault gouge.

The most recent surge of Black Rapids Glacier occurred in 1936-37 (Hance, 1937), when the terminus advanced 4 km. The event was the first ot its kind to attract the attention of the popular press (Anonymous, 1937). Although analysis of moraines suggests that Black Rapids has a 50 to 75 year surge period, recent variations in speed and the glacier's present geometry indicate that a new surge is not imminent (Heinrichs and others, 1995).

Like many other surge-type glaciers (Sturm, 1987), Black Rapids Glacier has small, supraglacial ponds called "potholes" near its equilibrium line (Figure 2). The hundred or so potholes range from 10 to 100 m in diameter. Some potholes appear to drain and fill englacially through complex systems that may persist from year to year (Sturm and Cosgrove, 1990). Unfrozen water found in a pothole during mid-winter (Sturm, 1987) suggests that water movement may occur throughout the year.

There are also several ice-marginal lakes on Black Rapids Glacier (Figure 2). Aurora Lake, located 13 km from the head of the glacier, may fill and drain every year. During a period in March, 1984 when there was no surface run-off , Aurora Lake filled, probably from an englacial source. In 1989, it drained supraglacially into neighboring potholes, which subsequently drained englacially. Willsear Lake, at 15 km, also fills and drains periodically (Sturm and Cosgrove, 1990).

Lake drainages may cause short-term increases in velocity on Black Rapids Glacier similar to the increases ("mini-surges") observed on Variegated Glacier (Raymond and others, 1995), where releases of englacial reservoirs initiated hydraulic waves, which propagated (Humphrey and others, 1986; Kamb and Engelhardt, 1987). On Black Rapids Glacier in 1987, Raymond and others (1995) observed a propagating strain wave following the drainage of a small, ice-marginal lake. The wave moved at a speed similar to waves on Variegated Glacier.

Black Rapids Glacier also experiences seasonal variations in velocity. Time-lapse photography from 1982-1989 shows a sharply defined increase in velocity in mid- to late June, followed by a period of complex motion that tends to be the most rapid of the year and is, on the average, 100-400% of the early winter speed (Figure 3). It may be caused by both the onset of summer melting and the drainages of lakes and potholes. A smaller, late-summer velocity increase sometimes occurs in mid- to late August, followed by a decrease to a minimum in November-December. The current project investigates the relationship between subglacial hydraulics and velocity variations--both short-term and seasonal.

CHAPTER 3: MEASUREMENTS, METHODS, AND RESULTS

I. MEASUREMENTS AND METHODS

We conducted field measurements and maintained automated equipment at the terminus streams and on the glacier from mid-May until mid-July (days 133-193), 1993. Automated measurements continued until September 19 (day 262), just prior to freeze-up. Table 1 shows the location and timing of the different measurements. We were primarily concerned with relative changes in glacier and stream variables rather than with absolute numbers.

On the dominant terminus stream, hereafter called "Main Stream", we employed an automated system developed by the University of Washington (Humphrey and others, 1986). The system consisted of a boom with an attached sonic ranger that measured stream height, or stage. The stage measurements give only a qualitative measure of discharge because of cut-and-fill in the channel and the lack of depth profiles.

A floating instrument "boat" was also part of the system and was attached to the boom by a tether. A resistance cell in the boat measured electrical conductivity (hereafter termed "conductivity"). Conductivity is proportional to solute concentration if water temperature and the proportions of ionic components remain somewhat constant; since temperature changes were small and proportions of ionic concentrations remain fairly constant in proglacial streams (Raiswell and Thomas, 1984), we assume that conductivities were proportional to total solute concentrations. Turbidity, which is related to suspended sediment concentration, was measured by a light transmission cell. (Since we are interested only in relative *changes* in turbidity, we did not extensively calibrate measured turbidity with suspended sediment in water samples.) A thermistor in the boat measured water temperature.

On the glacier, surface velocity was measured both by triangulation using automated, time-lapse photography and by optical surveying, which took place at a site 15 km from the head of the glacier. Although time-lapse photography yields velocity data with lower resolution than velocity determined by surveying, it useful not only because it is automated and operates year-round, but also because it records the drainages and infillings of lakes and potholes as well as gross weather variations.

Also at the 15 km site, a short-period , 10 Hz geophone was directly connected to a data logger. The voltage input to the data logger was converted to the number of seismic events per hour. The low occurrence of regional earthquakes during this period (Charlotte Rowe, UA-Fairbanks, personal communication) indicates that the supraglacial seismicity was due primarily to ice-quakes. We measured vertical strain at 15 and 27 km from the head using resistance wires frozen into shallow holes (as described by Harrison and others, 1993); these data will be shown in future papers.

Air temperature, precipitation, and incoming solar radiation were measured automatically on the glacier margin above Willsear Lake until the data logger failed in mid-July (day 190). We supplemented these data with temperature and precipitation data from Gulkana Glacier, twenty-five miles south of Black Rapids Glacier (unpublished USGS report, B. Kennedy and R. March, personal communication). Temperatures from Gulkana Glacier correlate well with temperatures on Black Rapids Glacier, and periods of heavy precipitation probably coincided on both glaciers (Figure 4).

We also conducted a dye-tracing experiment. We began the experiment by injecting a seven kg slug of undiluted Rhodamine B dye into a subglacially-connected moulin that was located 14 km from the head of the glacier (C. Raymond, personal communication). The injection occurred on day 165, shortly after Aurora Lake began draining into this moulin. We sampled both terminus streams (Figure 2) for a total of forty days prior to and following the injection. Samples were analyzed in the laboratory with a Turner fluorometer.

II. RESULTS

The hydrology, meteorology, velocity and seismicity data are shown in Figure 4. Short-period increases in velocity or seismicity, called "events", are numbered along the top of the figure. The initiation of each observed lake or pothole drainage is represented by a vertical line. Figures 5 and 6 show the results from the dye-tracing experiment.

CHAPTER 4: DISCUSSION OF RESULTS

I. DIURNAL PATTERNS

Diurnal variations in proglacial stage (stream height) are indicators of glacial drainage processes. On Black Rapids Glacier, daily maxima in stage early in the season (days 136-164) occurred 2 hours after daily maxima in incoming solar radiation, which reflect melting maxima according to Rothlisberger and Lang (1987). This short travel time for melt-water from the glacier surface to the terminal stream indicates the presence of a well-integrated drainage system; i.e., water moved continuously and with high velocity, as would be expected in a system of conduits. Following the drainage of Aurora Lake on day 165 (Event 3), however, diurnal variations were suppressed, reflecting diminished drainage system integration (Figure 4). The drainage system was such that either 1) water moved continuously, but through a very dispersed network, or 2) some water was held in storage. Strong diurnal variations in stage reappeared for two short periods in mid-season, which were during high air temperatures (Figure 7), and at the end of the season.

Fluctuations in stream conductivity (correlated to solute concentration) are inversely related to fluctuations in water discharge because of the effects of dilution, such that high conductivity values represent high solute *concentrations* and not necessarily high solute *loads*. For example, periods of high conductivity in 1993 coincide with periods of relatively low stage (low discharge). Diurnal variations in the conductivity of proglacial streams typically occur when free-flowing, solute-enriched water (often subglacial) is diluted by water that is solute-free (usually supraglacial meltwater) on a daily basis (see Humphrey, 1987). Thus, diurnal variations in conductivity should occur only when diurnal variations in stage also occur. In 1993, however, diurnal variations in conductivity were strong even ion periods when diurnal variations in stage were (e.g., days 170-185, 230-233). Also, the fractional variations of conductivity were quite large relative to those of stage (Figure 8). In other words, the 1993 conductivity diurnals were independent, at least some of the time, of stage diurnals.

Diurnal variations in turbidity (approximately correlated with suspended sediment concentration) may indicate daily flushing and exhaustion of sediment sources. In 1993, turbidity diurnals were not often present. When they were present, they were approximately in phase with diurnal variations in conductivity: high suspended sediment concentrations correlated with high solute concentrations. The gaps in turbidity data during early-season events occurred because the measurement boat completely filled with sediment, presumably because of the high water velocities and large increases in sediment that were observed visually during this period.

In 1993, diurnal variations in seismicity--ice-quakes--were observed on the glacier and were approximately in phase with variations in stage. They were roughly anti-phased with conductivity (Figures 9-11). Furthermore, the presence of diurnal variations in seismicity always coincided with the presence of diurnals in conductivity.

Ice quakes are either the cause or the consequence of changes in water pressure, according to Smart and Clarke (in press) and Hodge (1976). On Black Rapids Glacier, a large local peak in seismicity on day 176 (Event 5) correlated, according to Matt Nolan (personal communication), both with the peak in discharge from Willsear Lake and with increased glacier surface elevation (for a discussion of glacier uplift, see Iken and others, 1983). In addition, other large, local peaks in seismicity correlated with additional lake and pothole drainages. Thus, large variations in seismicity in 1993 may be directly related to subglacial water pressure. The coincidence of daily peaks in seismicity with peaks in meltwater input further suggests that *daily* variations in seismicity may reflect daily variations in subglacial water pressure, which have been observed by Rothlisberger (1976).

II. EVENTS AND LAKE DRAINAGES

On Black Rapids Glacier in 1993, short-period increases in seismicity and velocity are called "events". Eight events occurred during the 130 days of measurements (Figure 4). They were clustered at the beginning and end of the measurement season: Events 1-5 occurred before day 180 (June 29), and Events 6-8 occurred after day 225 (August 13). The events are also apparent in records of turbidity and stage. Pulses in turbidity occurred during or just before at least 5 of the 8 events, and increases in stage preceded 6 events.

Based on the morphology of seismicity/velocity versus time, we divide the events into two groups: "humps" and "spikes" (Figure 4). Events 1 and 2 are humps and did not coincide with lake or pothole drainages (Table 2). A dramatic rise in temperature precedes Event 1; the temperature peak on day 136 represents the first values above freezing for the spring season (Figure 7). Both seismicity and velocity then increase quickly, peaking on day 145 to form Event 1. Event 2 coincided with a local peak in temperature. Both these increases in velocity and seismicity (i.e, Events 1 and 2) are early relative to spring seismicity and velocity increases in previous years (see Figure 3).

Events 3-8 are spikes. Except for Event 8, each spike definitively corresponded to a lake or pothole drainage, as seen in the time-lapse photography (Table 2). (Foggy weather precluded the use of time-lapse photography data to determine whether or not a drainage occurred during Event 8.) Aurora Lake drained on day 165, coinciding with Event 3; potholes drained on days 170, 227, and 244, coinciding with Events 4, 6, and 7, respectively; and Willsear Lake drained on day 177, coinciding with Event 5. Water storage must have accompanied the drainages since increases in proglacial stage were small compared to input from the drainages.

The largest and most dramatic drainage was that of Willsear Lake on day 177 (Event 5). Most of the lake emptied in 24 h through a visible, subglacial tunnel several meters in diameter. The water input is conservatively estimated as 10^6 m^3. Very little proglacial flooding followed this drainage episode, but, at 15 km, glacier surface elevation increased (Matt Nolan, personal communication).

At least three of the spikes coincided with drainages of a group of potholes. Several potholes drained on day 170, triggering Event 4. Events 6 and 7 coincided with pothole drainages that occurred during periods of high stage. The high stage followed heavy rainfall and low temperature (B. Kennedy and R. March, personal communication). Event 6 was atypical in that the brief increase in seismicity was not accompanied by an increase in velocity (known from time-lapse photography data). The potholes began filling during or just following periods of high temperature (Figure 7).

III. DYE-TRACING EXPERIMENT

The results of the dye-tracing experiment, which was initiated during the drainage of Aurora Lake, are shown in Figures 5 and 6. Figure 5 shows the dye-return for Main Stream and South Stream; dye is found in Main Stream 21 days after injection. The shaded areas of the figure depict the duration of lake or pothole drainages. Peaks in the dye-return roughly follow drainage episodes and do not coincide with changes in stage (Figure 6).

CHAPTER 5: MODEL AND CONCLUSIONS

I. A SCHEMATIC MODEL OF THE SUBGLACIAL HYDRAULICS IN 1993

Our simultaneous observations of hydrology and motion in 1993 have led us to envision a simple, schematic model for the subglacial hydraulics and its evolution. We suggest that the subglacial hydraulics both affected--and was affected by--glacier motion. Based on our observations, the model is separated into the following four stages:

- (1) Days 136-165: Persistent diurnal variations in stage reflect a primarily conduit drainage system.
- (2) Days 165-178: Development of storage cavities with links to conduits.
- (3) Days 178-226: Variations in conductivity reflect mechanisms of water flow between the conduits and cavities.
- (4) Days 226-261: Pothole drainages are more probable during low subglacial pressure.

Table 3 identifies other characteristics of the data relevant to our model. For the model, we consider only temporal variations in the subglacial hydraulics, not spatial variations, and we are concerned only with the dominant aspects of the drainage system's architecture. The composition of the glacier bed is not a component (or an assumption) of this model.

(1) Days 136-165: Persistent diurnal variations in stage reflect a primarily conduit drainage system.

The presence or absence of strong diurnal variations in stage may be the key to unlocking the architecture of the 1993 drainage system. The strong diurnal variations in stage between days 136-165 reflect a well-integrated drainage system, perhaps one composed primarily of conduits (see p.38 in Humphrey, 1987). The persistence and phase-similarity of stage diurnals during Events 1 and 2 show that the drainage system was not altered dramatically by the increases in velocity. These spring velocity/seismicity increases were early relative to increases in previous years.

Spring speed increases on glaciers may be caused, at least partially, by the transition from winter to summer drainage conditions (Iken, 1981; Smart and Clarke, in press; Iken and Bindschadler, 1986; Kamb and Engelhardt, 1987; Humphrey and others, 1986). In 1993, the sudden temperature increase from day 132 to a large peak on day 136 (Figure 7) prior to Event 1 suggests that a rapid onset of summer-time melting may have overloaded the winter drainage system, causing increased subglacial pressure and, subsequently, increased glacier velocity. We hypothesize that the pressurization of water-filled *conduits*--versus water-filled cavities--caused the hump-like morphology of Events 1 and 2 (Figure 4): both pressurization as well as pressure dissipation occur slowly in conduits relative to cavities (Kamb, 1987; Walder, 1986).

(2) Days 165-178: Development of storage cavities with links to conduits.

The abrupt suppression of diurnal variations in stage on day 165, coincident with the drainage of Aurora Lake and Event 3, reflected a dramatic change in the drainage system architecture. Day 165 also marked the initiation of significant water storage, as evidenced both by the absence of proglacial flooding following large water inputs (from lake and pothole drainages) and by the dye-return curve. We believe that the drainage system, which originally had little storage capacity and was composed predominantly of conduits, developed into a system of conduits with links to supplemental storage cavities.

The dye-tracing experiment, initiated on day 165, yielded multiple peaks in the dye-return curve during a period of fairly constant stage (Figure 6). Multiple dye peaks *can* result from dispersed flow, such as through anastomosing channels (Seaberg and others, 1988). However, on Black Rapids Glacier the juxtaposition of dye peaks and motion events, as well as the large time lapses between the dye peaks, suggest instead that dye-contaminated water was stored during Event 3 and subsequently released following Events 3, 4, and 5 (for comparison, see experiments 87-2 and 87-7 in Willis and others, 1990; Brugman, 1986; and Figure 11a in Kamb and others, 1985). Furthermore, the experiment shows a long period (23 days) of dye release following the dye injection (Figure 5), indicating that long-term water storage, as well as gradual release from storage, also existed.

The suppressed diurnal variations in stage indicate that variations in supraglacial water input were attenuated at the stream due to low drainage system integration, as discussed in the Discussion of Results section. For a drainage system to a) have suppressed stage diurnals, b) allow the immoblization and release of dye, and c) gradually release dye from long-term storage, water flow is required between the storage units and the drainage system. This requirement is satisfied by a system consisting of conduits with links to subglacial storage cavities. (The nature of the flow between the cavities and conduits is most evident between days 178-226 and will be discussed in the next section.)

We believe that the cavities--and the links between the cavities and conduits--developed because the drainage conduits were suddenly overpressurized by water from the lake and pothole drainages (Events 3-5). The development and expansion of cavities, and the creation of permanent links to conduits, may rapidly dissipate subglacial pressure by increasing storage capacity (Kamb, 1987 and Walder, 1986). Such rapid pressure dissipation could account for the spike morphology of the increases in glacier seismicity and velocity (Events 3-5), assuming glacier motion is related to subglacial pressure.

(3) Days 178-226: Daily variations in conductivity reflect mechanisms of water flow between the conduits and cavities.

We believe that flow between the conduits and cavities occurs because of pressure differences. During high conduit pressure, water will flow from the conduits into the cavities, while during low pressure, it will flow out. The cavity sizes will vary accordingly like an inflatable bladder. The relationship among conductivity, stage, and seismicity illustrates this interaction.

Diurnal variations in conductivity in mid-season do not appear closely related to variations in stage. Instead, they persisted during periods of suppressed diurnal variations in stage and have larger fractional variations than those of stage (Figures 4 and 8). They were not, to reiterate, caused simply by dilution, as is the case for conductivity diurnals in most proglacial streams (see Discussion of Results section). Instead, conductivity diurnals may have been related to variations in seismicity.

But how could stream conductivity and glacier seismicity have been related? We believe the answer lies in water pressure: if variations in seismicity mirrored variations in subglacial water pressure, then daily peaks in water pressure coincided with daily lows in stream conductivity, and low water pressures coincided with high conductivities. Herein lies the crux of our model: highs in conduit pressure, due to daily peaks in meltwater input, allowed water flow into the bladder-like storage cavities, but not out. The cavities became pressurized, and glacier seismicity increased as a result. Meanwhile, the water trapped in the cavities became enriched in solutes because of a long period of contact with the glacier bed. This solute-enriched water was effectively isolated from the drainage system during periods of high discharge (high conduit pressure) of solute-free water. When it was released from the cavities at night during low conduit pressure (decreased meltwater), it formed a large proportion of the water in the drainage system and caused the peaks in stream conductivity. Collins (1979) comes to a similar conclusion concerning the conductivity variations of Gornergletscher.

Thus, the model suggests that the cavities were bladder-like; the amount of storage varied during the day and was dependent on water pressure. The model further suggests that the modus operandi for the drainage system in mid-season was high pressure. The cavities initially developed in response to high pressure and were continually re-used because of high pressure. At the end of the summer, however, the drainage mode may have changed in response to episodes of heavy precipitation.

(4) Days 226-261: Pothole drainages are more probable during low subglacial pressure.

Early-season lake and pothole drainages appear to have altered the subglacial hydraulics. We propose that the drainages may themselves be caused by the subglacial hydraulics; that is, the timing of drainages is not simply a question of sufficient hydrostatic pressure within the body of water. The coincidence of increased stage with heavy precipitation and pothole drainages suggests to us that pothole drainages are more likely during low subglacial pressure.

Increases and decreases in stage may cause changes in the subglacial hydraulics. Rothlisberger (1972) proposes that discharge and pressure are inversely related during steady-state in a tunnel-like drainage system. Persistent high tunnel pressures reflect tunnel contraction due to a long-term decrease in discharge, according to Rothlisberger. Low tunnel pressures suggest tunnel enlargement due to a long-term increase in discharge. As a corollary to this proposal, Rothlisberger suggests that supraglacial lakes fill in times of low discharge (high tunnel pressure) and empty when discharge is high (low tunnel pressure).

In 1993, heavy precipitation, high stage, and pothole drainages coincided (Figures 4 and 7). In light of Rothlisberger's reasoning, it seems possible to us that this "coincidence" was not coincidental, but causal. We believe that the long-duration precipitation caused the drainage system to enlarge, lowering pressure. This decrease in pressure created conditions that allowed the potholes to drain. Our idea has grounds in the observations of Sturm (1987) and Sturm and Cosgrove (1990), which suggest that potholes drained and filled englacially.

(5) The evolution of the subglacial hydraulics during the 1993 measurement season.

At the beginning of the measurement season, the onset of summer-time melting overloaded the winter drainage system, and excess water pooled in the potholes. Increases in glacier velocity and seismicity (Events 1 and 2) showed the effect that a pressurized drainage system, composed predominantly of conduits, has on glacier velocity. During and following these events, drainage conduits may have expanded as they began to adjust to summer-time melt input, and subglacial pressure may have decreased.

However, the conduits were overpressurized again by the pulse in water from the drainage of Aurora Lake (Event 3). Bladder-like storage cavities with links to the conduits formed and rapidly dissipated the pressure, as evidenced by the abrupt decreases in velocity and seismicity (Figure 4). Pressure increased twice more in response to the drainages of potholes (Event 4) and Willsear Lake (Event 5), and the cavities and links continued to develop, as evidenced again by decreases in velocity and seismicity.

The drainage system may have then begun to stabilize for a short period. Solute-enriched water was isolated and flushed from the cavities on a daily basis, causing strong, mid-season diurnal variations in conductivity (Figure 4). On day 187, temperature began to rise towards its 1993 maximum on day 197, which is when the potholes began filling again (Figure 7). The presence of strong diurnal variations in seismicity and of spiky diurnal variations in stage suggest that, during peak melting at mid-day, the drainage system was overloaded. A broad, low peak in smoothed camera velocity further suggests high subglacial pressures (Figure 4). Another period of high temperatures (days 207-212) was also accompanied by spiky diurnal variations in stage.

As temperature decreased after day 212, the drainage system may have contracted, only to enlarge again in response to precipitation between days 223-227 (Figure 7). Subglacial pressure decreased sufficiently to create conditions allowing the potholes to drain (Event 6). The small increase in seismicity and lack of velocity increase suggests that the links between the cavities and conduits were still open, allowing the excess water to enter cavities rather than pressurize the conduits.

Following Event 6, low stage suggests that the drainage system may have contracted again in response to low temperatures (Figure 7). The links between the cavities and conduits may have begun to disintegrate during this period. As temperature increased to a peak on day 240, we believe that subglacial pressure increased, causing the potholes to fill again. The heavy precipitation on days 242-245 caused enlargement of the drainage system and a decrease in subglacial pressure. The subsequent pothole drainage on day 244 (Event 7) was accompanied by large increases in both velocity and seismicity (Figure 12), suggesting that the links between the cavities and conduits were no longer open.

This model represents a generalization of glacier drainage processes and their evolution from spring to late-summer. It shows the value of simultaneous measurements of proglacial hydrology and glacier motion.

II. COMPARISON OF THE HYDROLOGY AND MOTION OF BLACK RAPIDS GLACIER IN 1986-1989 VERSUS 1993

Year-to-year differences among parameters measured in 1986-1989 were due, according to Raymond and others (1995), to yearly differences in weather patterns. The 1993 hydrologic and motion data are generally similar to those of 1986-1989. Trends through the measurement season are alike for both data sets, and event timing is similar. Diurnal variations in hydrologic parameters are also similar; for instance, stage diurnals in both data sets reflect a 2-4 h meltwater travel time. However, the 1993 data appear different from any of the data sets compiled by Raymond and others in two major ways. These differences were not *simply* due to "year-to-year differences in weather patterns" (Raymond and others, 1995). We believe that the differences, while they may have been *triggered* by weather, represent fundamental changes in drainage system architecture.

First, conductivity variations in 1986-89 appeared related to stage variations and were probably due to dilution. Raymond and others (1995) conclude that, to accomplish dilution with the travel times they observed, the drainage system must have had two subsystems: a "slow" system and a "fast" system. In their model, solute-enriched water flowed continuously through the "slow" system and continuously mixed with and was diluted by the variable discharge within the fast system. The dilution caused diurnal variations in conductivity.

The conductivity-stage-seismicity relationship proposed for 1993 has not been observed before on Black Rapids Glacier (or on any glacier, to our knowledge, as Collins, 1979 bases his conclusions on conductivity and stage). It suggests to us that the drainage system consisted of a single system composed predominantly of conduits that were supplemented by storage cavities. Flow into and out of the cavities was dependent on pressures within the conduits such that solute-enriched water was released from the cavities in pulses, creating diurnal variations in stream conductivity. In 1993, solute-enriched water had less contact, and therefore less mixing, with solute-free water relative to 1986-1989.

Second, our conclusions concerning the drainage system pressures and the pressure-dependence of motion events are different from those of Raymond and others (1995). They hypothesize that the mid-summer subglacial pressures in 1986-89 were low. Pressures then begin to build at the end of the summer as the drainage system contracted. Late-summer precipitation raised pressures further, enough to trigger motion events. It is unknown whether pothole drainages were associated with these motion events because of the lack of time-lapse photography data.

We believe that in 1993, subglacial pressure was high in mid-season. The existence of high pressure is supported by the pothole infilling on day 197, by strong diurnal variations in seismicity, and--if our model is valid--by the presence of auxiliary cavities with links to the conduits. The late-season, long-duration precipitation episodes enlarge the drainage conduits, creating *low* pressure. The low pressure created conditions that allowed the pothole drainages (Events 6 and 7), which caused high pressure and motion events.

The differences in the drainage regime in 1993 relative to 1986-89 were, perhaps, instigated by changes that took place early in the 1993 season. The abrupt onset of melting and early spring velocity increase may have shocked the drainage system into assuming, at the outset of the measurement season, a completely different architecture than in the past--that of conduits supplemented by cavities. But it is equally possible that this change, while superficially triggered by early high temperatures, is related to the evolution of the glacier towards its next surge. This question will be discussed below.

III. PLACEMENT OF 1993 INTO SURGE EVOLUTION

Heinrichs and others (1995) and Heinrichs and others (in press) have compiled and analyzed measurements of surface velocity, ice thickness change, and mass balance that were made on Black Rapids Glacier from 1971-1993 to determine how a glacier in quiescent phase evolves towards its surging phase. They find that ice speed varies with time: there are two periods of decreasing speed--1972-77 and 1987-90--and two of increasing speed--1978-86 and 1991-1993. The increases/decreases occur over both winter and summer seasons, indicating that the amount of *basal* motion increases/decreases. They conclude that a new surge is not imminent.

Glacier motion and subglacial hydraulics are believed to be coupled; the decreases and increases in speed found by Heinrichs and others (1995) may reflect changes in the subglacial drainage system. We conclude here that the drainage system in 1993, a year of increasing speed, was different from that of 1986-89, years of decreasing speed. The conductivity-stage-seismicity relationship in 1993 suggests that the drainage system had daily variations in water storage that did not exist in the 1986-89 drainage systems. The presence of storage further suggests that high subglacial pressures existed in 1993 relative to 1986-89. These differences in storage and in pressure may be related to the increasing speed in 1993 (see Iken and others, 1983). In addition, these differences may reflect mechanisms that are typical of evolution towards surging since surges are generally associated with water storage and disruption of the drainage system (for instance, Harrison and others, 1994; Humphrey, 1987, and Kamb and others, 1985).

CHAPTER 6: SUMMARY

In our schematic model of the 1993 drainage system, large water inputs early in the measurement season caused the incorporation of bladder-like storage cavities into a system composed predominantly of conduits. Water flow between the conduits and cavities was pressure-dependent and resulted in the isolation and release of solute-enriched water. At the end of the season, precipitation episodes caused low drainage system pressures, which created conditions suitable for pothole drainages.

This study illustrates the importance of long-term measurements; we were able to compare the 1993 drainage system to the systems of 1986-89. Differences between the systems include the 1993 relationship among conductivity, stage, and seismicity, which did not exist in 1986-89. It is presently unknown whether the differences resulted from an early spring velocity increase in 1993 or from other mechanisms, perhaps related to evolution towards surging flow.

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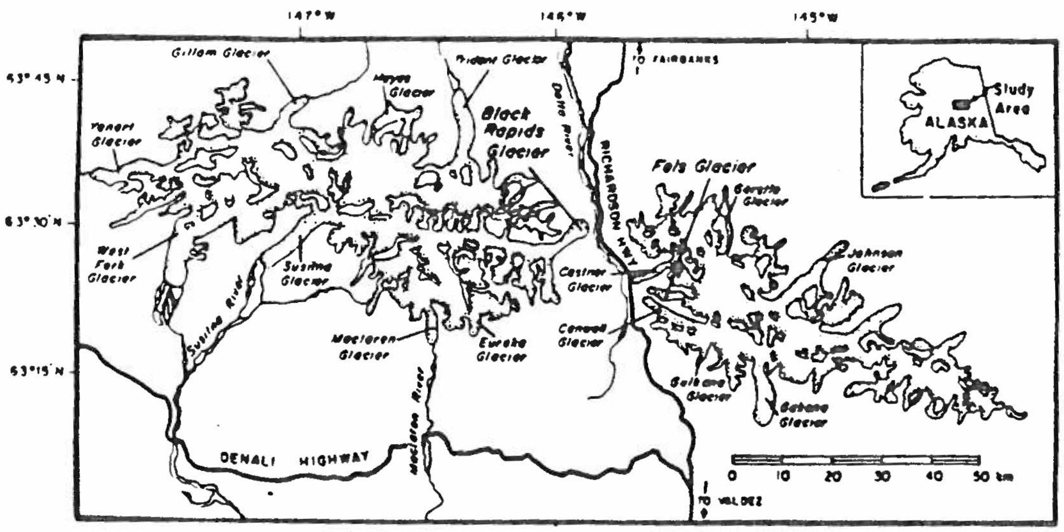

Figure 1: Location map showing Black Rapids, West Fork, Susitna, and Fels Glaciers.

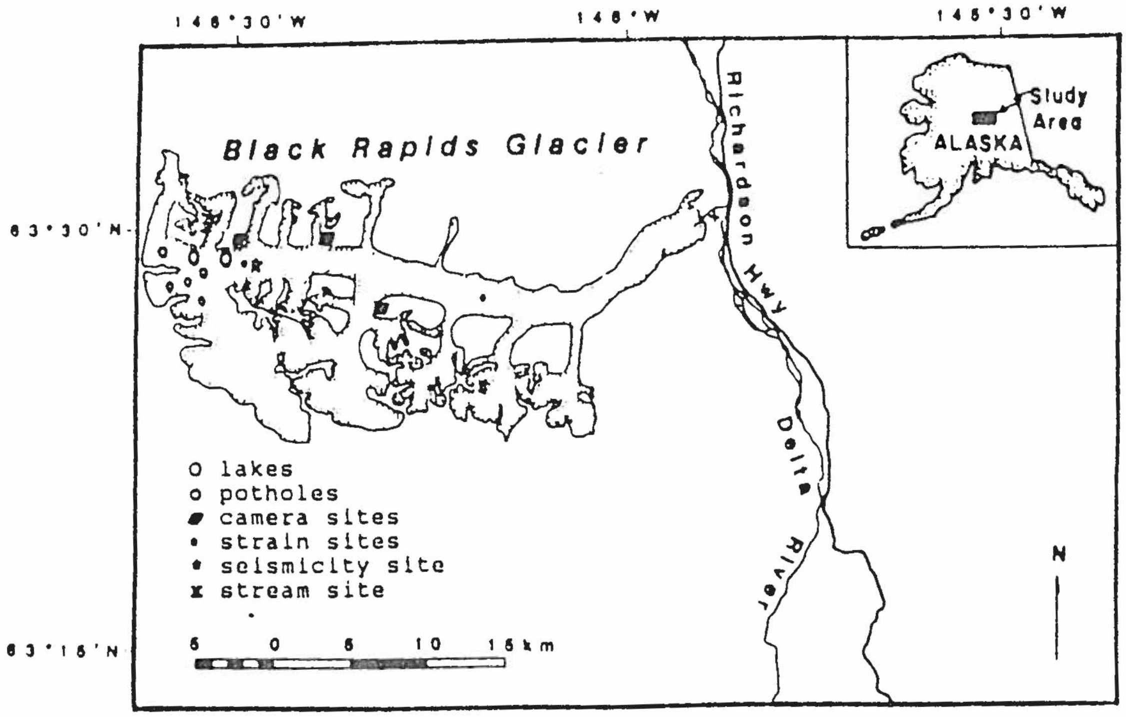

Figure 2: Map of Black Rapids Glacier showing locations of lakes and potholes and measurement sites.

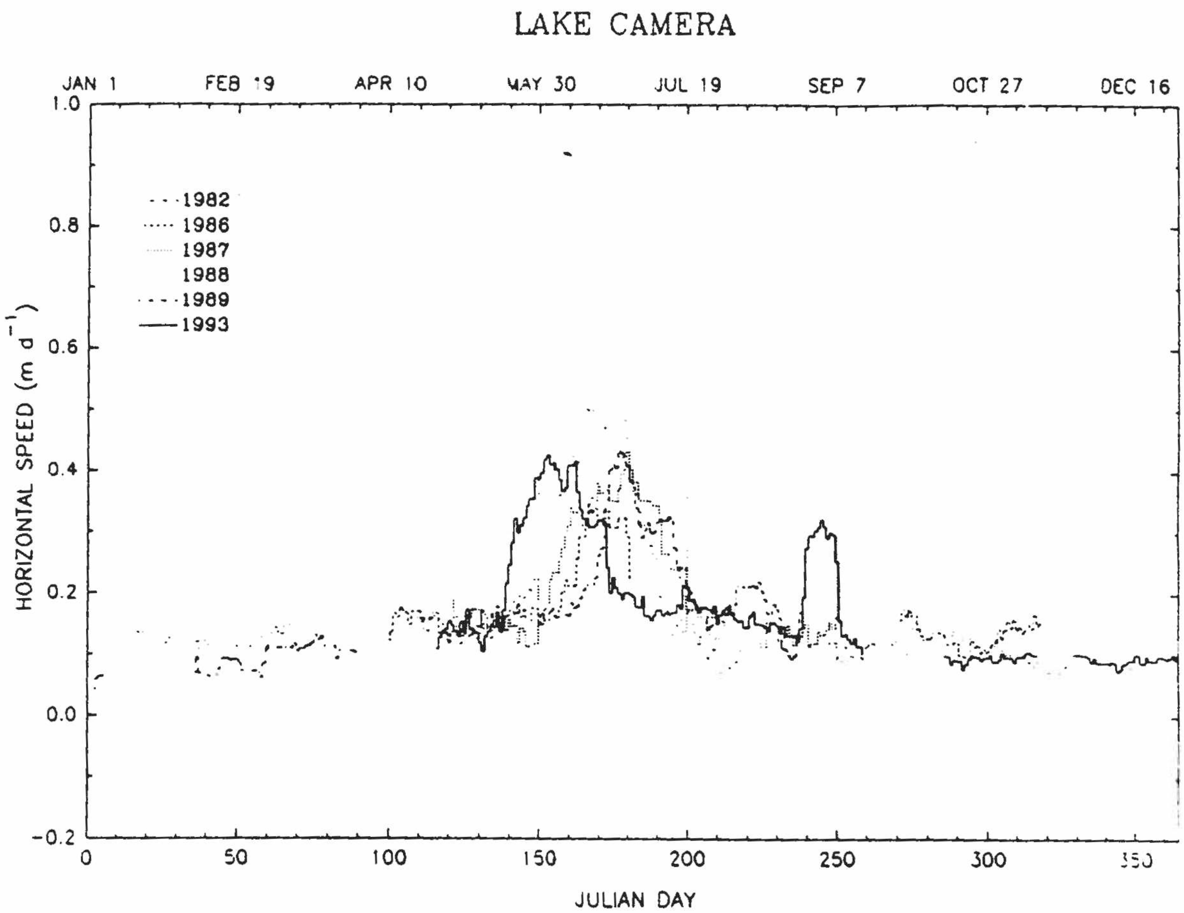

Figure 3: 10-day running average of velocity using time-lapse photography data from "Lake" camera, located 20 km from head of glacier.

The spring velocity increase in 1993 occurred earlier than in previous years.

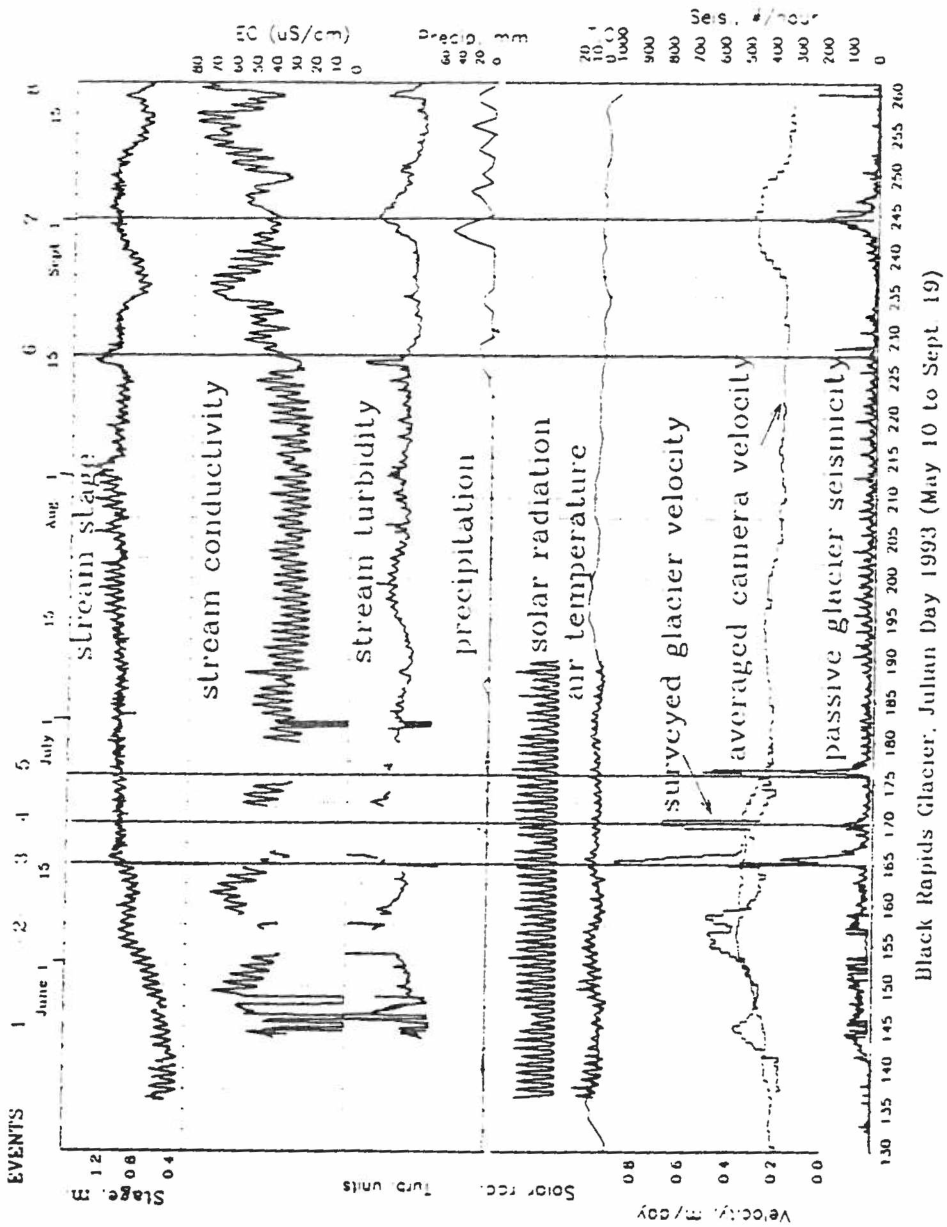

Figure 4: Proglacial Hydrology compared to Upglacier Meteorology, Seismicity, Surveyed Velocity, and 10-day Averaged Camera Velocity.

Solid, vertical lines represent the initiation of lake or pothole drainages as observed in time-lapse photography. Short-period velocity or seismicity increases, or "events", are labeled along the top of the figure. Precipitation and air temperature data are supplemented by data from U.S.G.S. measurements on Gulkana Glacier (B. Kennedy and R. March, personal communication), such that the smooth air temperature curve and solid precipitation curve are representative of Gulkana Glacier. The surveyed velocity and camera velocity are both located roughly 14 km from the head of the glacier but not at the same site. Seismicity data is explained in the text.

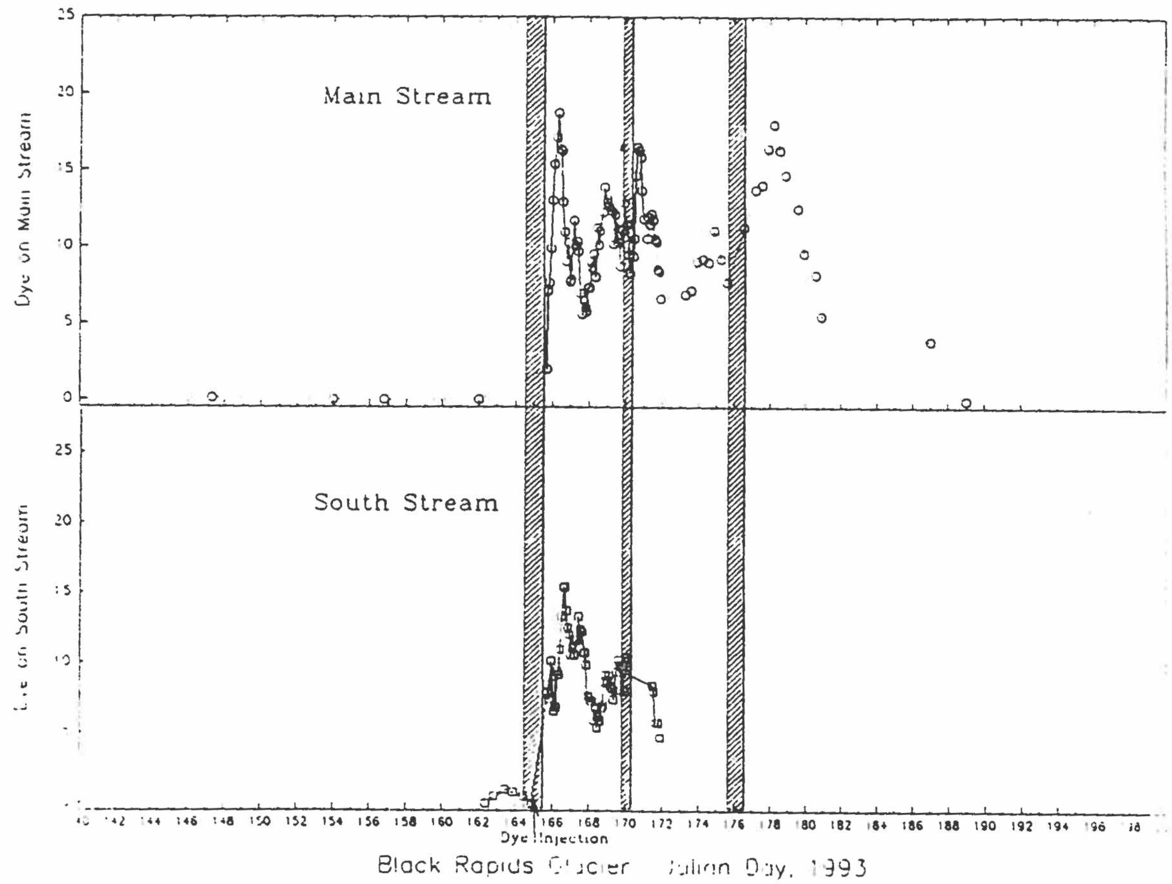

Figure 5: Results of dye-tracing experiment.

On Main Stream, a three-point, running average was used on the data between days 166-170 because of excessive scatter. On day 172, sampling frequency decreases from one sample/two hours to one sample/six hours on Main Stream. The shaded areas depict the duration of drainage episodes.

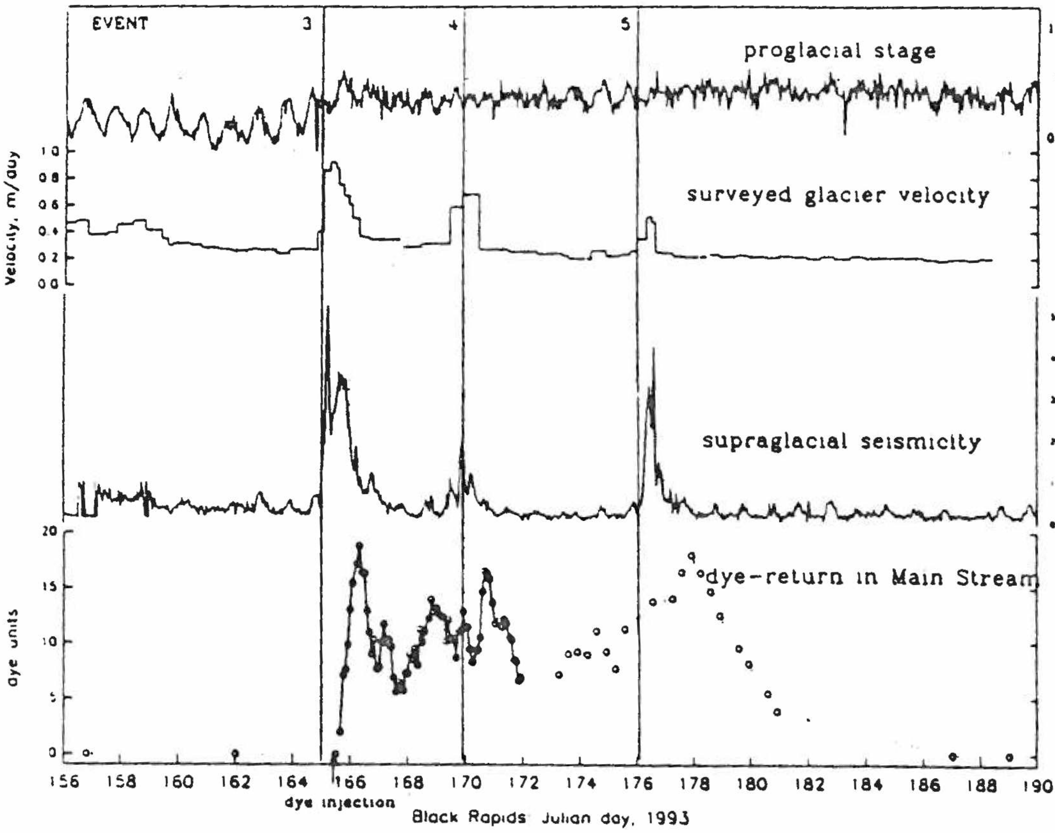

Figure 6: Dye-return in Main Stream compared to seismicity, velocity, and stage. Peaks in dye follow events.

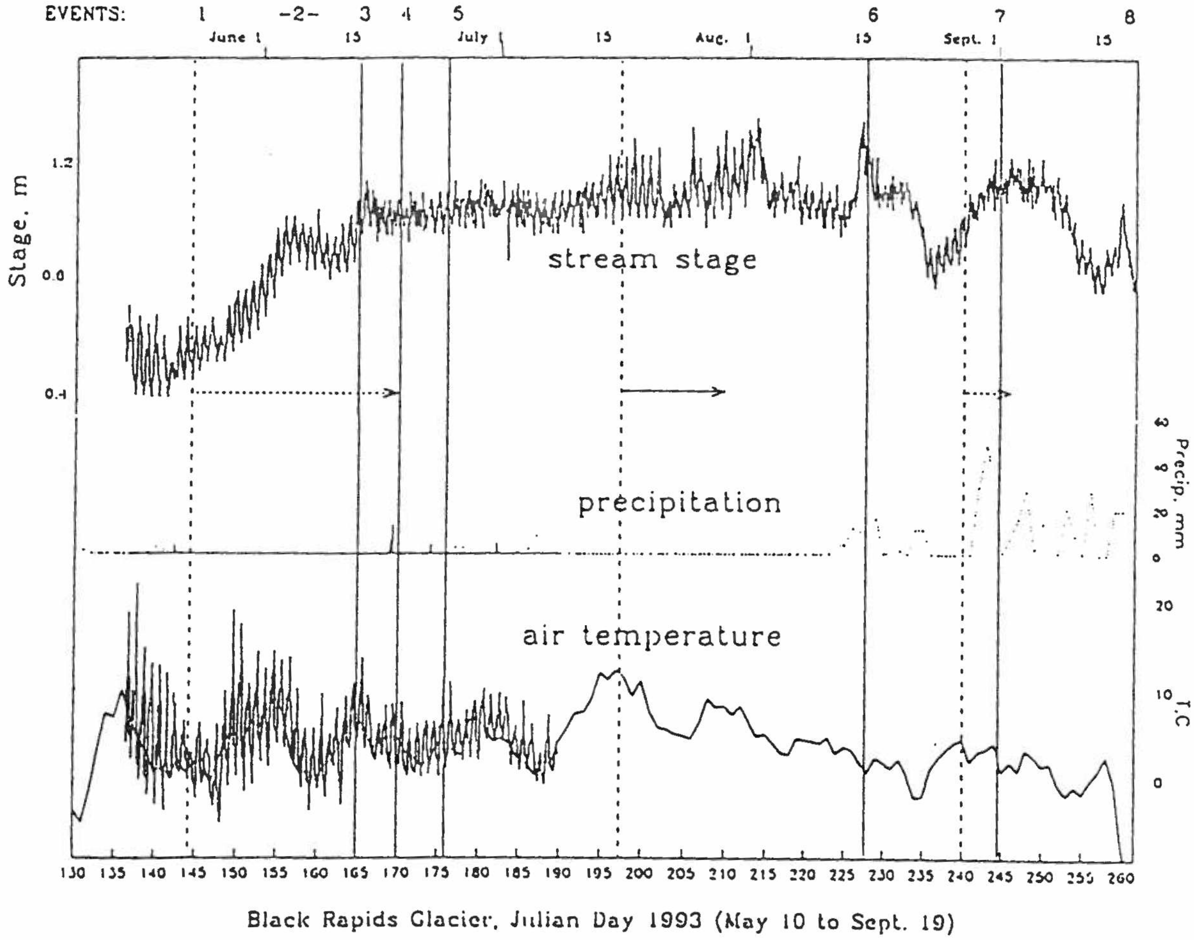

Figure 7: Stage, meteorology, lake and pothole drainages, and pothole fillings.

The initiation of lake and pothole drainages is represented by solid, vertical lines. Pothole infillings are represented by dashed, vertical lines with attached arrows that indicate duration of infilling. Precipitation data from Gulkana Glacier is dotted; air temperature from Gulkana Glacier is represented by the smoothed curve (B. Kennedy and R. March, personal communication).

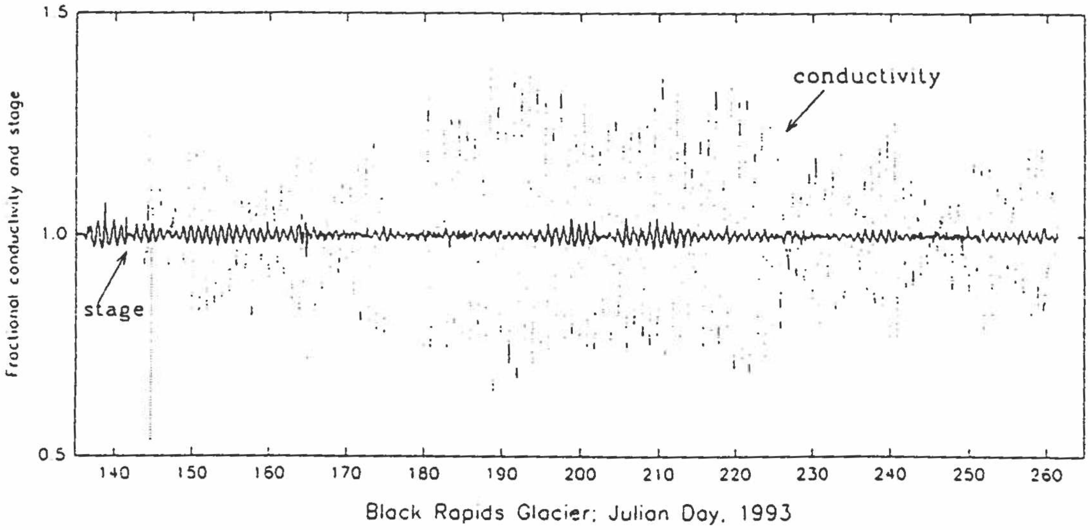

Figure 8: Fractional variations in conductivity compared to those in stage (hourly value/daily average).

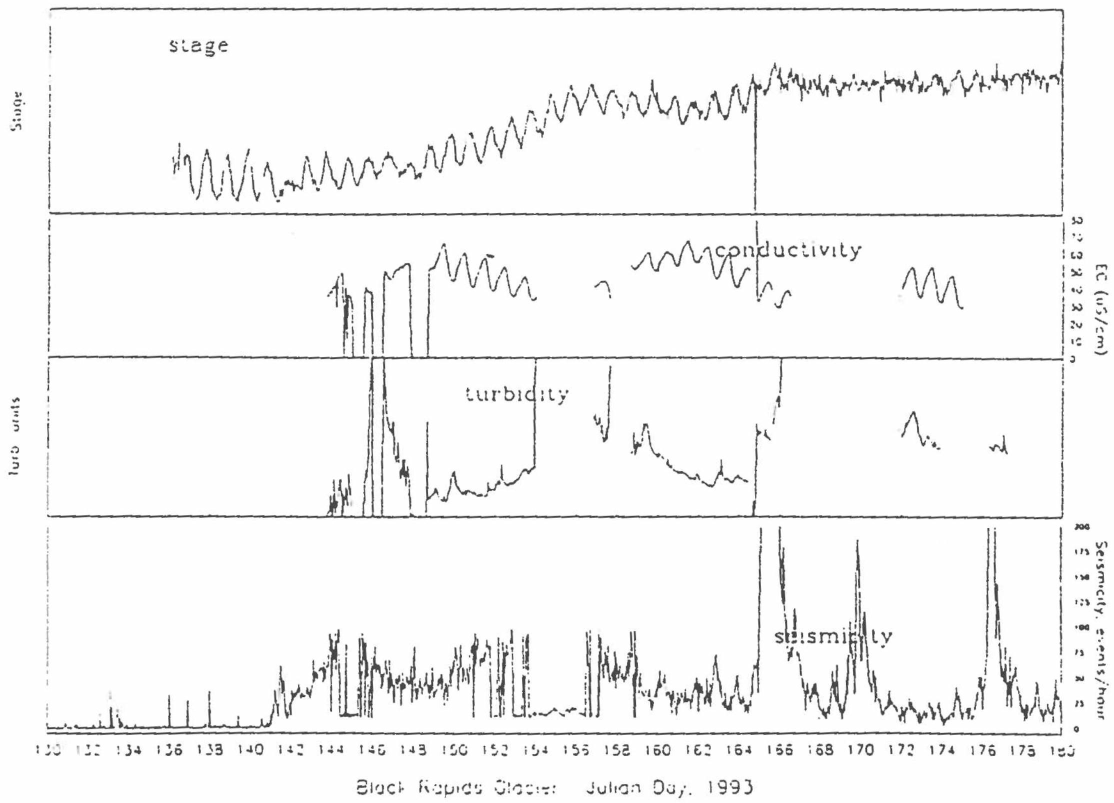

Figure 9: Hydrologic parameters and seismicity between days 130-180.

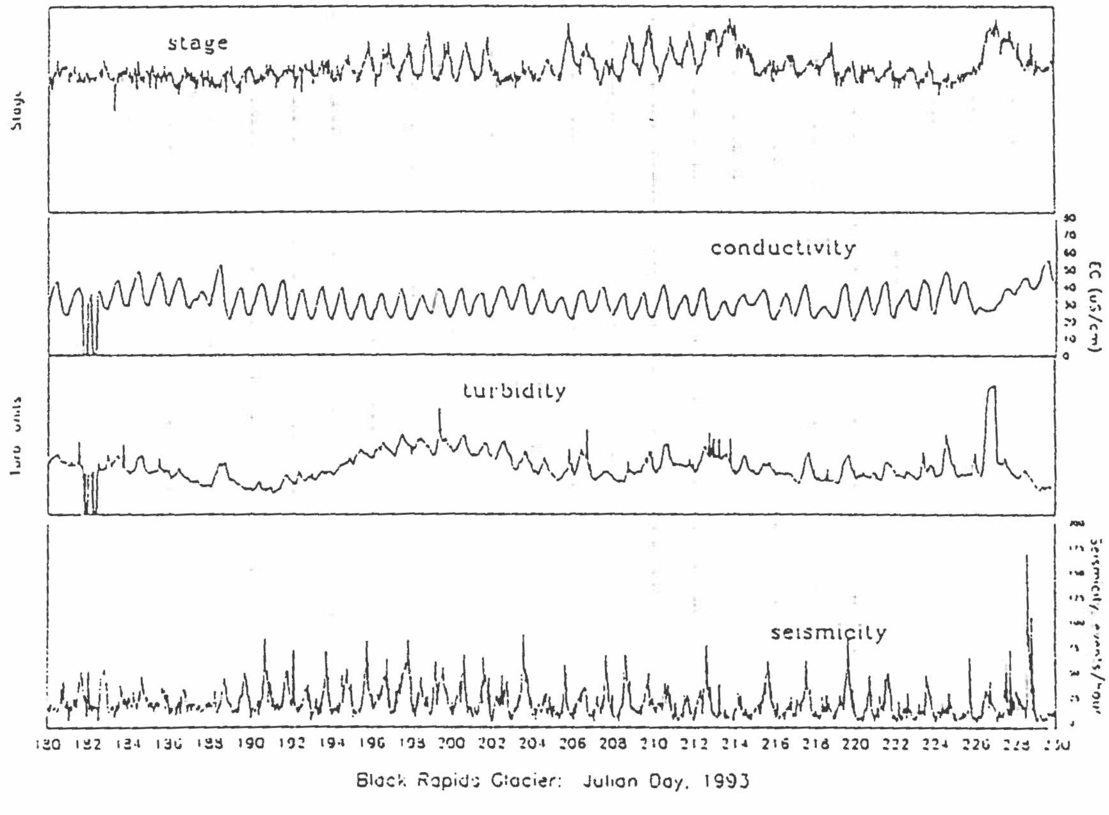

Figure 10: Hydrologic parameters and seismicity between days 180-230.

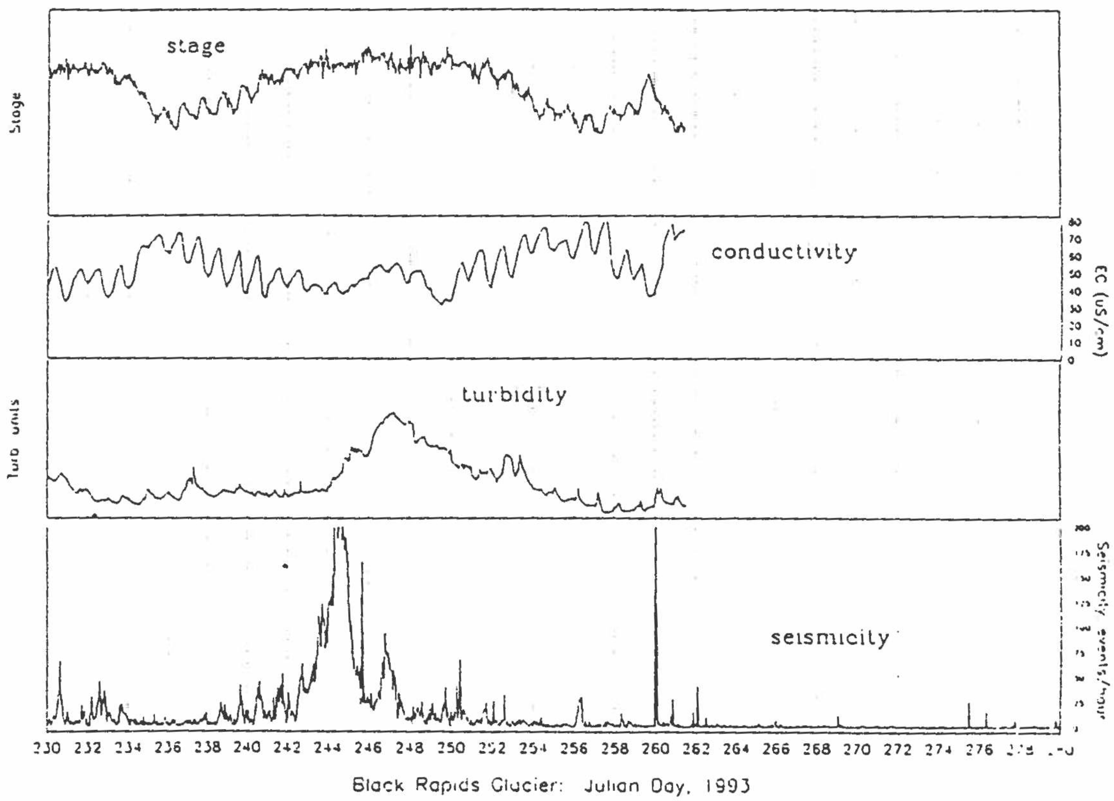

Figure 11: Hydrologic parameters and seismicity between days 230-280.

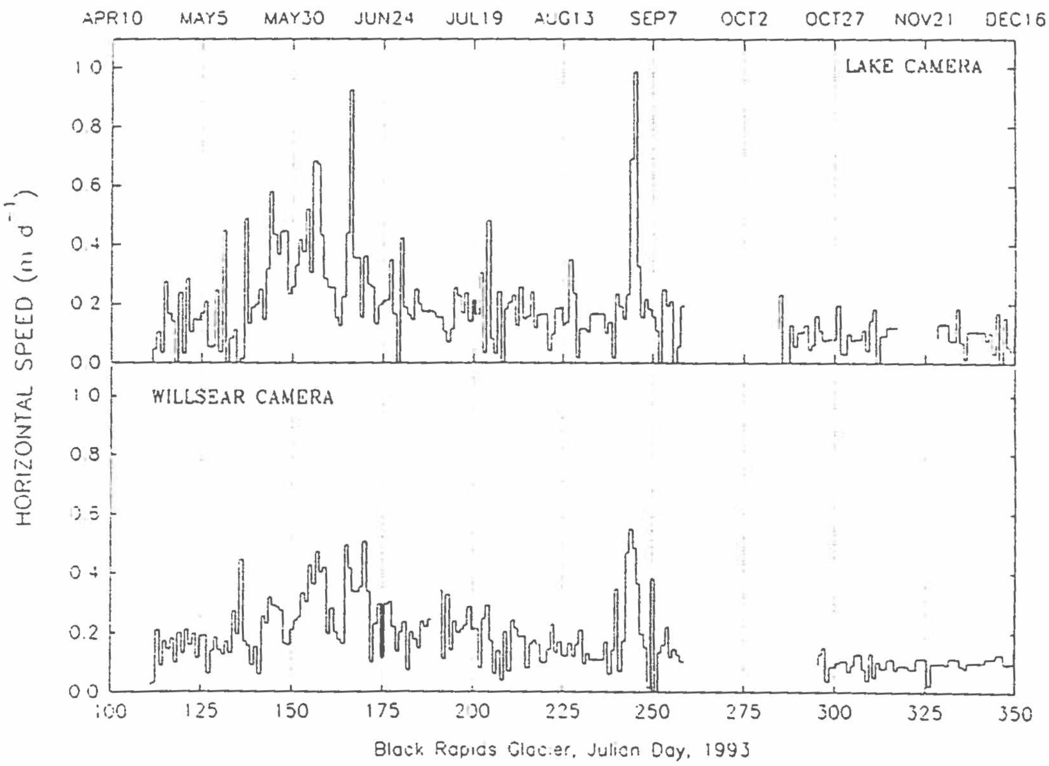

Figure 12: Unaveraged camera velocities.

Note late-season velocity increase (Event 7).

Table 1: Location and timing of measurements

LOCATION	MEASUREMENT	EQUIPMENT	TIME PERIOD	PERSONNEL
TERMINUS				measurements made by author unless otherwise noted.
Main Stream				
	stage	sonic ranger	days 136-261	
		camera	(data not used)	
	turbidity	photovoltaics	days 136-261	
	electrical resistivity	electric prongs	days 136-261	
	velocity	floats, stopwatch	days 136-180*	
	suspended sediment	sampled by hand, water sampler	days 136-261*	
	dye concentration	water sampler, fluorometer (in lab)	days 145-189	
South Stream				
	stage	hand measurements	days 136-180*	
	velocity	floats, stopwatch	days 136-180*	
	suspended sediment	sampled by hand	days 136-180*	
	dye concentration	water sampler, fluorometer (in lab)	days 165-172	
UPGLACIER				
13 km				
	travel-time	dye-slug	day 165	
15 km	velocity	survey/EDM	days 136-180*	K. Echelmeyer, M. Nolan, A. Gades, H. Conway
	passive seismicity	geophone	years*	K. Echelmeyer
	strain	strain wire	(data not used)	
	meteorology	thermometer, pyranometer, precipitation gauge	days 136-190	
29 km				
	strain	strain wire	(data not used)	
Misc.				
	velocity	cameras	years*	
	weather patterns	cameras	years*	
	lake/pothole filling and draining	cameras	years*	
GULKANA GL.				
	meteorology	thermometer, precipitation gauge	years	B. Kennedy, R. March

* intermittent measurements

Table 2: Events and their characteristics

EVENTS	VELOCITY morphology	SEISMICITY morphology	DRAINAGE	PRECIPITATION	STAGE INCREASE
1	hump	hump	no	no	no
2	hump	hump	no	no	yes
3	spike	spike	Aurora Lake	no	yes
4	spike	spike	Potholes	yes	no
5	spike	spike	Willsear Lake	no	no
6	none	spike	Potholes	yes	yes
7	spike	spike	Potholes	yes	yes
8	unknown	spike	unknown	yes	yes

Table 3: Charateristics of the data

TIME PERIOD	RESULTS	DISCUSSION	MODEL
Days 130-165			
	1 strong stage diurnals and short meltwater travel time	1 efficient drainage system	conduit drainage system
	2 suppressed seismicity diurnals	2 no periodic build-up of subglacial pressures	
Days 165-178			
	1 abrupt suppression of stage diurnals	1 alteration of the drainage system	storage cavities with links to conduits
	2 water from drainages> proglacial flooding	2 water was stored following lake/pothole drainages	
	3 long-term dye release and attenuation of stage diurnals	3 gradual release of stored water	
	4 rapid decreases in seismicity and velocity following Events 3-5	4 rapid pressure dissipation	
Days 178-226			
	1 large amplitude conductivity diurnals, suppressed stage diurnals	1 conductivity variations were independent of stage variations	water was trapped in cavities during high conduit pressure, became solute-enriched, and was then released from the cavities during low conduit pressure
	2 prominent seismicity diurnals	2 daily variations in subglacial water pressure	
	3 anti-phased conductivity and seismicity	3 solute concentrations are correlated to seismicity	
Days 226-261			
	1 potholes drained following increased stage and long episodes of precipitation (Events 6 and 7)	1 increased stage caused decrease in conduit pressure	pothole drainages were most likely during low subglacial pressure