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SEDIMENT AND WATER FROM TEN ALASKAN VALLEY
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SEDIMENTOLOGICAL AND GEOCHEMICAL
ASPECTS OF SEDIMENT AND WATER
FROM TEN ALASKAN VALLEY GLACIERS

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SEDIMENTOLOGICAL AND GEOCHEMICAL
ASPECTS OF SEDIMENT AND WATER
FROM TEN ALASKAN VALLEY GLACIERS

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ABSTRACT

The characteristics of superglacial sediments, suspended stream sediments, and meltwater from ten Alaskan valley glaciers were determined. The glaciers are eroding five different types of bedrock.

Superglacial sediments may be characterized as very poorly- to extremely poorly-sorted, muddy sandy gravels which are fine- to strongly fine-skewed and which have mean grain sizes in the very coarse sand to granule range. Superglacial sands contain high proportions of rock fragments and superglacial muds are composed largely of quartz and feldspar.

Superglacial sediments from six glaciers are relatively unmodified, but superglacial sediments from the other four glaciers are mixtures of relatively unmodified glacial sediments and proglacial sediments. Unmodified superglacial sediments are a-modal, but distinct size modes are present in mixed superglacial sediments.

The concept of the presence in nature of three basic particle-size populations cannot be applied to valley glacier sediments because particles of all sizes are produced by valley glacier action. Comparative grain-size characteristics of superglacial sediments, till, and outwash suggest that the classical explanations for the origin of deposits which exhibit the characteristics of till and outwash may not always be valid.

Mud is the major component of suspended stream sediments. These sediments are generally poorly-sorted and contain distinct size modes. Mean grain size of suspended sediments is a function of glacial stream velocity.

Comparative grain-size characteristics of superglacial sediments and suspended stream sediments indicate valley glacier sediments are selectively size sorted soon after contact with glacial streams. The environment of transport has a much greater effect on the grain-size characteristics of transported valley glacier sediments than does the source material (bedrock and primary sediment).

Mean Na+K+Ca+Mg+Si concentrations in meltwater streams range from 9.3 to 37 ppm. The pH, Eh, and temperature range from 7.3 to 8.9, +0.42v.

to +0.58v., and 0.5 to 3.2⁰ C, respectively. The relative abundance of cations in these streams is: (Ca+Mg) > (Na+K) > Si. Suspended sediment concentrations are variable among the streams and are dependent upon the nature of the stream environment.

The results suggest that dissolved constituents in glacial meltwater are derived through partial dissolution of suspended stream sediment. Initial dissolution probably occurs under the ice soon after sediment comes in contact with meltwater. The chemical composition of meltwater is probably established by the time a stream emerges at the glacier terminus and this composition is not significantly altered along the course of the stream. Bedrock control of meltwater chemistry has been demonstrated by comparing mineralogy and chemistry of superglacial sediments with meltwater chemistry.

The Norris Glacier tide-affected meltwater system was also studied. Major cation concentrations in the meltwater do not vary appreciably throughout the system. In the zone of mixing of meltwater and saline Taku Inlet water, however, major cation concentrations increase as a function of the degree of mixing. The clay content, organic matter content, and cation exchange capacity of tide flat sediments are also functions of the relative influence of the marine environment.

Different physical, chemical, and biological processes are operative in the various environments comprising the Norris Glacier area. The behavior of iron in the system could only be explained by studying these processes and environments individually.

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CHAPTER I

INTRODUCTION

General Statement

The present investigation concerns some sedimentological and geochemical aspects of sediment and water from ten active Alaskan valley glaciers. It is one of the few studies conducted on valley glacier sediment and meltwater. Therefore, a major objective was to describe sediment and meltwater at their source, prior to any modifications which might obscure their original characteristics. Sediment and stream water from ten glaciers on five different types of bedrock terrane were chosen for study. In this manner, the relationships among bedrock, sediment, dissolved and particulate meltwater constituents, and the nature of the glacial stream environment could be evaluated.

Sedimentologists generally work with transported and deposited material because the starting material is often unavailable. In the present investigation, both relatively unmodified valley glacier sediment and reworked valley glacier sediment were available, so a major objective was to compare their grain-size characteristics. This is of major and far-reaching significance as the relative influences of environment of transport and source (original sedimentary detritus as well as bedrock) on the grain-size characteristics of transported sediment could be evaluated.

A widely held concept is the presence in nature of three basic particle-size populations resulting from common weathering processes. Valley glacier detritus is the product of an extraordinarily intense physical weathering process. Therefore, an equally significant objective was to see if this concept was valid for valley glacier sediment.

There are classical explanations for the origin of till and outwash deposits. Another objective of the present investigation was to compare the textural characteristics of superglacial sediment, till, and outwash in order to evaluate these

explanations.

The Norris Glacier area was chosen for study of an entire glacial meltwater system, including ice, a lake, streams, and ground water. This system is influenced by the marine environment. Objectives were to: (1) describe the physio-chemical characteristics of an entire meltwater system and (2) evaluate the influence of the marine environment on (a) the chemical composition of meltwater and (b) some physical and chemical characteristics of sediments in the area.

A portion of the Norris Glacier area is the site of extensive iron accumulation. The behavior of iron in natural water systems often defies simple explanation. The hypothesis that one of the reasons for this is the approach taken by researchers was also tested in the Norris Glacier area.

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CHAPTER II

PHYSICAL SETTING

During 1968-69 sediment and meltwater were studied from ten active valley glaciers in Alaska (Fig. 1 and Table 1). The choice of glaciers was based primarily upon bedrock lithologies. The object was to obtain sediment and meltwater from glaciers eroding a wide variety of bedrock, and yet to sample from more than one glacier on the same type of terrane. On this basis, five groups of glaciers were sampled.

I. Worthington and Matanuska Glaciers: meta-sedimentary terrane. Worthington Glacier lies entirely upon phyllitic graywacke (Coulter and Coulter, 1961). This lithology predominates around Matanuska Glacier, but some plutonic, extrusive, sedimentary, and porphyry dike rocks are present near its terminus (Dutro and Payne, 1954; Grantz, 1961). Graywackes have been defined differently by various authors; this graywacke appears to conform to Pettijohn's (1957) classification.

II. Castner and Fels Glaciers: quartz-mica schist terrane (Moffitt, 1954).

III. Gulkana and College Glaciers: complex terrane consisting of metamorphic, intrusive, extrusive, and sedimentary rocks. Lithologies include greenstone, granulite, migmatite, quartz diorite, andesite, basalt, limestone, conglomerate, sandstone, and siltstone (Bond, 1965).

IV. Rendu and Reid Glaciers: mixed granitic and metamorphic terrane. Granodiorite which predominates in both areas is associated with meta-sediments around Rendu Glacier and with undifferentiated metamorphic rocks around Reid Glacier (Rossman, 1963; MacKevett, and others, 1967). Less abundant lithologies in both areas include limestones,

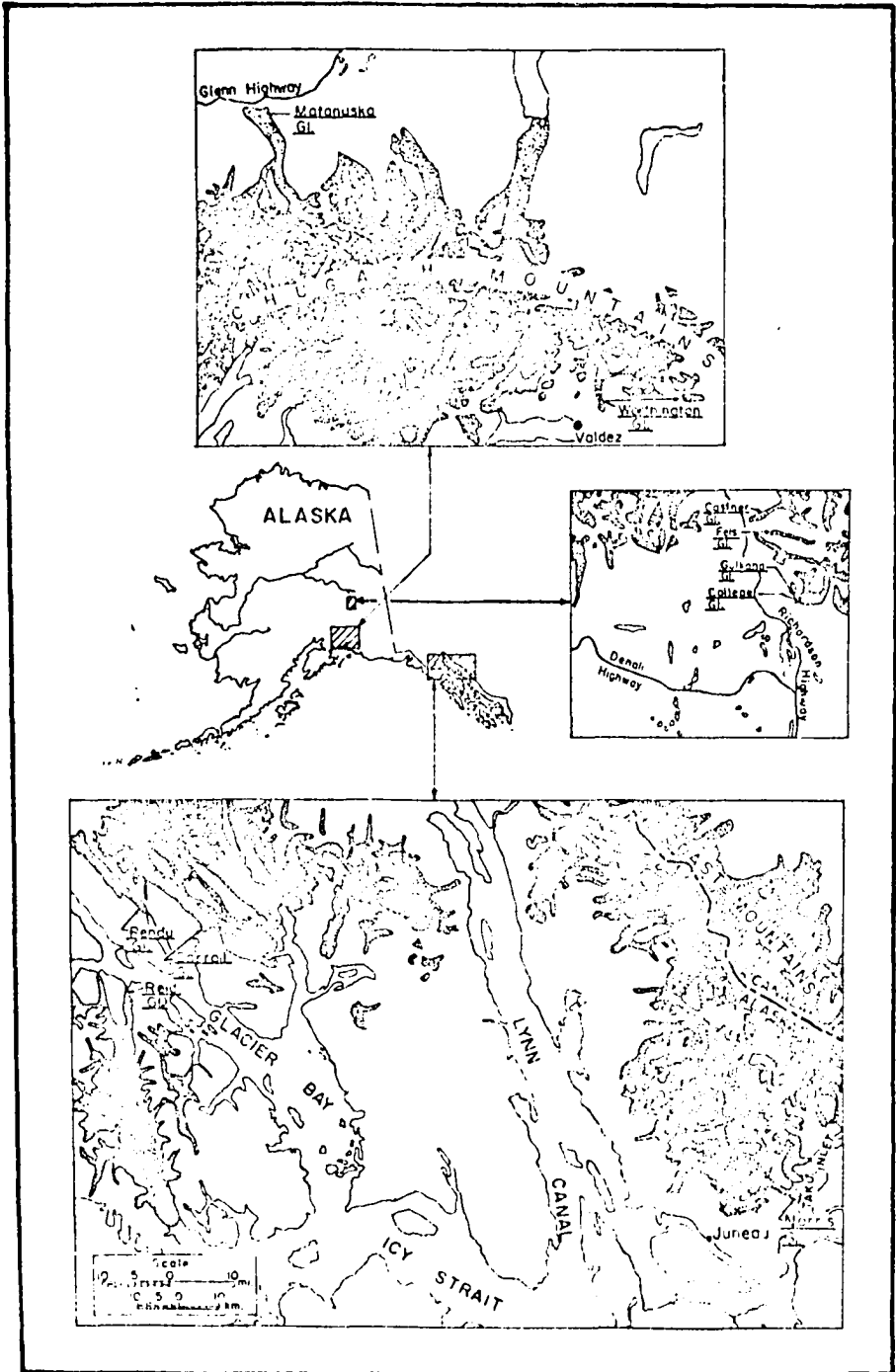


Fig. 1 - Index map showing the ten glacier locations.

Table 1. Location and areal extent of glaciers, and regional climatic data.

Glacier	Location		Est. Area (sq. kms.)	Mean Annual Precipitation (cms.)*	Est. Mean Jan. Temp. Range (°F)*	Est. Mean July Temp. Range (°F)*
	N. Lat.	W. Long.				
Worthington	61°10'	145°45'	8	152	4 to 16	46 to 66
Matanuska	61°20'	148°40'	91	51	4 to 16	46 to 64
Castner	63°25'	145°40'	83	30	- 8 to - 4	46 to 66
Fels	63°23'	145°38'	13	30	- 8 to - 4	46 to 66
Gulkana	63°18'	145°25'	11	30	- 8 to - 4	46 to 66
College	63°15'	145°21'	8	30	- 8 to - 4	46 to 66
Rendu	59°04'	136°50'	78	152	16 to 32	44 to 64
Reid	58°48'	136°52'	10	152	16 to 32	44 to 64
Carroll	59°01'	136°30'	91	152	16 to 32	44 to 64
Norris	58°24'	134°08'	25	152	20 to 28	48 to 58

*Data from Searby (1959).

gneisses, and volcanics.

V. Carroll and Norris Glaciers: gneissic terrane.

Dioritic gneisses predominate around Carroll Glacier (MacKevett, and others, 1967). Quartz dioritic to granodioritic gneisses predominate around Norris Glacier (Forbes, 1969; Rossman, 1963). Amphibolites, schists, granulites, and marble are also present.

Of secondary importance in choosing the study areas were a knowledge of recent glacial history, areal extent of the glacier, and climate. A knowledge of present and recent glacier regimen is important in interpreting the possible extent of mixing of proglacial sediment with younger, less thoroughly reworked debris, particularly during stages of advance. Each glacier sampled has experienced multiple advances and recessions on the order of at least a few kilometers in the very recent past (Lawrence, 1950; Nielsen and Post, 1953; Péwé, 1957; Williams and Ferrians, 1958; Coulter and Coulter, 1961; Field, 1964; Goldthwait, and others, 1966; Reger, 1968; Field, 1968--personal communication). During 1968-69, all of the glaciers studied were receding except Carroll and Matanuska, which were advancing. Reid Glacier had a tidal terminus and the Rendu Glacier terminus was separated from high tidewater by only a narrow end moraine. The termini of all others were terrestrial.

The areal extent of a glacier affects the volume of meltwater produced. It also might affect sediment by controlling the length of time particles are in transit and the degree of stress to which they are subjected. Areas of all glaciers studied fall into two categories, 8 to 25 and 78 to 91 square kilometers (Table 1).

To a large degree precipitation and air temperature affect the volume of meltwater produced. The climatic data presented in Table 1, taken from Searby (1959), are for the regions in which the glaciers occur. Anomalies probably exist at the glaciers, but in general, precipitation and temperature near coastal glaciers are higher than near inland glaciers.

CHAPTER III
SUPERGLACIAL SEDIMENT AND SUSPENDED
STREAM SEDIMENT

Introduction

Prior studies of valley glacier sediment have generally ignored the primary or unreworked material at a glacier's terminus. Most studies have dealt with extensively reworked material deposited in proglacial environments such as lakes (Kindle, 1930; Mathews, 1956), fjords (Gross and others, 1963; Holtedahl, 1965; Hoskin and Burrell, 1968), and tide flats (Slatt and Hoskins, 1968). Outwash fans have been described by Hjulström (1952), Krigström (1962), and Slatt and Hoskin (1968). Suspended stream sediments have been described by Borland (1961) and Arnborg and others (1967). Soils on glaciated terranes have been described by Ugolini (1966). The morphological features of ice-contact sediment have been noted by Sharp (1947 and 1949). Other than one study of ice-cored morainic debris (Østrem, 1964), I know of no detailed sedimentological description of the primary nature of modern valley glacier sediment.

A major objective of the present investigation was to describe glacial sediments at their source, prior to any extensive modifications which might obscure their original characteristics. As is discussed in detail below, it is unlikely if any truly unmodified valley glacier sediment is available for collection. Therefore superglacial sediment was chosen for study as this material is probably the least reworked type of modern valley glacier sediment.

Sedimentologists generally work with material that has been transported and deposited because the source material usually is unavailable. Therefore the initial detritus and end products of transport and deposition cannot be directly compared. The relative influences of source and environment on the resulting sediment must be inferred. Since major emphasis in the present study was placed on describing the starting material, a comparison of this sediment with extensively reworked sediment from the same sources is valuable.

In this manner, the relative influences of source and environment could be evaluated. Sediment presently being transported by glacial streams was chosen for study as it is actively being reworked.

Superglacial Sediment

Definition and sources of superglacial sediment

Superglacial sediment is debris mantling glacier ice. This sediment is particularly abundant in a glacier's stagnant terminal zone. Superglacial sediment is derived from (1) valley walls by rock falls, avalanches, and other mass movements and (2) englacial debris exposed by ablation below the firn line. Sources of englacial debris include (1) material dropped from valley walls onto the ice above the firn line and subsequently buried by later snow, (2) subglacial debris transported into the englacial position by upward movement along shear planes in the terminal zone, and (3) moraines of tributary ice streams (Sharp, 1949). In most instances the volume of debris originating from valley walls is probably small compared to that derived from the other sources. Superglacial debris typically lacks some of the finer-size fractions due to winnowing by surficial meltwater.

Theory of sampling

Some of the problems encountered in sampling superglacial sediment are worth mentioning. These problems arise because of the complex nature of glacier sediment-forming, transportational, and depositional processes. A knowledge of these processes as well as the specific type of information desired is necessary prior to collection of glacial material.

Because of the variety of superglacial sediment mentioned above, the transportational history of any particle may be complex. Similarly, glacial sediment-forming processes are complex. The majority of sedimentary particles originate at the ice-bedrock surface through abrasion and quarrying (plucking) (Flint, 1964). Rock fragments are primarily produced by mechanical wear of bedrock by a glacier's detrital load rather than by ice abrading

bedrock. Although the exact mechanism of glacial quarrying is unknown, common theories suggest frictional drag and subsequent adhesion as the ice moves over bedrock, or loosening of bedrock by expansion and contraction of ice in fractures. Once a fragment of bedrock is removed it becomes entrained in the base of the ice and in this position is transported by any of the above means. In fractured rocks quarrying is quantitatively more effective in producing fragments than abrasion of the bedrock floor. Large fragments removed by quarrying subsequently are broken into finer particles by mutual abrasion within a short distance of travel under the ice (Charlesworth, 1957; Flint, 1964).

The stagnant terminal zone of a glacier, where most superglacial debris accumulates, is actually a dynamic environment. Reworking and grain-size reduction may take place by the action of running water, mass movements, frost processes, and wind action. These processes, along with differential ice ablation, produce a myriad of surficial features such as debris-covered ice mounds and ridges, mud ridges, and sinkholes (Sharp, 1947 and 1949; Clayton, 1964; McKenzie, 1969).

Superglacial debris may consist of a mixture of relatively recently exposed sediment or older, better sorted proglacial sediment. Mixing of these two populations is one result of multiple ice advances and recessions. This aspect is particularly important here due to the complex recent history of the particular glaciers studied. To cite two examples: superglacial sediment at the Matanuska Glacier terminus is presently being mixed with extensive proglacial fine sand-coarse silt beds due to overriding by ice; and, part of the sediment from the Norris Glacier terminus appears to be former Taku Inlet tide flat sediment. Field evidence for the latter includes the presence of gravel- and sand-size shell fragments and an abundance of ice-cored, well-sorted sand mounds which appear similar to the modern tide flat sand in that area (Slatt and Hoskin, 1968).

In the present study, a primary objective was to characterize the primary product of glacial action upon bedrock, prior to reworking. Therefore deposits sampled should have ideally met two criteria: (1) they should have been relatively recently exposed, and (2) they should not have been reworked (i. e., no grain-size reduction or selective sorting and removal should have occurred). The

first criteria was fairly easily met by sampling ice-contact deposits at the terminus. However, because of the complex glacial processes described above, obtaining unmodified sediment is virtually impossible. Superglacial sediment was thus chosen for study, since this is probably the least reworked material available.

To minimize the problem of reworking, three criteria were adopted and consistently met for sampling superglacial deposits: (1) the deposit was ice-cored, usually an ice-cored mound, (2) it appeared to be poorly sorted, and (3) it appeared to be typical and representative of deposits in the area. Although these criteria immediately introduce the bias of selective sampling, the major advantage to this study is that even though some removal of finer-size fractions undoubtedly occurred, the maximum number of grain-sizes could be studied by sampling poorly sorted sediment.

Because some of these samples were actually mixtures of recently exposed glacial sediment and older proglacial sediment, and because pebbles from outwash were invariably rounded, pebble roundness was used as a criterion for recognition of the degree of mixing and reworking.

Texture

Methods of collection and analysis. Large samples were required to insure proper representation of the coarser-size fractions. Seven 250 kg (approx. 500 lbs) samples, three from Worthington, two from Castner, and once each from Carroll and Rendu Glaciers, were collected along with nineteen 5 to 10 kg (approx. 10 to 20 lbs) samples. Three channel samples were collected from each glacier terminus except Carroll and Reid Glaciers, where only one channel sample each was obtained.

Grain-size distribution analysis of the 250 kg samples was done by a combined field-laboratory method (Figs. 2 and 3). This involved splitting the sample into a number of manageable fractions, determining the dry weight and grain-size frequency distribution of each fraction, and, by applying appropriate multiple splitting factors, calculating the frequency distribution of the entire sample. Gravel coarser than -3.65 phi was analyzed in the field and discarded; material finer than -3.65 phi was retained for analysis in the labora-

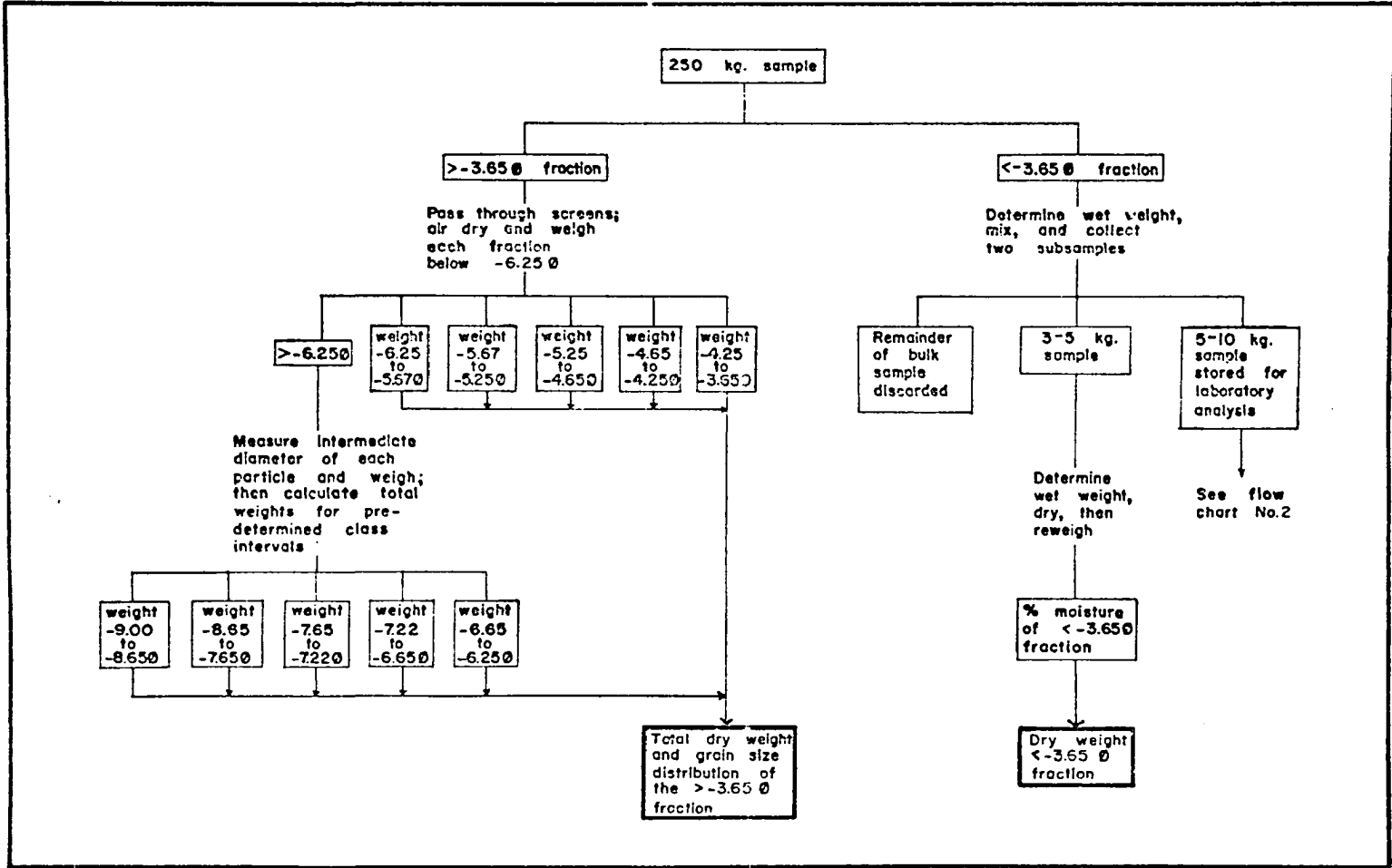


Fig. 2 - Flow chart No. 1: Field procedure for grain-size distribution analysis of 250 kg superglacial sediment samples.

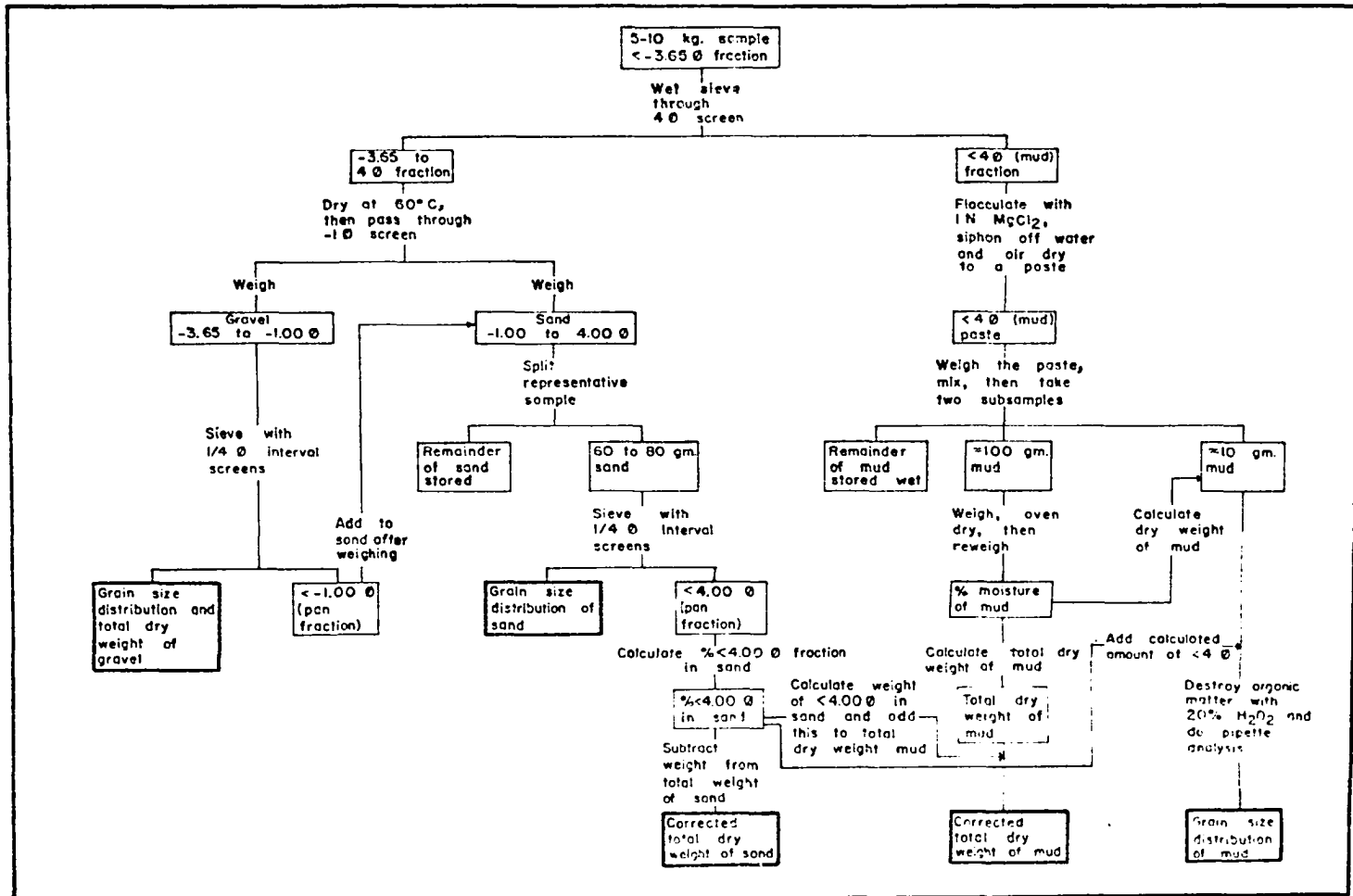


Fig. 3 - Flow chart No. 2: Laboratory procedure for grain-size distribution analysis of 250 kg super-glacial sediment samples.

tory. Gravel (-3.65 to -1.00 phi) and sand (-1.00 to 4.00 phi) were sieved through one-quarter phi interval screens, and mud (finer than 4.00 phi) was pipetted, all according to standard methods (Folk, 1968).

Equipment required for sieving in the field included (1) tarpulin for spreading the sample, (2) 50 lb hanging balance attached to a collapsible tripod, (3) coal bucket for sample weighing, (4) Soiltest CL-320 field sieve set, (5) large calipers or scaled steel tape for measuring intermediate diameters of particles coarser than -6.25 phi, and (6) frying pan, Coleman camp stove, and gram balance for determining the moisture content of the less than -3.65 phi fraction.

Although tedious and time-consuming, the technique is straightforward except for the following special procedures. First, cobbles and boulders were often too large to be weighed on the scale used. This necessitated breaking up the particles and weighing the fragments.

Second, and most important, preliminary rough splitting into gravel, sand, and mud in the laboratory is never totally efficient. Some material belonging to a finer-size class will always remain with the coarser fraction and show up as a pan fraction after sieving. Invariably most of the pan fraction from the gravel sievings was in the very coarse sand range (-1.00 to 0.00 phi). Applying this finding to the pan fraction (finer than 4.00 phi) obtained from sand sieving, most of these particles would presumably be coarse silt (4.00 to 5.00 phi). Since the entire gravel fraction was sieved it was merely a matter of adding this fraction to the bulk sand, but since only an aliquot of sand was sieved, it became necessary to calculate the percent less than 4.00 phi material in the sand fraction and to add an appropriate amount to the aliquot of mud before pipetting, as shown in Fig. 3. In order to obtain the correct splitting factor, it was also necessary to subtract the calculated total weight of less than 4.00 phi material from the original weight of sand and then to add this weight to the previously calculated bulk dry weight of mud.

The final point worth noting is that because of these problems, it was necessary to do the grain size analyses in a step-wise manner: first gravel, then sand, and then mud.

The smaller 5 to 10 kg samples were collected by first obtaining a much larger channel sample, then mixing it thoroughly and passing the appropriate

amount through a -5.25 phi screen. The fraction finer than -5.25 phi was analyzed in the laboratory by the method shown in Fig. 3: for these samples the upper size limit is -5.25 phi rather than -3.65 phi (Fig. 3).

With the resulting data, cumulative curves were constructed on arithmetic coordinate paper (14 phi = 100%). Mean size, standard deviation, skewness, and kurtosis were calculated from the cumulative curves, using the formulas of Folk and Ward (1957).

Roundness of 100 pebbles in the -5.25 to -4.00 phi range was measured from one sample from each glacier (with the exception of Reid Glacier, where only 54 pebbles were available). Pettijohn's (1957) roundness classification was used. Mean roundness was calculated by the formula:

$$R = \frac{\left[\sum_1^5 (X)(M) \right]}{\sum X}$$

where $\sum_1^5 X$ refers to Pettijohn's five roundness classes, X = the number of grains and M = Pettijohn's mid-point value for each class. A sixth class, "rounded to well-rounded, broken grains" was added as these also are good criteria for recognizing mixed sediment; this class was not included in computing mean roundness values and the number of pebbles in the other five classes was recalculated to 100%.

Results and interpretation. Matanuska, Rendu, Carroll, and Norris Glacier pebbles are subrounded or rounded (Table 2), indicating mixing with proglacial sediment. This supports field evidence previously described for Matanuska and Norris Glacier deposits. The possibility that these pebbles were rounded by subglacial or superglacial streams is unlikely since the deposits sampled were typical of the areally extensive superglacial debris. Pebbles from the other six glaciers are subangular so these deposits probably have not undergone extensive mixing or reworking aside from the probable loss of some fine material. Superglacial sediment from these six glaciers is therefore considered to be "primary" or unmodified even though this is not necessarily true in the strictest sense.

Weight percent of gravel, sand, and mud and mean size, standard deviation, skewness, and kurtosis data are presented in Appendix A. For direct comparison of all twenty-six samples, the seven 250 kg samples were recalculated so that only the finer than -5.25 phi fraction was considered. Fig. 4 shows the

Table 2. Roundness of superglacial pebbles.

Sample No.	% Angular (0-0.15)	% Subangular (0.15-0.25)	% Subrounded (0.25-0.40)	% Rounded (0.40-0.60)	% Well Rounded (0.60-1.00)	% Rounded- Well Rounded/ Broken	Mean Sample Roundness	Classification
WorS-9	26	56	17	1	-	-	0.20	Subangular
MatS-1	2	4	18	40	29	7	0.40	Rounded
CasS-13	39	55	6	-	-	-	0.18	Subangular
FelS-1	35	51	14	-	-	-	0.19	Subangular
GulS-4	44	49	7	-	-	-	0.18	Subangular
ColS-3, 4	35	49	14	2	-	-	0.20	Subangular
RenS-5	-	13	38	39	3	7	0.39	Subrounded
*ReiS-1	22	61	17	-	-	-	0.20	Subangular
CarS-1	-	4	16	46	25	9	0.54	Rounded
NorS-1, 3	4	10	30	33	6	17	0.40	Rounded

*54 pebbles counted.

Sample designations are coded according to the first three letters of each glacier. Where two sample numbers are present, pebbles from both (totaling 100 pebbles) were used.

Classification modified from Pettijohn (1957, p. 58).

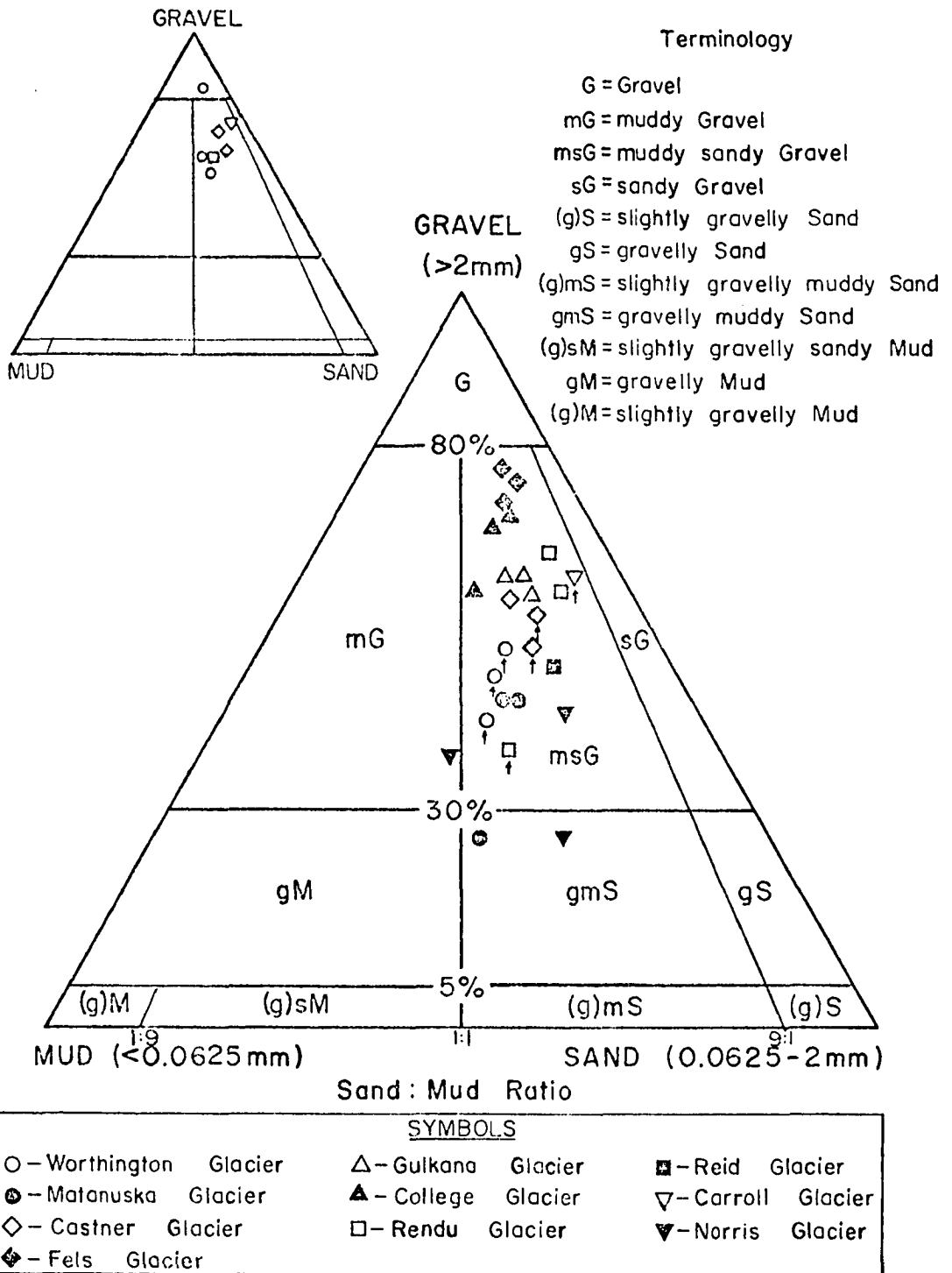


Fig. 4 - Texture of the finer than -5.25 phi fraction of superglacial sediments. Arrows denote 250 kg samples and the insert shows the texture of the 250 kg samples. Classification modified from Folk (1954).

proportions of gravel, sand, and mud for all samples. According to Folk's (1954) classification, all but three samples are muddy sandy gravel and these three (MatS-3, NorS-1 and -2) are mixed deposits.

Mean size values fall within the medium sand to pebble range (Folk, 1968), however, the majority of primary superglacial sediment samples fall in the very coarse sand to granule range. Nineteen samples have a standard deviation falling within the very poorly sorted class and six are extremely poorly sorted. With the exception of two samples from mixed deposits, all are fine-skewed to strongly fine-skewed. Most samples are platykurtic or mesokurtic, however, there is some variation within a given set of samples from the same glacier and there appears to be no distinction between mixed and primary deposits on the basis of kurtosis. There is no correlation between these parameters and type of bedrock terrane.

These data suggest a general description of superglacial sediment: very poorly- to extremely poorly-sorted, fine- to strongly fine-skewed muddy sandy gravel, with a mean size in the very coarse sand to granule range. Kurtosis seems too variable to be a defining characteristic. The characteristics of superglacial sediment are independent of source rock-lithology.

In general, the effect of recalculating 250 kg samples on the basis of finer than -5.25 phi material is to reduce the relative proportion of gravel (Fig. 4 and Fig. 4, inset) which results in finer mean size, standard deviation, and kurtosis, but skewness either increases or decreases. In most instances, recalculated values did not change the grain size name or standard deviation and skewness classifications, but did change mean size and kurtosis class names. Since no upper particle size limit was imposed upon the 250 kg samples, it appears that 5 to 10 kg of sample, with the coarser than -5.25 phi fraction removed, is probably sufficient for gross classification of coarse sediment on the basis of texture, standard deviation, and skewness, but not for mean size and kurtosis. For more precise numerical classification, samples should be standardized by setting an upper grain size limit to be collected. The size range analyzed should be included in statistical parameter data.

Fig. 5 shows frequency curves for the twenty-six samples. Curves of primary superglacial sediments are similar and exhibit a definite lack of size modes except for a very slight peak in the 4 to 5 phi range on some curves.

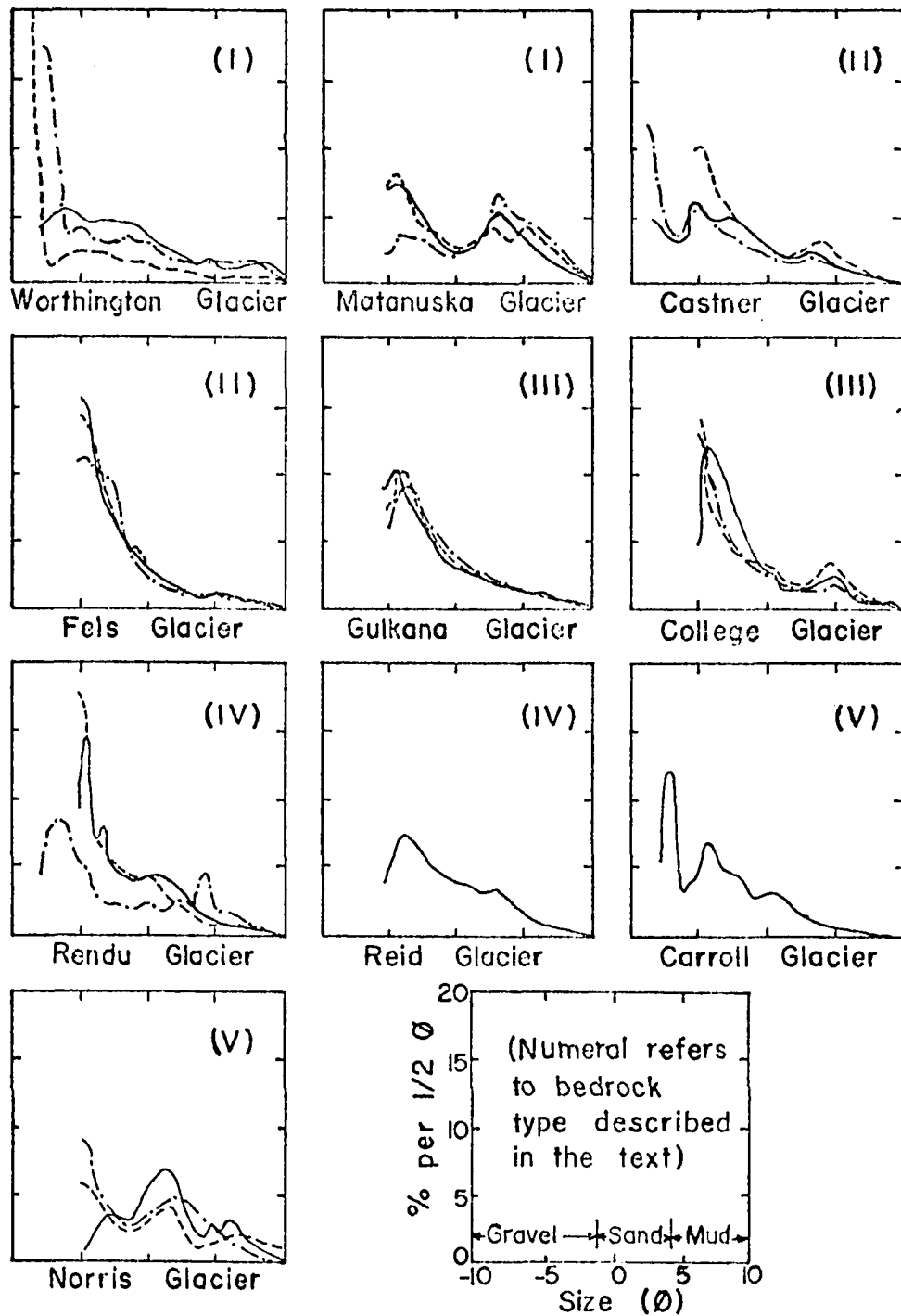


Fig. 5 - Frequency curves showing grain-size distribution of superglacial sediments.

This peak may be real or merely a result of converting from dry sieving to pipette analysis at 4 phi.

Five conclusions may be reached by examining these curves: (1) primary superglacial sediment is typically a-modal except for the possibility of a small 4 to 5 phi mode in some instances, therefore the process of particle size reduction by glacial action is indiscriminant and all particle sizes are produced; (2) the grain size frequency distribution of superglacial sediment is independent of source rock lithology; (3) there is no apparent lack of particles near -2 to 0 phi as reported by Wentworth (1933), Pettijohn (1957), and Folk (1968) or 6 to 8 phi as reported by Wentworth (1933) and Folk (1968) relative to adjacent size ranges for sediment of glacial origin; (4) the relative proportions of the major size classes of superglacial sediment are gravel > sand > mud; and (5) superglacial sediment is texturally immature. It is generally assumed that there are three basic populations of particles in nature (Folk, 1968): (1) pebbles resulting from blocky breakage of rock along joint or bedding planes, (2) sand-coarse silt resulting from weathering of rocks to their constituent minerals (the size of the resultant particles corresponding to the original size in the parent rock), and (3) clay representing the end products of chemical weathering. Gravel and sand, which are abundant in these superglacial sediments, are undoubtedly products of valley glacier action. The fact that silt is a common constituent of these superglacial sediments indicates silt-sized particles are also primary products of valley glacier action. This conclusion is in agreement with Kuenen's (1969) conclusion that both fine-grained and coarser crystalline rocks provide an abundant source of quartz silt upon disintegration such as through glacial grinding. Since evidence of intense chemical weathering was not observed, it is further concluded that the clay-size fraction of these superglacial sediments is the product of valley glacier action. This conclusion is in agreement with Kunze, Knowles, and Kitano's (1968) and Slatt and Hoskin's (1968) conclusion that clay-sized sediments in the Norris Glacier-Taku Inlet area are the product of glacial abrasion of bedrock.

At least two sets of samples from mixed deposits exhibit distinct, although not sharp, size modes. All three Norris Glacier samples have a distinct mode at 1 to 2 phi and two samples exhibit a lesser mud mode. This agrees well with the previous interpretation that the sediment at the present glacier

terminus is, at least in part, tide flat sand, since the present tide flat sand is largely 1 to 2 phi in size (Slatt and Hoskin, 1968). Matanuska Glacier sediment exhibits a distinct 2 to 3 phi sand mode and one sample shows a lesser mud mode. These samples apparently are the product of mixing of the fine sand-coarse silt beds fronting the terminus with more recent sediment.

Curves from two of the Rendu Glacier samples and the one from Carroll Glacier exhibit steep changes in slopes beginning at about 2 phi which suggests that much finer sediment has been removed. The third sample from Rendu Glacier shows a distinct 4 to 5 phi mode. This sample was collected from a thin veneer of superglacial sediment (approx. 1 m thick) in which most of the mud had worked its way to the base, leaving residual concentrates of coarser material at the surface. Silt was also observed to overlie clay (reverse graded bedding). The clay was concentrated at the ice surface where melting ice could easily remove it. Apparently this process represents preferential removal of the finest grain-size fractions and accounts for the relatively high content of 4 to 5 phi silt in that sample.

Two conclusion may be reached by examining the grain-size frequency curves of mixed deposits: (1) the development of modes in originally a-modal sediment is a result of mixing with previously sorted sediment and (2) the presence of modes in superglacial sediment is a possible indication of mixing with proglacial sediment.

Comparison of superglacial sediment, till, and outwash. Figs. 5, 6, 7, and 8 show the relationships among statistical parameters for these superglacial sediments. Data points for till and outwash taken from Landim and Frakes (1968) are also included, and till and outwash field boundaries have been added. Till refers to non-stratified, poorly-sorted sediment deposited directly by a glacier and which has undergone a minimum of reworking and redeposition by water; outwash, on the other hand, refers to stratified proglacial sediment deposited by streams (Landim and Frakes, 1968). Although not specifically stated, their "till" presumably refers to lodgement till (Flint, 1964). Landim and Frakes (1968) data are for material finer than -2 phi in size (granule to clay fraction), thus superglacial sediment parameters were recalculated for this range, using the formulas of Folk and Ward (1957).

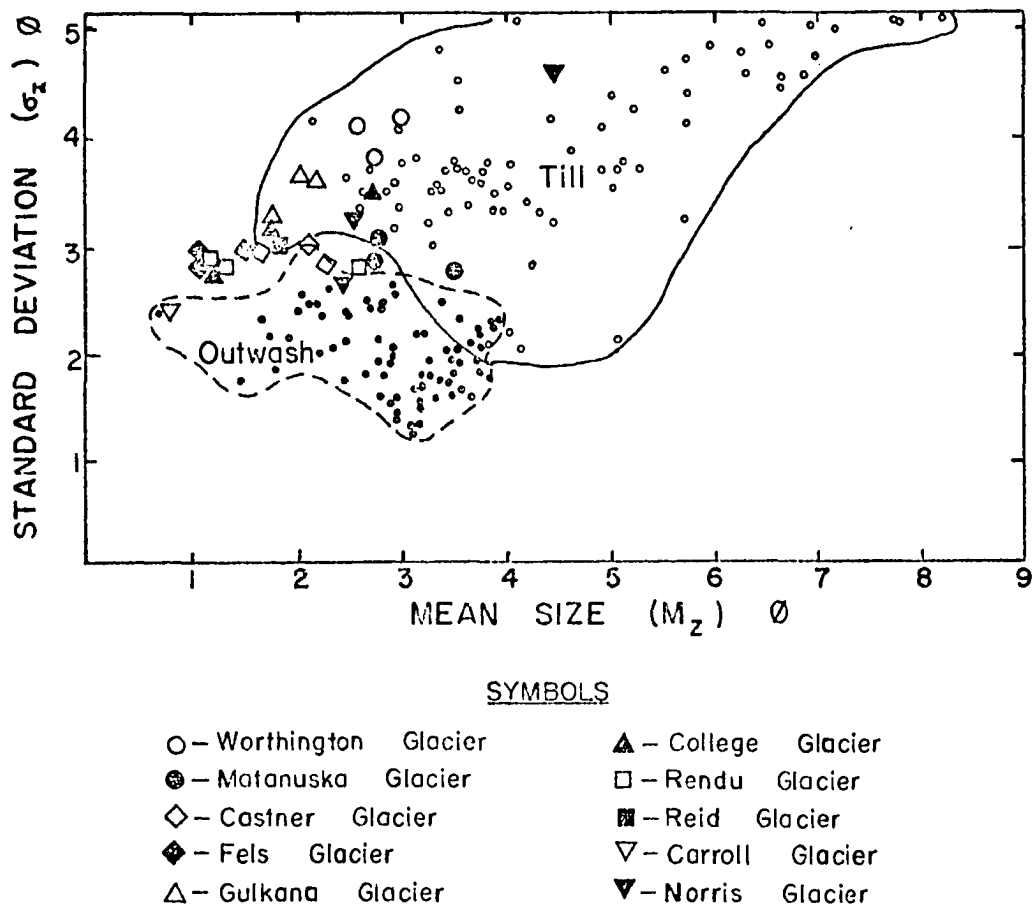


Fig. 6 - Relationship between mean size and standard deviation for samples of superglacial sediment, till (open circles), and outwash (closed circles). Till and outwash plots are from Landim and Frakes (1968). Till and outwash field boundaries have been added.

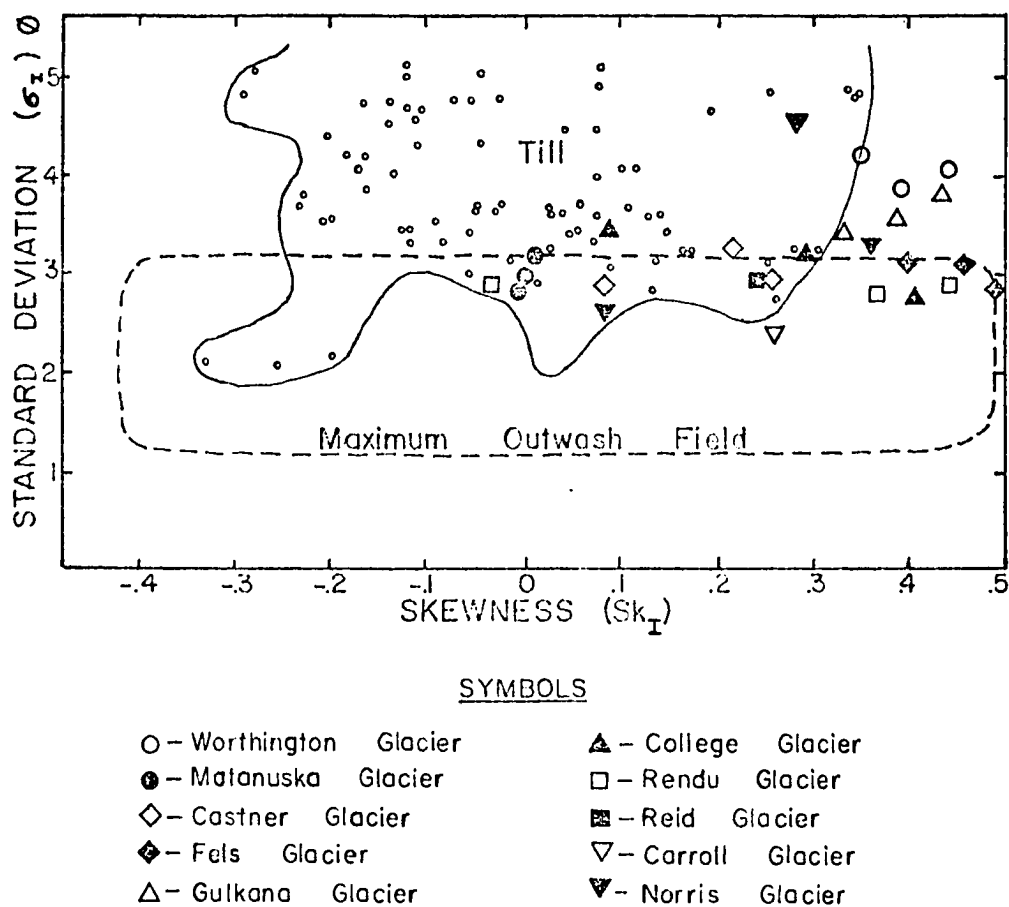


Fig. 7 - Relationship between skewness and standard deviation for samples of superglacial sediment, till (open circles), and outwash. Till plots are from Landim and Frakes (1968). The till field boundary has been added and the maximum outwash field boundary has been constructed from Landim and Frakes (1968) data.

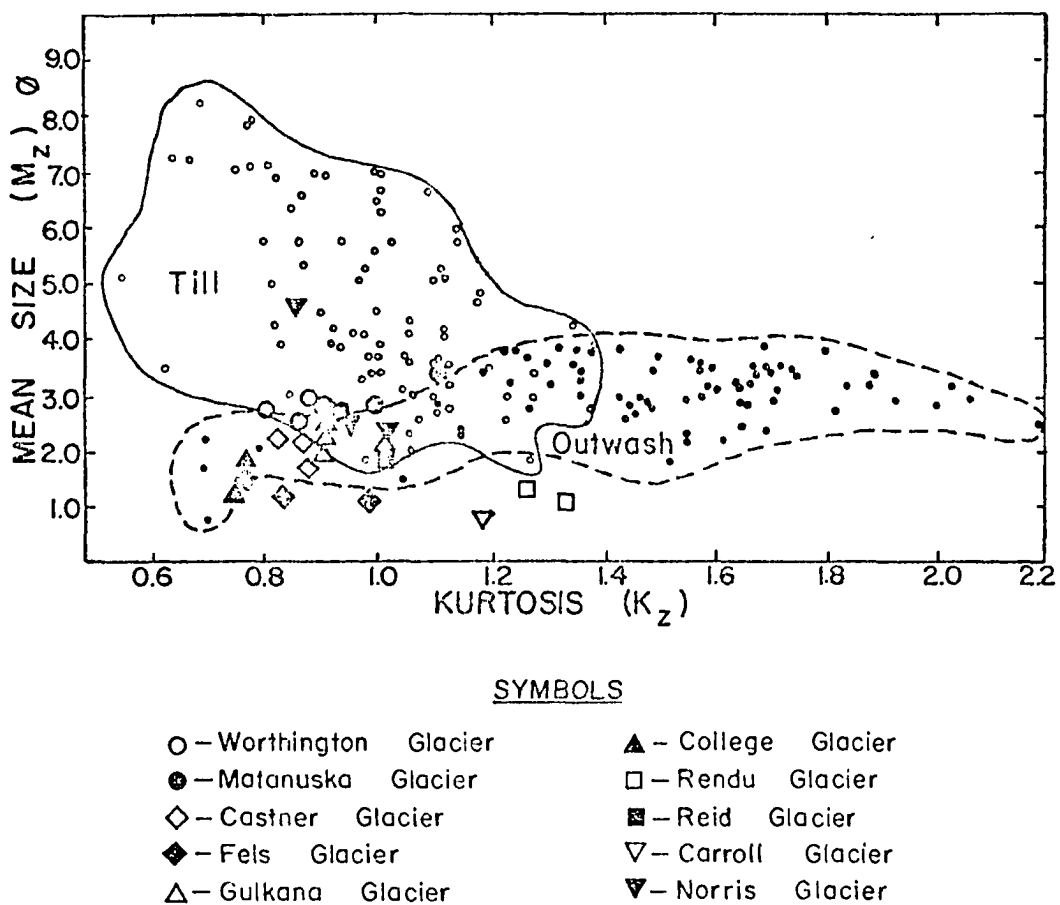


Fig. 8 - Relationship between kurtosis and mean size for samples of superglacial sediment, till (open circles), and outwash (closed circles). Till and outwash plots are from Landim and Frakes (1968). Till and outwash field boundaries have been added.

Data points for superglacial sediment generally lie within or near the overlapping areas of the till and outwash fields (Figs. 6, 7, and 8). This suggests that the finer than -2 phi size fraction of superglacial sediment is intermediate in character between lodgement till and outwash.

As one of the characteristics of superglacial sediment and outwash is a relative deficiency of fine material, it is of interest to compare superglacial sediment with till and outwash and to speculate on how superglacial sediment would be altered under two circumstances: (1) continued in situ loss of fines through removal by melting ice underlying the sediment and (2) increase of fines, primarily through mixing with proglacial sediment. With continued loss of fines, mean size would become coarser and sorting would improve. The particle-size distribution would also become more symmetrical and leptokurtic. The superglacial sediment points would therefore plot within or closer to the outwash field (Figs. 6, 7, and 8). With an increase in fines, mean size would become finer and sorting would become worse. If the increase were great enough, the majority of particles would be contained in relatively finer-size fractions, therefore the particle-size distribution would become more nearly symmetrical, or even coarse-skewed, and more leptokurtic. The superglacial sediment points would therefore plot within or closer to the till field (Figs. 6, 7, and 8).

From this discussion it appears that the finer than -2 phi fraction of superglacial sediment is intermediate in character between lodgement till and outwash due to partial removal of fine sediment. Given either of the two situations described above, this sediment with time could exhibit the sedimentological characteristics of till or outwash. This is geologically significant in that alternate hypotheses for the origin of till and outwash sediment, as defined above, can be proposed. Continued winnowing by a thin sheet of meltwater at the stagnant terminal zone of a glacier could produce sediment exhibiting all characteristics of outwash, except perhaps stratification. Upon complete melting of the stagnant ice and continued glacier recession, this residual sediment could be deposited in place, never having been transported and deposited by meltwater streams.

In contrast, increase of fines during ice advance by mixing with proglacial sediment (with lake beds, for example) could result in a deposit exhibiting the characteristics of till, but which actually is a mixture of proglacial and superglacial sediment. The result of this latter process can be demonstrated by at

least one of the Norris Glacier samples which falls well within the till fields (Figs. 6, 7, and 8).

It undoubtedly would be rash to assume all till and outwash deposits are formed in this manner. However it seems plausible that at least some outwash-like sediment could be deposited without the aid of streams and at least some till-like deposits could actually be mixtures of superglacial and proglacial sediment.

Mineralogy

Gravel fraction. Gravel fractions of all samples consisted entirely of rock fragments typical of the bedrock terrane from which they were derived.

Sand fraction. Sand-size fractions of all twenty-six samples were mixed with Boat-Armor Super Iso-resin which acted as a rigid binder so thin sections could be prepared. The proportions of rock fragments, quartz, feldspars, and total heavy minerals (including micas) were determined on a number percent basis by point counting 300 grains on each slide.

The relative proportions of the four constituents are presented in Table 3 and number percentages of rock fragments, quartz, and feldspars recalculated to 100% by omitting heavy minerals, are plotted in Fig. 9. The relatively high percent of heavy minerals associated with Castner and Fels Glacier sediment is largely fine mica flakes and the high percent for Gulkana Glacier sediment is largely amphibole. The dominant feature of the superglacial sands is the relatively high proportion of rock fragments (Fig. 9). Varieties of fragments and quartz/feldspar ratios appeared to be equivalent to those of the bedrock and rock fragments generally constituted the larger-size grains. Norris Glacier superglacial sediment has an anomalously low rock fragment content. Norris Glacier tide flat sands (Slatt and Hoskin, 1968) plot in the same region of the mineralogy classification diagram and emphasize the mixed nature of this sediment.

Fig. 9 shows a tendency for sands from glaciers in granitic and gneissic terranes (Rendu, Reid, Carroll, and Norris Glaciers) to contain relatively fewer rock fragments than sands from other terranes (see dashed boundary on Fig. 5). This could be due to finer-grained rocks with a metamorphic fabric tending to break along distinct planes of weakness. The resulting compact fragments might

Table 3. Mineralogic point count data for the sand-size fraction of super-glacial sediments.

Sample	(number %)			
	Quartz	Feldspar	Rock Fragments	Heavy Minerals
WorS-2	10.7	3.0	84.0	2.3
WorS-7	10.1	5.0	77.9	6.9
WorS-9	11.0	4.0	65.0	14.8
MatS-1	22.2	14.1	55.0	9.0
MatS-2	22.7	14.6	58.1	4.7
MatS-3	19.6	15.6	56.5	8.3
CasS-1	19.3	9.0	40.3	31.3
CasS-4	18.3	7.3	45.2	29.2
CasS-13	21.0	11.0	40.7	27.3
FelS-1	18.0	4.7	49.0	28.3
FelS-2	12.7	3.0	40.0	44.3
FelS-3	14.0	5.0	46.7	34.3
GulS-3	4.8	10.9	58.5	25.7
GulS-4	5.6	5.6	54.3	34.5
GulS-5	8.2	12.4	51.6	27.8
ColS-2	8.7	15.9	60.8	14.6
ColS-3	11.7	11.0	64.7	12.7
ColS-4	11.9	13.5	56.8	17.8
RenS-1	7.0	31.0	47.3	14.7
RenS-4	7.0	44.3	40.0	8.7
RenS-5	4.7	44.0	42.0	9.3
ReiS-1	13.3	32.3	46.3	8.0
CarS-1	8.3	27.7	54.5	8.6
NorS-1	25.3	48.7	14.3	11.7
NorS-2	22.7	54.0	15.0	8.3
NorS-3	21.7	58.0	6.0	14.3

Sample designations are coded according to the first three letters of each glacier.

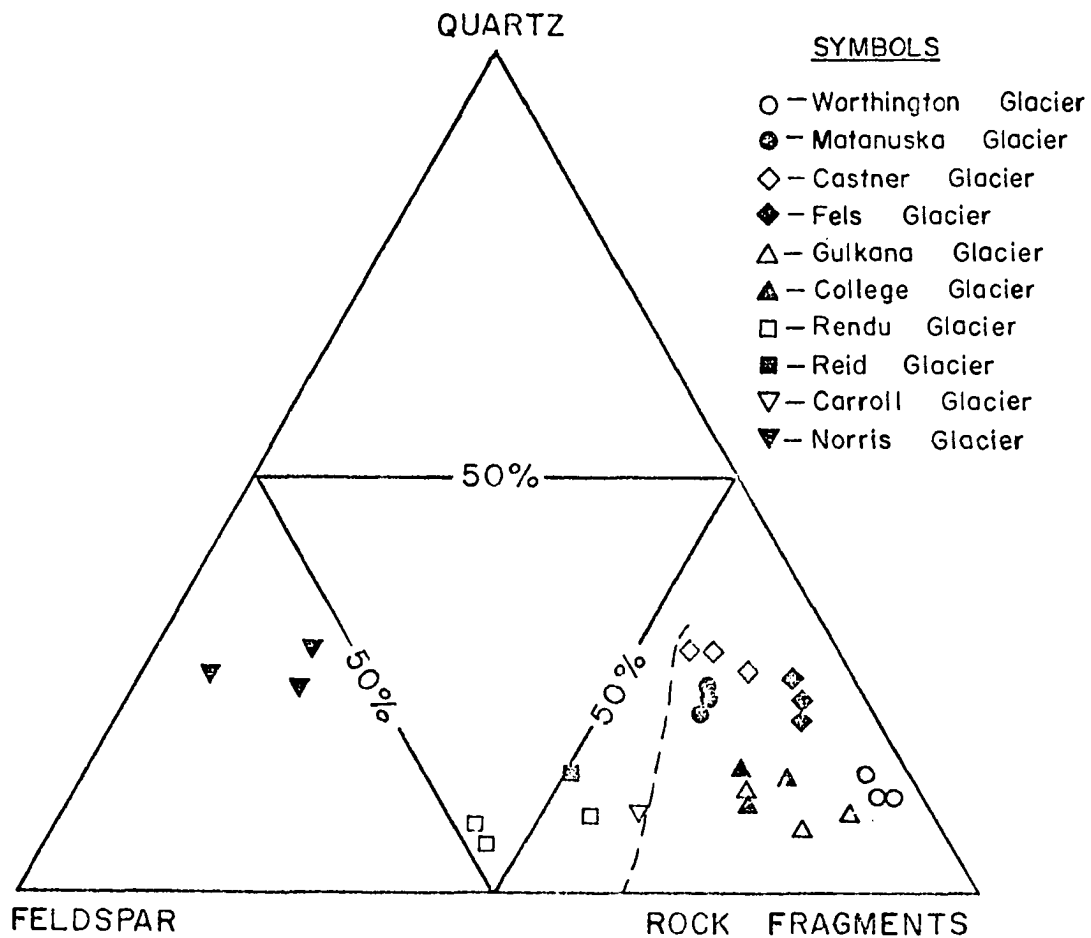


Fig. 9 - Light mineral composition of the sand-size fraction of superglacial sediments. Dashed line divides sands from glaciers eroding coarse-grained (to the left) and finer-grained (to the right) bedrock lithologies.

then be more resistant to further breakdown than individual mineral grains from rocks with coarser texture. However, this observation may also be a result of rapid destruction of rock fragments through more common sedimentary processes since three of the four sediments are from mixed deposits.

Aside from the above gross differentiation, the bulk mineralogy of these superglacial sands is independent of source rock lithology in the sense that glacier sediment-forming processes produce mineralogically immature sands which are characterized by high proportions of rock fragments.

Mud fraction. Because of the similarities in proportions of the sand-size mineral constituents from each set of samples (Fig. 9), mineralogy of the mud-size fraction was determined for only one sample from each glacier. Muds were obtained from a separate untreated split of sample (i. e. not wet-sieved, flocculated, etc.), air dried, mildly disaggregated, then dry sieved to remove coarser than 4 phi material. The mud was then ground to a uniform powder and randomly-oriented mounts for scanning X-ray diffraction analysis were prepared by packing the sample into an aluminum holder. Analyses were done with a Type 12045 Norelco Diffractometer employing Ni-filtered Cu K-alpha radiation generated at 40kv and 20ma. Mineral identifications were accomplished by a 1 to 60° scan of the sample at 2° 2θ/minute.

The results are shown in Table 4. Quartz, feldspar, mica, and chlorite are ubiquitous. Based upon relative peak areas, quartz and feldspar are most abundant. Calcite and amphibole were identified in Rendu, Norris, Carroll, Reid, College, and Gulkana Glacier superglacial muds. Treatment of a separate aliquot with cold 10% HCL revealed more than 6% acid soluble constituents in all samples from which calcite was identified (Table 4).

Although quantitative analysis was not performed, there appears to be no differentiation of these muds on the basis of the major constituents (quartz and feldspar) present, and therefore on source rock lithology. It is apparent that the superglacial muds are the mineralogically immature products of glacial action.

Chemistry of the mud fraction

Table 4. Qualitative mineralogy and weight percent of acid soluble constituents in the mud-size fraction of superglacial sediments.

Sample No.	Weight % Acid Soluble Fraction	Chlorite	Mica	Quartz	Feldspar	Calcite	Amphibole
WorS-9	2.5	X	X	X	X	-	-
MatS-2	4.7	X	X	X	X	-	-
CasS-13	2.6	X	X	X	X	-	-
FelS-1	2.7	X	X	X	X	-	-
GulS-4	13.5	X	X	X	X	X	X
ColS-3	6.6	X	X (?)	X	X	X	X
RenS-5	12.2	X	X	X	X	X	X
ReiS-1	6.9	X	X	X	X	X	X
CarS-1	17.0	X	X (?)	X	X	X	X
NorS-1	10.6	X	X	X	X	X	X (?)

X = mineral present

- = mineral not detected

Sample designations are coded according to the first three letters of each glacier.

Separate aliquots of mud were analyzed for Na_2O , K_2O , CaO , MgO , and SiO_2 using a method modified from Shapiro and Brannock (1956). Disposable polyethylene flasks were used in place of nickel and platinum crucibles. Once in solution, all oxides but SiO_2 were analyzed by atomic absorption spectrophotometry. Analytical techniques are described in detail in a later section. Percent loss on ignition was estimated by weight loss of separate aliquots after heating to 650°C for four hours in a Thermolyne muffle furnace.

The natural crushing action of a glacier probably gives end products which are representative of the proportions of the various constituents in bedrock; this is particularly important for determining bulk chemistry of multi-lithologic terranes. No evidence of extensive chemical alteration was seen upon examination of the mud and larger size fractions. The results presented in Table 5 are thought to be representative of the bulk chemistry of relatively unweathered bedrock.

Variations in absolute amounts and the relative proportions of these chemical constituents occur, even from superglacial muds from different glaciers in similar bedrock terranes. This is presumably a result of differences in the quantities and varieties of feldspar (and quartz) present in the muds, and to a lesser extent, quantities and varieties of heavy minerals.

Suspended Stream Sediment

Texture

Methods of collection and analysis. Nine samples of suspended sediment from meltwater streams were collected from eight of the areas (Appendix B), usually 1 to 2 km downstream from the glacier terminus. One of these samples (WorS-3) was collected from a subglacial stream at the point of its emergence from the Worthington Glacier terminus. A small meltwater lake flanks much of this terminus and is drained at its eastern end by an outlet stream. An additional composite sample (equal volumes of sediment-laden water from the head, mid-length, and mouth of the stream) was collected from this outlet stream (WorS-13). An eleventh sample was obtained from meltwater flowing from the base of an ice-cored sediment mound at Castner Glacier (CasS-2).

Table 5. Partial chemical analyses of the mud-size fraction of superglacial sediments.

Weight %	Sample No.								
	WorS-9	MatS-2	CarS-13	FelS-1	GulS-4	ColS-3	RenS-5	CarS-1	NorS-1
SiO ₂	59.00	68.10	56.30	63.60	35.00	55.10	52.80	47.00	59.50
CaO	2.28	4.38	0.44	0.66	11.12	9.56	12.57	13.55	7.45
MgO	2.05	1.43	2.11	1.99	7.17	4.85	5.52	3.47	3.49
K ₂ O	2.18	0.92	4.80	4.65	0.15	0.38	1.03	1.00	1.78
Na ₂ O	2.04	3.33	1.02	0.93	1.00	2.44	2.78	2.97	2.98
Loss on Ignition	3.94	0.81	1.92	1.70	1.07	0.49	0.52	0.62	1.23
Total	71.49	78.97	66.59	73.53	55.51	72.82	75.22	68.61	76.43

Sample designations are coded according to the first three letters of each glacier.

Samples from Worthington, Castner, Matanuska, and Rendu Glacier meltwater streams were collected through a submerged rubber tube attached to an Erlenmeyer flask-hand vacuum pump apparatus. The end of the hose was set on a scaled staff and equal volumes of sediment-laden meltwater were obtained from 3 to 6 cm above the stream bed, at mid-depth, and 3 to 6 cm below the surface. At the meltwater streams of Fels, Gulkana, College, and Norris Glaciers, equal volumes of water were collected from the same depths with a clean polyethylene bottle. In these turbulent streams, this more rapid method is suitable provided the water bottle is not allowed to fill and overflow while submerged, in which case there could be a relative loss of finer sediment. Samples were collected from as close to mid-channel as possible.

At the time of collection, surface velocities of the streams were measured by noting the time required for a surface float to travel a previously measured distance. Float travel times were measured in triplicate and the mean value was divided into the distance travelled, from which mean stream velocity in a vertical section was calculated by multiplying by 0.6 (Fahnestock, 1963).

The suspended sediment obtained was flocculated with 1N $MgCl_2$, and the meltwater siphoned off and discarded. In the laboratory grain-size analyses were performed by standard methods (Folk, 1968) after wet sieving organic removals and dispersion with sodium hexametaphosphate (Calgon). Because of the general scarcity of sand, dry sieving was done with a small set of three inch diameter 1 phi interval screens. In some instances too much mud was collected for size analysis of the total sample, so an aliquot was removed for pipetting and the remainder was oven-dried. By combining dry weights, the appropriate splitting factor was obtained.

Results and interpretation. Descriptive parameters, calculated the same way as for superglacial sediment, and stream velocity at the time of sample collection are presented in Appendix B. Suspended stream sediment is composed dominantly of mud with some sand, and in a few cases, a small amount of gravel. Mean size ranges from coarse silt to clay, according to Folk's (1968) classification. All samples are very poorly sorted and most are fine-skewed and leptokurtic to mesokurtic.

Fig. 10 shows the relationship between mean grain size and stream velocity plotted on a modified portion of Hjulström's (1939) diagram. Absolute particle size has been replaced by mean grain size in phi units on the abscissa. All samples except WorS-13 and CasS-2 fall within the Erosion field which indicates, in addition to carrying subglacial sediment, these streams are capable of eroding and transporting previously sorted streams and channel wall sediment. Fig. 10 also shows that mean grain size becomes coarser with increasing stream velocity. Velocity and discharge of glacial meltwater streams are quite variable, even on a diurnal basis (Rainwater and Guy, 1961; Fahnestock, 1963). Because mean grain size is related to velocity, it should not be assumed these samples necessarily represent the average transported material.

Fig. 11 shows the grain-size frequency distribution curves for the suspended sediment. Although poorly-sorted, all sediments exhibit distinct modal size-classes, mainly in the coarse- to fine-silt range. The sample collected from the subglacial stream emptying into the Worthington Glacier proglacial lake (dashed curve, Fig. 11) has a far greater range of particle sizes than the sample collected downstream from the lake (solid curve, Fig. 11), indicating most of the coarser material is deposited in the lake. The dashed curve (Fig. 11) for Castner Glacier is for sediment from the base of the ice-cored sediment mound. The unimodal nature of this sample is apparently a result of selective sorting and transport. There appears to be no correlation of grain-size distribution with source rock lithology for any of these sediments.

The correlation between mean size and stream velocity suggests grain-size distribution is controlled by the nature of the environment at the time of sampling. Fahnestock (1963) has noted diurnal variations in sediment concentration and Rainwater and Guy (1961) have described diurnal variations in concentrations as well as proportions of sand, silt, and clay resulting from discharge fluctuations. Distinct grain-size modes are present in stream sediment (Fig. 11) transported only a few kilometers from glacier termini, but distinct modes are lacking in primary superglacial sediment (Fig. 5). This indicates selective sorting occurs soon after valley glacier sediment is subjected to stream action. From these data it is concluded that the environment of transport has a much greater effect on the grain-size characteristics of transported valley glacier sediment than does the nature of the starting material.

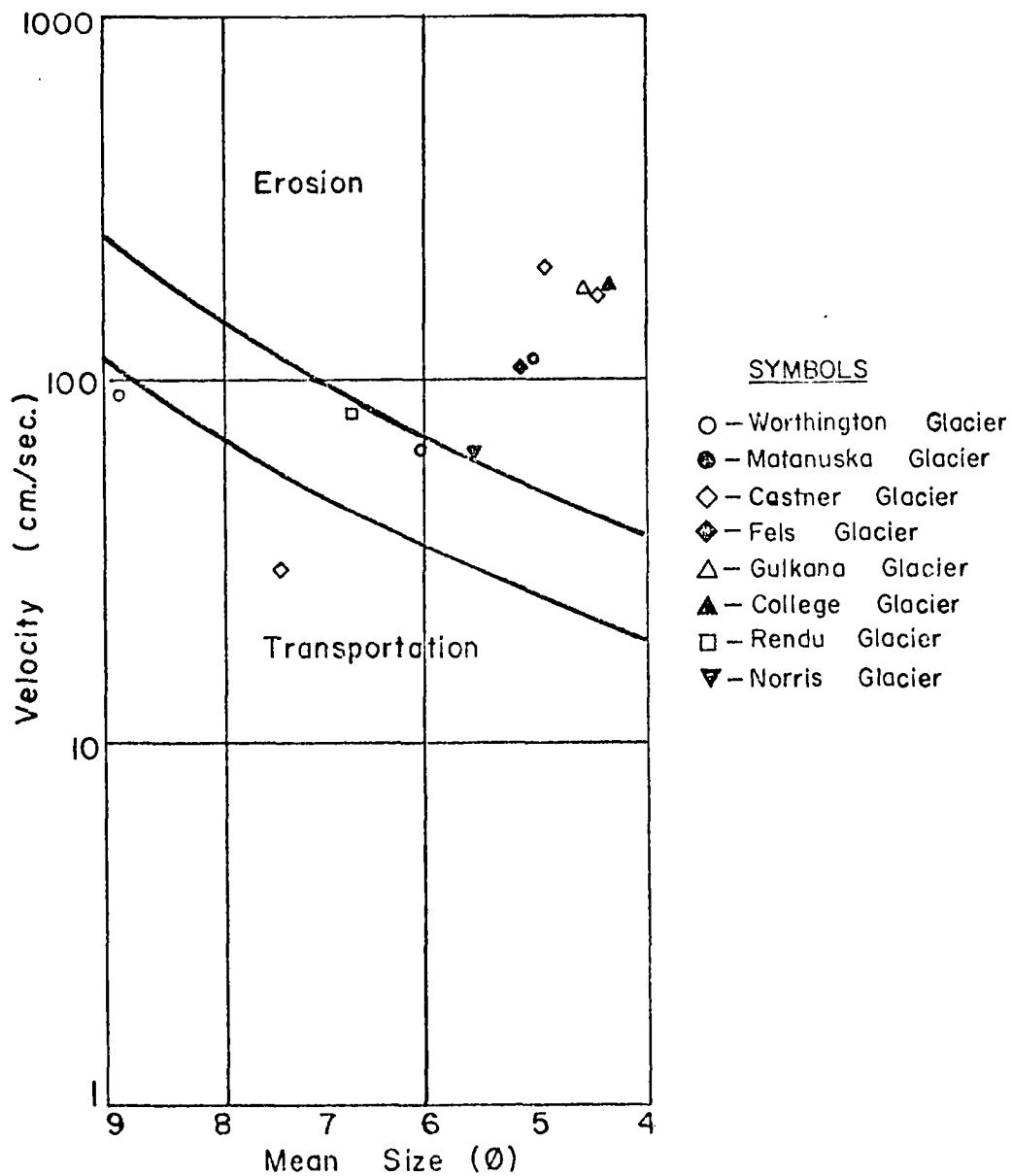


Fig. 10 - Relationship between mean grain size of suspended stream sediments and stream velocity at the time of sample collection. Diagram modified from Hjulström (1939).

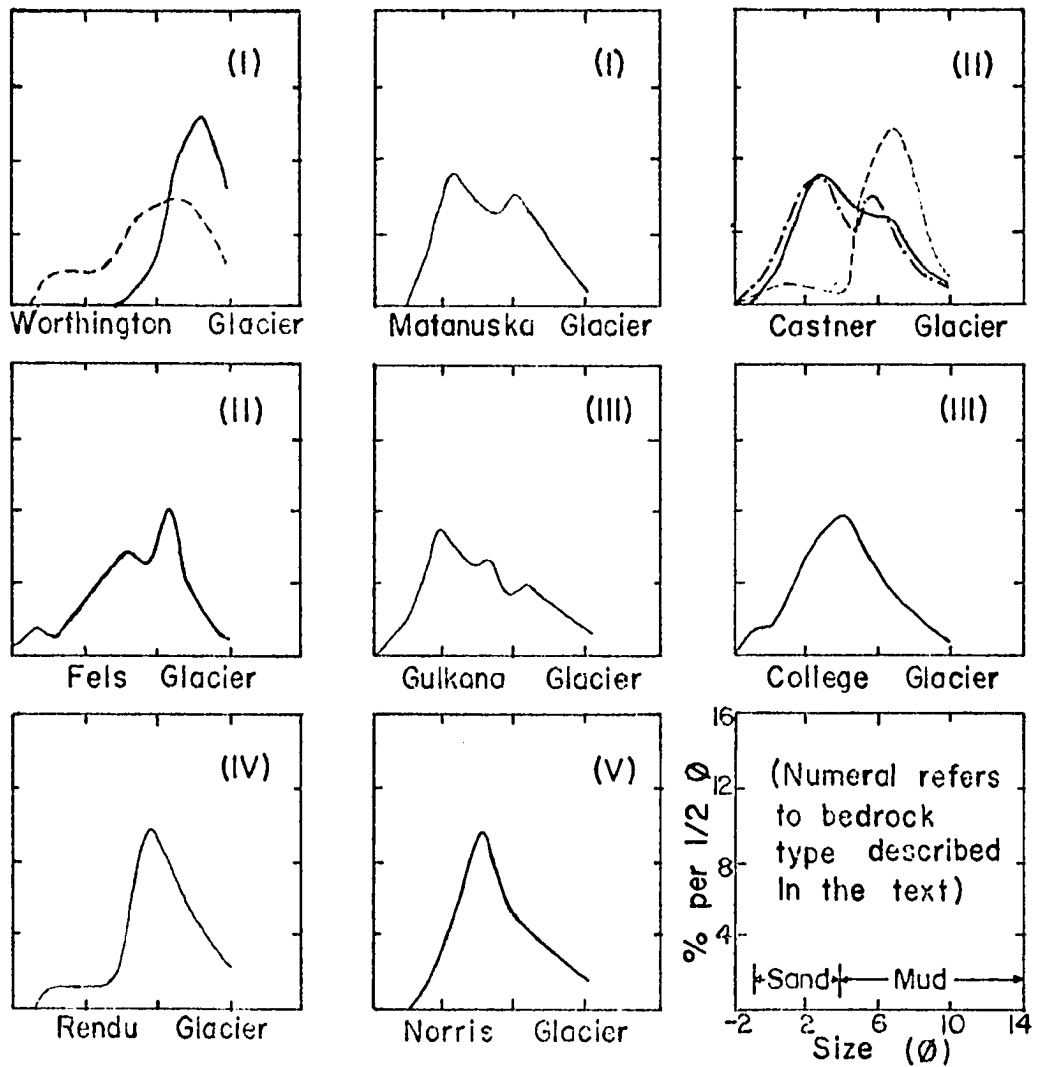


Fig. 11 - Frequency curves showing grain-size distribution of suspended stream sediments.

Conclusions

1. A method is described for grain-size frequency distribution analysis of coarse-grained sediment. This method was successfully employed for grain-size distribution analyses of 250 kg superglacial sediment samples. It is equally applicable, however, for other types of coarse sediment. Comparison of the grain-size distributions of these samples with distributions of the finer than -5.25ϕ fractions of the same samples indicates 5 to 10 kg of material are probably sufficient for gross classification of coarse sediment on the basis of texture, standard deviation, and skewness, but not for mean size and kurtosis. For more precise numerical classification and comparison, samples should be standardized by setting an upper grain size limit to be collected.

2. Superglacial sediment from six of the ten glaciers probably has not been extensively reworked aside from removal of some finer-size fractions by meltwater from underlying ice. Superglacial sediment from the other four glaciers has been mixed with proglacial sediment during ice advance(s).

3. Superglacial sediment is very poorly- to extremely poorly-sorted, fine- to strongly fine-skewed muddy sandy gravel. Mean size of the finer than -5.25ϕ fraction falls in the very coarse sand to granule class. The relative proportions of the major size classes are gravel $>$ sand $>$ mud. Primary unmodified superglacial sediment is typically a-modal except for the possibility of a small 4 to 5 ϕ mode. Some mixed superglacial sediment exhibits distinct grain-size modes.

4. The presence of distinct modal-size classes in superglacial sediment is a result of mixing with proglacial sediment. This property, plus the presence of rounded pebbles in superglacial sediment may be useful indicators of mixing.

5. Superglacial sands are mineralogically immature and are characterized by high proportions of rock fragments. Sands from glaciers on coarse crystalline bedrock contain relatively fewer rock fragments than sands from glaciers on finer-grained bedrock with a metamorphic fabric. Quartz and feldspar are the dominant constituents in superglacial muds.

6. Although the size frequency distribution and mean size of suspended stream sediment varies with the nature of the stream, mud is the major component. One or more distinct grain-size modes usually are present. These

suspended stream sediments generally are very poorly-sorted, fine-skewed, and leptokurtic to mesokurtic.

7. The size frequency distribution of superglacial sediment is in part a function of the degree of removal of the finer-sized fractions. Either there is no relationship between texture and source rock lithology or the relationship is obscured by removal of finer-sized fractions.

8. Particle size reduction by valley glacier action is indiscriminate and all particle sizes are produced. The concept of three basic populations of particles in nature (pebbles, sand-coarse silt, and clay) cannot be applied to valley glacier sediment because of the extraordinarily intense physical weathering process.

9. The finer than -2ϕ fraction of superglacial sediment is texturally intermediate between outwash and lodgement till. Given sufficient time, superglacial debris could exhibit the sedimentological characteristics of (1) outwash through continued in situ removal of fines by meltwater from underlying ice or (2) till by an increase of fines through mixing with proglacial sediment during ice advances. Some outwash-like sediment may have been deposited without the aid of glacial streams and some till-like deposits could be mixtures of superglacial and proglacial sediment.

10. Valley glacier sediment is selectively sorted soon after it is subjected to stream action. The environment of transport has a much greater effect on the grain-size characteristics of transported valley glacier sediment than does the nature of the starting material (bedrock and primary sediment).

CHAPTER IV

GLACIAL MELTWATER

Introduction

Glacial meltwater has received scant attention in the literature. Major studies have emphasized hydrology of glacier-fed rivers (Arnborg, 1955; Fahnestock, 1963; Arnborg and others, 1966; Østrem and others, 1967) and meltwater chemistry (Rainwater and Guy, 1961; Keller and Reesman, 1963). Most of these studies have dealt with water that has travelled some distance from its source. Furthermore, aside from Keller and Reesman's (1963) work, no major effort has been put forth to characterize glacial meltwater and relate it to chemical weathering of rock.

A major objective of the present investigation was to describe glacial meltwater at its source, prior to any modifications. The relationships among dissolved and particulate meltwater constituents, bedrock, glacial sediment, and the nature of the glacial stream environment were also evaluated.

Methods of Collection and Analysis

Glacial meltwater was collected during the summers of 1968 and 1969 from major streams from all but Reid Glacier, which has a tidal terminus. The number of samples ranged from three at four of the glaciers to twenty-three at Worthington Glacier. Six samples from the Worthington Glacier proglacial lake were also collected. Samples were obtained in the same manner as suspended sediment, and stream velocities were also determined at the time of collection by the method described previously.

Measurements of pH, Eh, and water temperature were taken at the time of sampling. The pH and Eh were measured with a Beckman Model N portable pH meter employing a fibre-type calomel reference electrode in conjunction with glass (pH) and platinum (Eh) electrodes. The pH measurements were read dir-

ectly, while potentials measured against the calomel electrode were converted to true Eh (in volts) by the following equation:

$$E_h = E_{\text{meas.}} + [0.2415 - (0.00076)(T - 25)]$$

where T = temperature in degrees centigrade (Back and Barnes, 1965). Several sample measurements at one-minute intervals from 0 to 10 minutes indicated the electrode had to be immersed in the sample solution for 3 to 4 minutes before a constant reading was obtained. This probably is the time required for the electrode to cool to the temperature of the solution.

Water samples were filtered immediately upon collection through 0.22 micron millipore filters. About half the samples were filtered with a standard millipore filtering apparatus attached to a hand-vacuum pump. The other half were pressure filtered through a one-liter cyclinder constructed of PVC and with a millipore filter base plate. Pressure was applied with a manual pressure pump. Approximately 250 to 350 mls of sample were filtered, acidified with eight drops of 20% HCL, and stored in previously weighed, acid washed, polyethylene bottles. The sediment-laden filter papers were also stored for laboratory analysis.

Equal aliquots of several meltwater samples were collected and stored at room temperature for periods of time ranging from 2 to 62 days before filtration in the laboratory. Sets of samples filtered at the time of collection and after 15, 30, 60, 90, and 120 days were also obtained from Matanuska, Castner, and Norris Glacier meltwater streams. Samples stored prior to filtration were shook every ten days.

In the laboratory, the volume of water filtered was calculated from the weight of the water, assuming a density of 1gm/ml. This method was checked against known volumes of water. Suspended sediment concentrations were obtained by weighing the sediment-laden filter papers after oven-drying for twelve hours at 60^o C and determining the mean weight of several dried papers.

Dissolved sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) concentrations were determined using Perkin-Elmer 303 and Techtron Model A. A. 3 atomic absorption spectrophotometers. Na was analyzed directly. Interferences in the analysis of K were eliminated by approximately matching the Na concentrations of the standards with those of the samples; interferences

in the analyses of Ca and Mg were eliminated by diluting both samples and standards to 1/1 v/v with 2% SrCl₂ (Angino and Billings, 1967). Silica (Si) was determined by the molybdate blue method (Rainwater and Thatcher, 1960), employing a Bausch and Lomb Spectronic 20 Colorimeter.

Combined error due to sampling, storage time, analyses, etc. was determined with three separate samples, collected and filtered at the same time, from seven of the meltwater streams, followed by independent chemical analyses. For each of the seven sets, the mean concentration and standard deviation about the mean (in percent) for each constituent was computed. The range of deviation about the mean for each constituent was then calculated, from which their mean deviations (in percent) were obtained. Results for the chemical constituents, as well as for suspended sediment, done in the same manner, are shown in Table 6. Mean deviations are lowest for Na and K, which were analyzed directly from the solution, followed by Ca and Mg for which samples were diluted with SrCl₂, then Si for which the addition of four reagents to the sample was required for analysis. Even though a different instrumental technique was employed in Si analyses, this suggests addition of reagents to these already dilute solutions may be the greatest source of error. The average deviation about the mean for all the chemical constituents analyzed was 7.3%.

Specific conductance was also found to be a useful measure of the validity of chemical analyses for these meltwater samples. Although not a consistent rule, conductance of some natural waters increases linearly with increasing dissolved-solids concentration (Hem, 1959). Since the cations analyzed in meltwater were thought to represent the major dissolved constituents, these should considerably affect the conductance. Thus, by comparing the sum of the analyzed constituents (in ppm) with the conductance, a linear relationship might be established such that any sample from which the chemical analysis deviated considerably from the general trend would be suspected of being erroneous. Si was not included in the summation as most dissolved Si exists as nonionized H₄SiO₄ (Krauskopf, 1967), and as such, would not appreciably affect conductance. Measurements of forty-six samples were taken with an Industrial Instruments Type RC Conductivity Bridge immediately after filtration in the laboratory. As conductance increases with increasing temperature, all measurements were standardized to 25^o C after temperature measurement, using the formula rec-

Table 6. Combined error for chemical and suspended sediment analyses.

Constituent	Mean Concentration (ppm)	Mean Deviation about the Mean Concentration (%)
Na	1.5	6.7
K	1.1	7.3
Ca	15.	9.9
Mg	3.7	10.4
Si	0.80	13.3
Total five cations	23.	7.3
Suspended sediment	5280.	6.5

ommended by the manufacturer. By the least-squares method (Freund, 1967), the equation

$$C = 5.6T - 12.$$

was established, where C = conductance in micromhos at 25^o C and T = (Na+K+Ca+Mg) concentration in ppm. Conductance values for the forty-six samples ranged from 23 to 316 micromhos and (Na+K+Ca+Mg) concentrations ranged from 5.4 to 58 ppm. A correlation coefficient of r = 0.958 was obtained which indicates a high degree of linear relationship between conductance and (Na+K+Ca+Mg) concentration. No sample analyses deviated considerably from this general trend so all analyses are considered valid and within the range of error shown in Table 6.

As polyethylene bottles are capable of adsorbing dissolved constituents, effects of sample storage could be important in the analysis of these dilute solutions. In general, samples were stored for a period of two weeks to one month, but some were stored for as long as four months before chemical analysis. Repeated analyses of several samples over this time period revealed no concentration changes, so this source of error was considered negligible.

Results and Interpretation

Factors affecting the characteristics of meltwater

Results of field measurements and laboratory analyses are presented in Appendix C and are summarized in Table 7. Absolute cation concentrations, as well as values for the other variables measured vary from stream to stream. Many factors could account for this. The type of rock material being weathered is perhaps the most important factor; however, any stream is a dynamic system and both temporal and spatial variations in its physio-chemical characteristics are present (Livingston, 1963).

The most important temporal variation is discharge. In river systems, discharge is controlled by the amount of surface runoff and groundwater contributed to the river. During periods of high rainfall most river water is surface runoff. During dry periods, ground water, which is usually enriched in dissolved

Table 7. Physio-chemical characteristics of glacial meltwater.

Date	No. of Samples	Mean Dissolved Cation Concentrations (ppm)						Mean Suspended Sediment Concentration (ppm)	Mean pH	Mean Eh (+ volts)	Mean Water Temperature (°C)	Mean Stream Velocity (cms./sec.)
		Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations					
<u>Location: Worthington Glacier - outflow stream</u>												
6-68	12	0.57	0.29	7.6	0.30	0.35	9.1	172	7.6	0.53	2.4	3.0
8-68	7	0.18	0.11	4.7	0.30	0.07	5.4	116	7.5	0.48	2.6	4.3
8-69	3	0.14	0.15	5.4	0.38	0.21	6.3	101	7.5	0.51	2.8	2.7
Weighted mean for outflow stream:												
	22	0.39	0.17	6.4	0.31	0.24	7.5	143	7.6	0.51	2.6	3.4
<u>Location: Worthington Glacier - meltwater lake</u>												
6-68	5	0.86	0.36	7.8	0.31	0.46	9.8	138	7.6	0.58	2.6	-
8-68	1	0.09	0.09	5.0	0.30	0.13	5.6	106	7.3	0.49	3.2	-
<u>Location: Worthington Glacier - subglacial stream</u>												
8-68	1	0.57	0.36	7.7	0.30	0.33	9.3	880	8.2	0.42	1.0	2.2
<u>Location: Matanuska Glacier</u>												
8-69	3	1.3	0.39	9.0	0.65	1.3	13.	3,813	8.8	-	1.3	3.8
<u>Location: Castner Glacier</u>												
7, 8-68	11	2.6	1.0	16.	4.2	0.45	25.	3,552	8.7	0.43	0.9	6.4

Table 7, cont. Physio-chemical characteristics of glacial meltwater.

Date	No. of Samples	Mean Dissolved Cation Concentrations (ppm)						Mean Suspended Sediment Concentration (ppm)	Mean pH	Mean Eh (+ volts)	Mean Water Temperature ($^{\circ}$ C)	Mean Stream Velocity (cms./sec.)
		Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations					
<u>Location: Castner Glacier, cont.</u>												
6-69	2	1.1	1.0	19.	4.5	0.68	27.	2,524	8.6	-	1.0	-
8-69	3	3.7	1.4	37.	15.	1.0	58.	270	8.1	0.49	1.0	3.2
Weighted mean:		2.6	1.1	21.	6.3	0.58	32.	2,814	8.6	0.44	0.9	5.6
<u>Location: Fels Glacier</u>												
6-69	3	1.5	2.4	25.	6.6	1.0	37.	9,829	8.3	-	2.0	3.4
<u>Location: Gulkana Glacier</u>												
6-69	3	0.54	0.39	8.0	0.71	0.94	11.	1,667	8.9	-	1.7	6.0
<u>Location: College Glacier</u>												
6-69	3	1.4	1.3	14.	1.4	0.98	19.	4,988	8.9	-	3.0	6.0
<u>Location: Rendu Glacier</u>												
9-69	3	1.3	0.82	9.9	0.77	0.85	14.	7,538	-	-	1.0	-

Table 7, cont. Physio-chemical characteristics of glacial meltwater.

Mean Stream Velocity (cms./sec.)	-	-
Mean Water Temperature (^o C)	0.5	1.0
Mean Eh (+ volts)	-	0.44
Mean pH	-	9.4
Mean Suspended Sediment Concentration (ppm)	12,803	1,431
Mean Dissolved Cation Concentrations (ppm)		
Total Five Cations	15.	10.
Silica (Si)	0.91	0.60
Magnesium (Mg)	1.4	0.58
Calcium (Ca)	9.2	6.2
Potassium (K)	1.2	0.64
Sodium (Na)	1.8	2.4
No. of Samples	3	3
Date		
<u>Location: Carroll Glacier</u>		
9-69	1.8	1.2
<u>Location: Norris Glacier</u>		
7-69	2.4	0.64

constituents, comprises much of the river water. For a glacial system the reverse is true during the summer ablation period. Warm weather increases ablation rate and thus discharge whereas cool and overcast conditions have the opposite effect. Rainfall plays a dual role by diluting meltwater and aiding ablation through heat transfer from the relatively warmer rain drops to the colder ice, yet cloudiness associated with rain hinders ablation. The areal extent of a glacier, its orientation with respect to the sun, and the length of day also affect ablation and thus discharge. Because of the relatively large volume of meltwater produced during summer melt seasons, the contribution of ground water is probably negligible in glacial streams.

It is apparent that all the factors could affect the physio-chemical character of meltwater to some degree, both on a long term and diurnal basis. Data in Appendix C and Table 7 support this. Weather conditions at Castner Glacier from 1 Aug. to 9 Aug. 1968 were first overcast and cool, followed by warm and dry conditions culminating on 7-8 Aug., then a return to cooler conditions on 9 Aug. During this period stream velocity (and discharge) increased from 156 cm/sec to a maximum of 262 cm/sec then dropped to 180 cm/sec. Suspended stream sediment concentrations fluctuated accordingly, increasing from 2292 ppm (CasWF-3) to a maximum of 7445 ppm (CasWF-8) then back to 4120 ppm (CasWF-10B). Cation concentrations varied slightly during this time. Four measurements taken at six hour intervals at Worthington Glacier on 28-29 June 1968 (WorWF-17A-D) showed a slightly higher stream velocity during daylight hours, but no other pertinent changes were recorded (Appendix C). Rainwater and Guy (1961) and Fahnestock (1963) have noted diurnal variations in discharge and sediment concentration for glacial streams. As was noted previously, mean grain size of suspended sediment varies with stream velocity and grain-size distribution in any meltwater stream is largely controlled by the nature of the stream at the sampling time. Variations occurred in absolute cation and suspended sediment concentrations and stream velocity during three separate sampling periods at Worthington and Castner Glaciers (Table 7).

Spatial variations in physio-chemical characteristics are also common in rivers and streams. Velocities were variable along different segments of the meltwater streams due to local conditions, while downstream variations in suspended load could occur through deposition of suspended sediment or bank

erosion. As mentioned previously, measured velocities were of sufficient magnitude to cause bank erosion. Downstream variations in dissolved constituents can result from dissolution of or sorption by rock and suspended sediment, but at least in major rivers, this latter process appears to be minimal (Livingston, 1963). These two factors are considered in more detail below. An attempt to minimize these variables was made by sampling at the same time on successive days at sites as close as possible to the glacier terminus. Contributions from tributary streams flowing into a meltwater stream can also affect its characteristics. This factor was eliminated by sampling near the terminus upstream from any tributary streams.

One attempt to study spatial variations was made on the Worthington Glacier system during Aug. 1968. Here a subglacial stream flows into a proglacial lake, which is drained at its eastern end. The outlet stream flows for approximately one km before emptying into a larger stream of non-glacial origin. Samples WorWF7-14 (Appendix C), collected at approximately 0.2 km intervals along this outlet stream, showed no variations among the parameters measured. Suspended sediment concentration was more than four times higher in the subglacial stream, however, indicating deposition of much of the suspended load in the lake. Chemical composition of the subglacial stream, lake, and outlet stream water (included in mean values for 6-68, Table 7) are similar.

It can be concluded that caution should be used when interpreting data from spot samples, particularly when attempts are made to compare different streams. This has been emphasized by Livingston (1963). In the present study this appears to be particularly true for suspended sediment concentration data. Most meltwater streams were sampled during only one field period. However, data from three sampling periods at Castner and Worthington Glaciers imply that, even though the relative proportions of dissolved constituents in the meltwater streams are similar, absolute concentrations can vary with time.

Characteristics of glacial meltwater

The data summarized in Table 7 indicate certain characteristics common to all of the meltwater. All are dilute solutions with mean total cation concentra-

tions (of those measured) ranging from 9.3 to 37 ppm. The water is slightly basic, ranging in pH from 7.3 to 8.9. Although fewer Eh measurements were obtained, values range from +0.42 to +0.58, indicating a highly oxidizing environment. Obviously, the water is quite cold, with mean temperatures ranging from 0.5 to 3.2^o C. Keller and Reesman (1963) studied meltwater from fifteen glaciers in the United States and Europe. The pH range of those streams was slightly lower (6.4 to 7.5 for thirteen of the streams).

Ca is the dominant cation in all these meltwater streams. Keller and Reesman (1963) also found Ca to be dominant in all but two of their fifteen streams. In the present study, emphasis was placed on the relative proportion of dissolved constituents when comparing different meltwater streams because of the possible temporal variations discussed above. For comparison, Ca and Mg, and Na and K, were grouped together (as Ca+Mg and Na+K). Triangular plots with %(Ca+Mg), %(Na+K), and %Si as end members (Fig. 12), based on 100% for the sum of these constituents, bear out the high proportion of (Ca+Mg) (mainly Ca) in these streams. The good relationship established between specific conductance and (Na+K+Ca+Mg) concentration indicates another common characteristic and suggests conductance measurements might be useful for estimating the total concentration of these dissolved constituents in other meltwater streams.

The major variation among the streams was in suspended sediment concentrations (Table 7). This is due largely to stream velocity variations at the time and location of sampling. This modifies Keller and Reesman's (1963) conclusion that the amount of suspended material in meltwater is controlled by the type of rock eroded, glacial abrasion, and glacial melting.

Suspended sediment-meltwater interactions and the source of dissolved constituents in glacial meltwater

The reason for obtaining equal aliquots of meltwater which were not filtered for a considerable length of time was to see whether suspended sediment and meltwater interact to any great extent, and if so, to what degree this might affect meltwater chemistry. The two most likely interactions should be dissolution of suspended sediment and cation exchange between sediment and water. Data for samples not filtered for several days are presented in Appendix C.

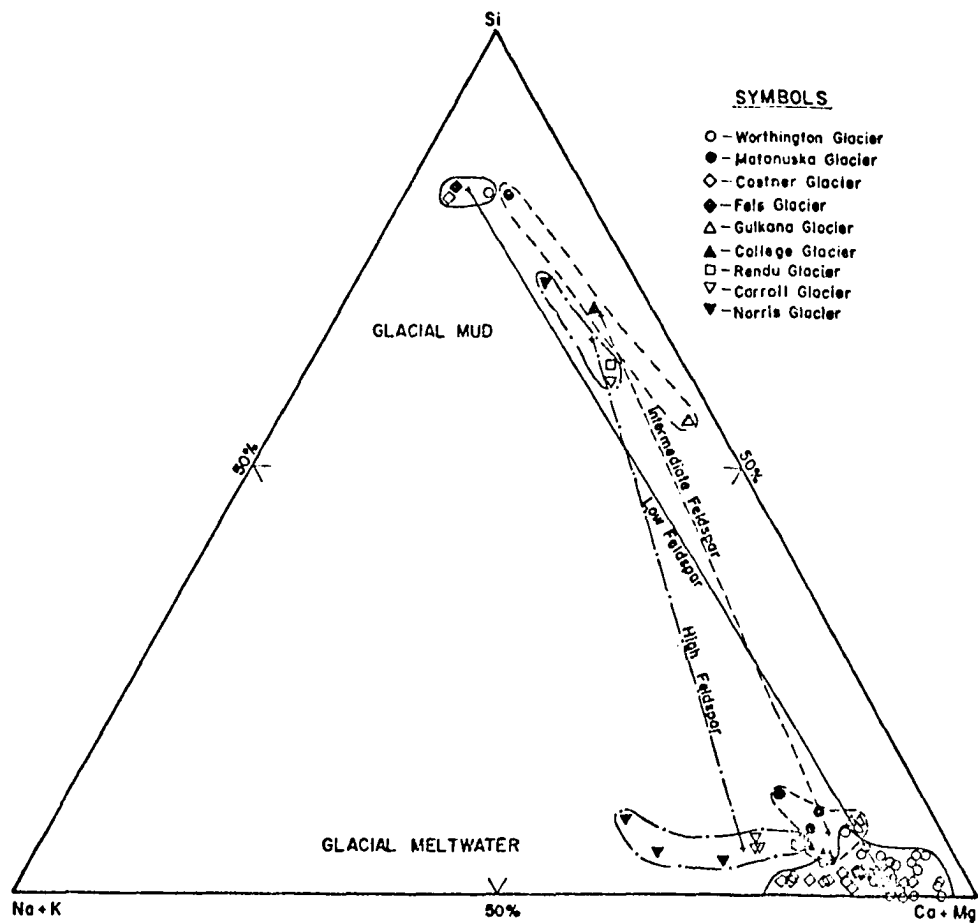


Fig. 12 - Chemical composition of glacial meltwater and superglacial muds. Data points are grouped according to the feldspar content of respective superglacial sands. Tie-lines are connected at points (+) corresponding to mean values for each group.

Mean chemical and suspended sediment data for these unfiltered samples (designated \bar{X}_u) and samples filtered at the time of collection (designated \bar{X}_f) are compared in Table 8. The numbers of days before filtration are not tabulated in Table 8. In general, \bar{X}_u values for the cations are higher than \bar{X}_f values, although in a few instances the opposite is true. The Mann-Whitney U-test (Siegel, 1956) was employed to test the null hypothesis that the differences between \bar{X}_f and \bar{X}_u values for each cation from each stream are not significant at the 95% confidence level against the alternate hypothesis that \bar{X}_u values are significantly greater than \bar{X}_f values (or in the appropriate cases, that \bar{X}_f values are significantly greater than \bar{X}_u values). This test takes into account both the magnitude of change for each sample pair (\bar{X}_f and \bar{X}_u) as well as the number of pairs compared from each meltwater stream. It was used in preference to the student-t test because of the small number of sample pairs for most streams.

The results of this test (Table 8) show significantly greater Si, K, and Ca concentrations for almost all unfiltered meltwater; fewer significant Mg and Na increases. Inability to reject the null hypothesis does not necessarily indicate no concentration change, as in several instances small increases were observed and a greater number of samples would possibly have shown these differences to be significant.

The same test was applied to mean suspended sediment concentrations in filtered and unfiltered samples. In the majority of cases, no significant differences were noted. Of the three sets of Worthington Glacier meltwater, however, the suspended sediment concentration of filtered samples was significantly higher in one set ($\bar{X}_f > \bar{X}_u$), significantly lower in another ($\bar{X}_f < \bar{X}_u$), and there was no significant difference in the third set ($\bar{X}_f = \bar{X}_u$). The reason for this discrepancy is not known.

Increases in cation concentrations as a function of time were observed in sets of samples from three meltwater streams filtered at the time of collection and after 15, 30, 60, 90, and 120 days (Table 9). To test the significance of these changes at the 95% confidence level, plus and minus values for two standard deviations, based on mean deviation data in Table 6, were calculated and are included in Table 9. Concentration changes are significant for all cations but Na in Matanuska and Norris Glacier meltwater. Although absolute concentration increases are apparent for Castner Glacier meltwater, except for Si these

Table 8. Comparison of mean cation concentrations and suspended sediment concentrations between meltwater filtered at the time of collection (\bar{X}_f) and meltwater not filtered until several days after collection (\bar{X}_u).

Glacier	No. of Samples	Sodium (Na) (ppm)			Potassium (K) (ppm)			Calcium (Ca) (ppm)		
		\bar{X}_f	\bar{X}_u	P	\bar{X}_f	\bar{X}_u	P	\bar{X}_f	\bar{X}_u	P
Worthington										
6-68	12	0.57	1.0	X	0.29	0.33	X	7.6	7.7	-
6-68	3	0.15	0.86	X	0.09	0.22	X	4.7	5.0	-
8-69	3	0.14	0.15	-	0.15	0.18	X	5.4	4.7	?
Matanuska	3	1.3	1.3	-	0.39	0.58	X	9.0	17.	X
Castner										
7, 8-68	4	3.0	2.5	-	1.0	1.1	-	20.	22.	-
6-69	2	1.1	1.2	-	1.0	1.2	X	19.	22.	X
8-69	3	3.7	3.7	-	1.4	1.5	X	37.	37.	-
Fels	3	1.5	1.4	-	2.4	2.7	X	25.	31.	X
Gulkana	3	0.53	0.54	-	0.39	0.71	X	8.0	11.	X
College	3	1.4	1.2	-	1.3	2.4	X	14.	17.	X
Rendu	3	1.3	1.5	X	0.82	1.3	X	9.9	14.	X
Carroll	3	1.8	2.1	X	1.2	2.3	X	9.2	16.	X
Norris	3	2.4	2.3	-	0.64	1.5	X	6.2	9.3	?

\bar{X}_f = Mean values for samples filtered at the time of collection.

\bar{X}_u = Mean values for samples not filtered until several days after collection.

P = Probability.

X = $P < 0.05$ = Significant difference

? = $0.05 < P < .10$ = Possible significant difference

- = $P > 0.10$ = No difference in populations

Table 8, cont. Comparison of mean cation concentrations and suspended sediment concentrations between meltwater filtered at the time of collection (\bar{X}_f) and meltwater not filtered until several days after collection (\bar{X}_u).

Glacier	Magnesium (Mg) (ppm)			Silica (Si) (ppm)			Suspended Sediment (ppm)		
	\bar{X}_f	\bar{X}_u	P	\bar{X}_f	\bar{X}_u	P	\bar{X}_f	\bar{X}_u	P
Worthington									
6-68	0.30	0.46	X	0.35	0.87	X	172	161	X
8-68	0.18	0.19	-	0.04	0.13	?	100	147	X
8-69	0.38	0.42	-	0.21	0.59	?	101	99	-
Matanuska	0.65	0.91	X	1.2	1.3	-	3,813	3,574	-
Castner									
7, 8-68	5.4	5.5	-	0.44	1.05	X	2,257	2,203	-
6-69	4.5	4.5	-	0.68	0.85	X	2,524	2,772	-
8-69	15.	15.	-	1.0	1.7	X	270	225	?
Fels	6.6	8.2	X	1.0	1.7	X	9,829	10,726	-
Gulkana	0.71	0.71	-	0.94	0.96	-	1,667	1,590	-
College	1.4	1.3	-	0.98	1.3	X	4,988	5,091	-
Rendu	0.77	1.1	X	0.85	2.7	X	7,538	7,813	-
Carroll	1.3	2.1	X	0.91	2.9	X	12,803	12,737	-
Norris	0.58	1.2	?	0.60	1.1	X	1,431	1,380	?

\bar{X}_f = Mean values for samples filtered at the time of collection.

\bar{X}_u = Mean values for samples not filtered until several days after collection.

P = Probability.

X = $P < 0.05$ = Significant difference

? = $0.05 < P < .10$ = Possible significant difference

- = $P > 0.10$ = No difference in populations

Table 9. Variations in cation concentrations, suspended sediment concentrations, and pH of meltwater as a function of length of time between sample collection and filtration.

No. of Days before Filtration	Sodium (Na) (ppm)	Potassium (K) (ppm)	Calcium (Ca) (ppm)	Magnesium (Mg) (ppm)	Silica (Si) (ppm)	Suspended Sediment (ppm)	pH of Filtered Samples	Hydrogen (H) (ppm)
<u>Location: Matanuska Glacier</u>								
0	1.3±.2	0.40±.06	10. ±2.	0.76±.16	1.3 ±.3	2,415±314		
15	1.2±.2	0.54±.08	----- 17. ±3.4	1.0 ±.2	1.4 ±.4	2,590±337	7.5	3.2x10 ⁻⁵
30	1.1±.1	0.50±.07	17. ±3.4	0.97±.20	1.1 ±.3	2,360±307	8.1	0.8x10 ⁻⁵
60	1.1±.1	0.54±.08	21. ±4.2	1.0 ±.2	1.2 ±.3	2,402±312	7.8	1.6x10 ⁻⁵
90	1.1±.1	0.57±.08	23. ±4.6	1.1 ±.2	1.2 ±.3	2,378±309	7.8	1.6x10 ⁻⁵
120	1.2±.2	0.58±.09	24. ±4.7	1.6 ±.3	2.2 ±.6	2,188±284	7.8	1.6x10 ⁻⁵
P	-	X	X	----- X	----- ?	-		
<u>Location: Castner Glacier</u>								
0	1.2±.2	1.1 ±.2	20. ±4.0	5.2 ±1.1	0.75±.20	2,157±281		
15	1.4±.2	1.2 ±.2	21. ±4.2	6.0 ±1.2	0.94±.25	2,451±318	7.2	6.3x10 ⁻⁵
30	1.2±.2	1.3 ±.2	23. ±4.5	6.0 ±1.2	0.94±.25	2,167±282	8.1	0.8x10 ⁻⁵

Table 9, cont. Variations in cation concentrations, suspended sediment concentrations, and pH of meltwater as a function of length of time between sample collection and filtration.

No. of Days before Filtration	Sodium (Na) (ppm)	Potassium (K) (ppm)	Calcium (Ca) (ppm)	Magnesium (Mg) (ppm)	Silica (Si) (ppm)	Suspended Sediment (ppm)	pH of Filtered Samples	Hydrogen (H) (ppm)
<u>Location: Castner Glacier, cont.</u>								
60	1.2±.2	1.2 ±.2	24. ±4.7	6.5 ±1.4	0.94±.25	2,147±279	7.4	4.0x10 ⁻⁵
90	1.2±.2	1.2 ±.2	25. ±4.9	6.4 ±1.3	0.94±.25	2,362±307	8.0	1.0x10 ⁻⁵
120	1.2±.2	1.2 ±.2	26. ±5.1	6.9 ±1.4	1.3 ±.3	2,136±278	8.0	1.0x10 ⁻⁵
P	-	-	-	-	----- X	-	-	-
<u>Location: Norris Glacier</u>								
0	2.4±.3	0.65±.09	5.7±1.1	0.71±.15	0.52±.14	1,431±186	-	-
15	2.0±.3	0.94±.13	8.4±1.7	0.67±.14	0.85±.23	1,400±182	7.7	2.0x10 ⁻⁵
30	2.5±.3	1.6 ±.2	9.6±1.9	1.2 ±.2	1.6 ±.4	1,464±191	7.3	5.0x10 ⁻⁵
60	2.6±.4	1.7 ±.2	10. ±2.0	1.3 ±.3	1.6 ±.4	1,305±170	7.2	6.3x10 ⁻⁵
90	2.4±.3	1.9 ±.3	9.7±1.9	1.4 ±.3	1.4 ±.4	1,503±196	7.6	2.5x10 ⁻⁵

Table 9, cont. Variations in cation concentrations, suspended sediment concentrations, and pH of meltwater as a function of length of time between sample collection and filtration.

No. of Days before Filtration	Sodium (Na) (ppm)	Potassium (K) (ppm)	Calcium (Ca) (ppm)	Magnesium (Mg) (ppm)	Silica (Si) (ppm)	Suspended Sediment (ppm)	pH of Filtered Samples	Hydrogen (H) (ppm)
<u>Location: Norris Glacier, cont.</u>								
120	2.4 ⁺ _{-.3}	1.9 ⁺ _{-.3}	10. ⁺ _{-.2.0}	1.2 ⁺ _{-.2}	2.1 ⁺ _{-.6}	1,709 ⁺ ₂₂₂	7.4	4.0x10 ⁻⁵
P	-	X	X	X	X	-		

----- = Significant change in concentration.

X = P < 0.05 = Significant difference.

? = 0.05 < P < 0.10 = Possible significant difference.

- = P > 0.10 = No significant difference.

differences are not significant by this method of testing. By comparing Tables 8 and 9 it may be seen that for these three sets of meltwater samples a few concentrations increased significantly using one test, but not when the other test was applied. This is apparently a result of (1) neglecting the time factor in the former test, since the time required for a significant concentration increase to occur varied for each cation in the three meltwater streams and (2) the small number of samples used (three) in the error (standard deviation) determinations.

These results indicate significant increases in cation concentrations (except possibly Na) in meltwater upon prolonged contact with suspended sediment. It remains to be determined if these increases are a result of suspended sediment dissolution or cation exchange reactions. Dissolution would release cations to the water and thus increase the concentrations upon prolonged contact with sediment, whereas cation exchange reactions would probably result in increased concentrations of some cations in meltwater and decreased concentrations in others. These results imply that dissolution of suspended sediment is the cause of increased cation concentrations in unfiltered (X_u) meltwater. The fact that suspended sediment concentrations in unfiltered samples were not significantly lower than those in filtered samples is a result of the relatively small amount of dissolution that did occur. Dissolution is particularly favored because Si showed consistent increases and this ion is generally not considered to be readily exchangeable. The remaining possibility is for exchange of these cations on the sediment by H ions in the water. Exchange with H could result in the observed concentration increases, but the pH of the solution would also increase. To test this, pH measurements were made immediately after filtering samples from the three sets of meltwater upon which 120 day experiments were conducted. The pH values and the calculated H ion concentrations (Table 9) are nearly the same over this time period, which indicates little removal of this ion from solution. Furthermore, the fact that H ion concentrations are five orders of magnitude lower than the other cation concentrations indicates there is not enough of this ion available to account for the observed increased concentrations through exchange reactions.

In light of these facts, it is concluded that suspended sediment was dissolved in the meltwater stream samples. This is in agreement with McKenzie

and Garrels' (1965) finding that Si (the only cation they analyzed) was rapidly released from several varieties of clay minerals in contact with sea water. This agrees also with Keller and Ressman (1963), who infer that the chemical weathering of suspended sediment (termed "rock flour" by them) is the result of dissolution of hydrated silica tetrahedra and exposed metal cations from the surface of silicate particles.

To get some idea of the rate of dissolution, total concentrations of the constituents analyzed (Na+K+Ca+Mg+Si) were plotted against the time between sampling and filtration (Fig. 13). The zero point on the abscissa is for samples filtered immediately upon collection in the field. Values to the left of this point are considered the time (in days) from which a sediment particle comes in contact with a subglacial stream to the time that suspended particle emerges from under the ice and is carried 1 to 2 km downstream, the usual stream sampling distance from the terminus. Subglacial streams generally originate well above the glacier termini, yet it was generally observed that near the termini, these streams flowed quite rapidly (see stream velocity data in Appendix C). Considering the areal extent of the glaciers studied (Table 1), it would seem that the time required for a particle suspended in a subglacial stream to travel the length of a glacier would be short. This time was plotted on the abscissa as one day, but this might even be an over-estimate. The concentration of dissolved constituents in ice is probably low, even though this may not be the case near the sole of a glacier where melting and refreezing occur and where sediment is in abundance. However, considering that ice was once almost pure, the original concentration of meltwater at the time of initial contact with suspended sediment can be plotted as shown in Fig. 13.

Fig. 13 indicates by the time meltwater reaches the ice terminus, its chemical character has largely been established. This implies initial suspended sediment dissolution is quite rapid, on the order of one day. Much longer periods of time are thereafter required for sufficient dissolution to occur such as to appreciably change the chemical composition of the meltwater.

This latter point was explored further by estimating the degree of change in chemical composition that would occur over the entire length of these meltwater streams. The abscissa in Fig. 13 (to the right of the zero point) can also be considered a measure of the distance a parcel of water or sediment travels

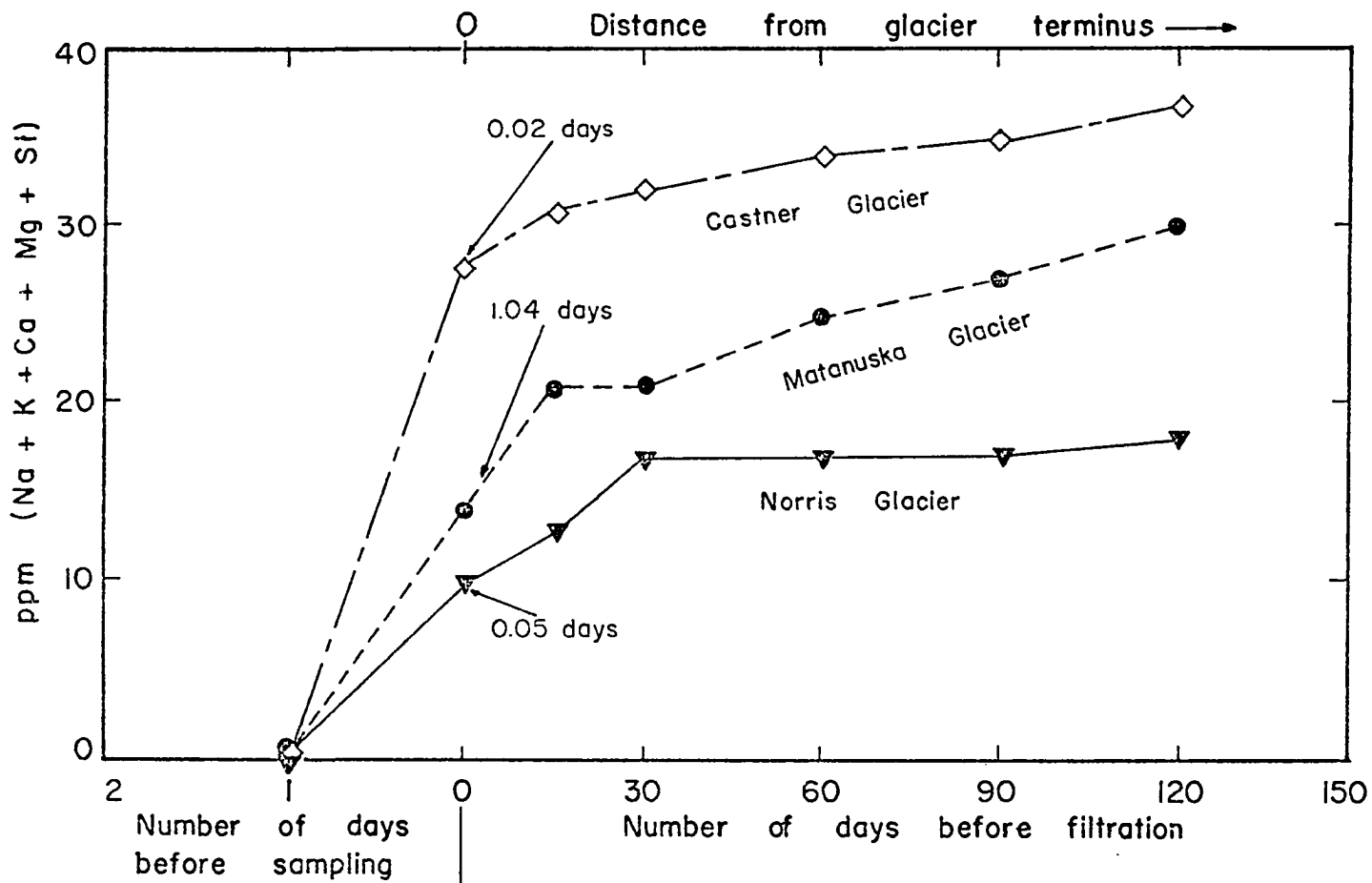


Fig. 13 - Relationship between total cation concentrations in meltwater and the length of time before sample filtration. Intercept values are postulated times between initial pure water-sediment contact under the ice and sample collection. Estimated times required for a parcel of stream water to travel from the glacier terminus to the stream mouth and the total cation concentration of water at the mouth are also shown.

from the terminus, because downstream distance travelled would increase with time. Stream lengths, approximated from topographic maps, were: Matanuska River--102 km (64 mi), Castner Creek--2.4 km (1.5 mi), and Norris Glacier meltwater stream--3.2 km (2 mi). With these data and mean velocity values in Table 7, it was possible to estimate the length of travel time from the terminus to the stream mouths (Fig. 13). It is apparent from Fig. 13 that once the chemical composition is established, meltwater is not in contact with suspended sediment for sufficient periods of time in these streams to appreciably alter its composition.

To summarize the above discussion, these data indicate that the dissolved constituents in meltwater are derived through dissolution of suspended stream sediment. Dissolution is rapid enough (on the order of one day) so that by the time a parcel of meltwater emerges from under the ice, the chemical character of that parcel has largely been established. During the typical course of these streams, further dissolution is slow enough as to not appreciably alter this character. These statements can only be presented as a hypothesis because (1) the laboratory experiments were not conducted under the same conditions as those of a meltwater stream, (2) temporal variations in meltwater chemistry occur, even though in the present study these were not found to deviate considerably about the mean values used, and (3) temporal and spatial variations in stream velocities are common and thus would affect the estimated travel times. However, the evidence in support of this hypothesis is fairly strong. In addition, these results indicate that for an accurate description of the chemical composition of meltwater, samples should be filtered immediately upon collection at the stream site.

In most literature pertaining to chemical weathering, dissolved constituents in water are usually referred to as being derived from the "weathering of rock." It is particularly satisfying that, in the present study, a more precise source, suspended sediment, has been established with reasonable certainty.

Relative mobility of cations in glacial muds

Smyth (1913), Polynov (1937), Anderson and Hawkes (1958), and Feth,

Robertson, and Polzer (1964) have determined the relative mobility of major cations for the earth's crust and for igneous and metamorphic rocks by comparing the chemical composition of the rock with the composition of water in contact with it. Their method consists of calculating the weight percentages of cations (not oxides) in the rocks and in the water so that total cation concentrations equal 100% for each, then computing the ratio: (% cation in water)/(% cation in rock). The larger the ratio, the greater the relative mobility of the cation for a given lithology.

Their method was employed in the present study by comparing the percentages of cations in superglacial muds, recalculated from percent oxide data in Table 5, with those in the respective meltwater streams. Since it was established that the majority of these muds probably have not undergone much reworking, they probably have not been in contact with glacial streams. The mud content of suspended stream sediment ranged from 50 to 97% (Appendix B). Since mud-sized particles are probably more responsive to chemical attack than larger particles, the bulk chemistry of the superglacial muds should therefore approximate that of the most readily attacked fraction of suspended sediment prior to contact with meltwater streams.

The relative orders of mobility are shown in Table 10. In all instances Ca is either the most or next most mobile and Si the least mobile cations, thus accounting for the high Ca and low Si in these meltwater streams. These results are in general agreement with those of the other workers.

The anomalously high relative mobility of K in Gulkana, College, and Carroll Glacier superglacial muds is somewhat difficult to explain in light of the greater stability of K-feldspars relative to plagioclase varieties (Goldlich, 1938) and the lower mobility of K in the other muds. Rather than indicating anomalously high concentrations of easily weathered K-rich mineral phases in these muds, this more likely indicates anomalously low concentrations. The (% cation in water)/(% cation in rock) ratio would increase, thereby increasing the apparent mobility of K. The relatively low percent K_2O values (Table 5) for these muds support this inference.

Comparative meltwater chemistry and ultimate bedrock control of dissolved constituents

Table 10. Relative mobility of cations from the mud-size fraction of superglacial sediments.

Glacier	$\frac{\% \text{Ca}_w}{\% \text{Ca}_m}$	$\frac{\% \text{Mg}_w}{\% \text{Mg}_m}$	$\frac{\% \text{Na}_w}{\% \text{Na}_m}$	$\frac{\% \text{K}_w}{\% \text{K}_m}$	$\frac{\% \text{Si}_w}{\% \text{Si}_m}$	Relative Order of Mobility
Worthington	17.8	1.1	1.2	0.4	0.04	Ca > Na \geq Mg > K > Si
Matanuska	8.9	2.3	1.7	1.6	0.12	Ca > Mg > Na \geq K > Si
Castner	73.8	5.1	3.6	0.3	0.02	Ca > Mg > Na > K > Si
Fels	52.3	5.5	2.2	0.6	0.04	Ca > Mg > Na > K > Si
Gulkana	2.8	0.5	2.0	9.3	0.16	K > Ca > Na > Mg > Si
College	4.1	1.0	1.5	8.4	0.08	K > Ca > Na > Mg > Si
Rendu	3.2	0.7	1.8	2.9	0.10	Ca > K > Na > Mg > Si
Carroll	2.4	1.7	2.0	3.5	0.10	K > Ca > Na > Mg > Si
Norris	4.3	1.1	4.2	1.6	0.08	Ca \geq Na > K > Mg > Si

Subscripts "w" and "m" refer to water and mud, respectively.

Although the chemical composition of the meltwater streams is generally similar, there are subtle differences among them in the relative proportions of dissolved constituents (Fig. 12). It has been established that the chemical composition of meltwater is controlled by dissolution of suspended sediment and that high dissolved Ca and low dissolved Si concentrations in meltwater can be related to the chemistry of superglacial muds. However, since the chemical composition is controlled by the mineralogical assemblage of the muds, it would be useful to relate mud and meltwater chemistry on this basis. In addition, this would provide a simplified method of comparing the chemical composition of the various streams. Since the source of suspended sediment, as well as its mineralogy, is a simple function of bedrock, the ultimate bedrock control on water chemistry could also be established.

The classification of glaciers according to bedrock terrane (Chapter II) is subjective because it fails to take into account the presence of less extensive but easily weathered rocks which could appreciably affect meltwater chemistry. Rather than using the bedrock classification, the proportion of feldspar relative to quartz plus feldspar in superglacial sands was used to provide a somewhat more quantitative, yet simple, description of bedrock type. To be consistent, the proportions of feldspar in the glacial muds would probably have provided a better means of classification. Superglacial sands were used, however, because quantitative mineralogical data for sands is more readily obtained. Since both size fractions are the product of glacial grinding, the relative proportions of these constituents should be similar in both. The proportions of feldspar were calculated from data in Table 3 by the formula:

$$\% \text{ feldspar} = (\% \text{ feldspar} / \% \text{ quartz} + \% \text{ feldspar}) \times 100$$

The resulting classification is presented in Table 11 and shown in Fig. 12.

The rationale behind this classification scheme is that feldspar and quartz are the dominant constituents in these sediments and their proportions are considered to be similar to those in the source rock. Also, because of their abundance and relative solubilities, feldspar dissolution would probably exert the most influence on meltwater chemistry and quartz the least. This classification is obviously oversimplified, primarily because it neglects feldspar varieties, which are dissolved at different rates, and heavy minerals, which, although less abundant, are subject to chemical attack (Goldlich, 1938). Despite

Table 11. Classification of bedrock terranes on the basis of feldspar content in the sand-size fraction of superglacial sediments.

Glacier	$\frac{\% \text{ Feldspar}}{(\% \text{ Quartz} + \% \text{ Feldspar})}$	Classification
Fels	22	Low Feldspar
Worthington	27	Low Feldspar
Castner	32	Low Feldspar
Matanuska	41	Intermediate Feldspar
College	56	Intermediate Feldspar
Gulkana	61	Intermediate Feldspar
Norris	70	High Feldspar
Carroll	77	High Feldspar
Rendu	87	High Feldspar

this however, the classification provided a good method of comparing meltwater chemistry and interrelating chemical and mineralogical variations in the solid phase and chemical constituents in the liquid phase (Fig. 12).

The low feldspar group (high quartz) contains the greatest proportion of Si in the muds and the lowest proportion of dissolved Si in meltwater (Fig. 12). Meltwater from intermediate and high feldspar groups contains relatively more Si. These differences are due to greater feldspar dissolution. The shift from low Ca+Mg and high Si in the muds to high Ca+Mg and low Si in the meltwater is a result of the relative mobility of these cations.

Of particular interest are the slopes of tie-lines connecting the solid and liquid phases. Using the %Na+K pole for comparison, all three groups contain similar %Na+K in the mud, but %Na+K in meltwater increases with increasing feldspar content of the source material. The slopes of the tie-lines therefore steepen with increasing feldspar content. This again illustrates the effect of feldspar dissolution. This latter point could be stated conversely by using the %Ca+Mg pole for comparison. In this instance the greater the feldspar content in the source material, the less Ca+Mg in the meltwater. Since Ca+Mg are the major dissolved constituents, however, this is an artifact resulting from the closed array method of calculation (percentage basis).

Another possibility for the steeper tie-line slope of the high feldspar group remains to be explored. As previously noted, superglacial sediment from Matanuska, Rendu, Norris, and Carroll Glaciers is mixed with proglacial sediment. These latter three comprise the high feldspar group, and contain the highest proportion of Na+K in meltwater. In addition, all three are coastal glaciers (Fig. 1). It therefore is possible that either through greater exposure to potential chemical attack, or through some enrichment of Na+K in the superglacial muds, the sediments could supply relatively more of these constituents. This would imply that meltwater chemistry was environmentally, rather than mineralogically, controlled.

The possibility of environmental control seems unlikely for several reasons. First, it was determined that the chemical character of meltwater was attained through rapid suspended sediment dissolution, perhaps while the sediment is still in suspension under the ice. Furthermore, previously reworked sediment particles should actually be more resistant to weathering than relatively

fresh grains newly exposed to chemical attack. This is a result of "armoring" of the outer shell of grains during progressive weathering (Krauskopf, 1967). Since these glaciers are in proximity to marine waters, Na+K could be enriched in these muds through some such process as crystallization and deposition of atmospheric salts, however the Na+K concentrations of the muds are no different than those of muds from inland glaciers (Figs. 1 and 12). The final possibility is uptake of exchangeable Na+K prior to mixing with superglacial sediment, and present release of these ions to meltwater through exchange reactions. This too is unlikely since it was previously established that exchange reactions did not affect meltwater chemistry. A particularly good example is Norris Glacier superglacial debris, which is in part former tide flat sediment. The possibility for uptake of exchangeable Na+K would probably be greatest for this sediment, yet no evidence was found that ion exchange affected this meltwater composition over a 120 day period.

To summarize, the results shown in Fig. 12 indicate mineralogical control, and therefore, ultimate bedrock control of meltwater chemistry. This is in agreement with Keller and Reesman's (1963) findings that bedrock type is a major control of meltwater chemistry. Although it is generally assumed that chemical weathering is minimal in the glacial environment, it is at least effective to the extent that variations in the chemical composition of meltwater streams in different bedrock terranes are detected.

Conclusions

1. Both temporal and spatial variations in meltwater streams control suspended sediment concentrations, and, to a lesser extent, affect the absolute concentrations of dissolved constituents. The relative proportions of dissolved constituents appear to remain relatively constant.

2. Certain characteristics are common to all the meltwater streams studied. All are dilute solutions with mean total (Na+K+Ca+Mg+Si) concentrations ranging from 9.3 to 37 ppm. The pH, Eh (where measured), and temperature ranges from 7.3 to 8.9, +0.42v. to +0.58v., and 0.5^o C to 3.2^o C, respectively. Ca is the dominant cation. The relative abundance of dissolved

constituents in these streams is $(Ca+Mg) > (Na+K) > Si$. All meltwater studied exhibits a good linear relationship between specific conductivity and total $(Na+K+Ca+Mg+Si)$.

3. The dissolved constituents in glacial meltwater are derived through dissolution of suspended stream sediment. Initial dissolution is probably rapid enough (on the order of one day) so that by the time meltwater emerges from under the ice, its chemical character has largely been established. Further dissolution is slow enough that the chemical composition is probably not appreciably altered along the typical course of these streams.

4. Assuming the chemistry of superglacial muds to approximate that of suspended sediment prior to contact with glacial streams, Ca is generally the most readily mobilized cation and Si the least. This accounts for the high Ca and low Si in these meltwater streams.

5. Even though the chemical composition of these streams is generally similar, there are subtle differences in the relative proportions of dissolved constituents. These differences have been related to mineralogical and chemical variations in superglacial sediment, which are reflections of the ultimate bedrock control of meltwater chemistry.

CHAPTER V
PHYSICAL, CHEMICAL, AND BIOLOGICAL ASPECTS
OF A TIDE-AFFECTED GLACIAL MELTWATER SYSTEM

Introduction

The Norris Glacier area was chosen for study of an entire meltwater system. This system includes ice, a lake, streams, and ground water. The system is influenced by marine waters. Therefore, an effort was also made to describe some effects of the marine environment on meltwater and sediment.

A portion of the Norris Glacier area is the site of rather extensive iron accumulation. Literature on iron is vast. It is also well known that the occurrence of iron in natural water systems often defies simple explanation. It is hypothesized that one of the reasons for this is the approach taken by researchers. The behavior of iron is controlled by physical, chemical, and biological processes, but researchers have often only employed a single process to interpret results. Also, researchers have often assumed a particular study area consists of a single environment when in reality, the area consists of several distinct environments.

In order to test this hypothesis, a survey study was conducted in the Norris Glacier area. Several environments were studied individually, and physical, chemical, and biological processes were taken into account. Only the simplest aspects were considered, however the effort seems to have been justified because a satisfactory explanation for the behavior of iron in the Norris Glacier area was obtained.

Description of Study Area

A brief description of the bedrock terrane and recent history of Norris Glacier was presented in an earlier chapter. The terrane fronting the terminus may be divided into several sedimentologic and hydrologic environments (Fig.

14). The environments are described below along with specific terminology (underlined) used.

An eight-square mile gravelly outwash fan, hereafter called outwash, fronts the Norris Glacier terminus. A dense Sitka spruce-Western hemlock forest rims the eastern half of the emergent portion of the fan. East of the forest is intertidal sediment overlying gravelly outwash. The intertidal environment may be divided into a mud flat and sand flat, which are separated by a dry tributary meltwater stream channel. Within the sand flat, vegetation is lacking, but marsh grass thrives in the upper reaches of the mud flat. A bog occupies the northern part of the mud flat.

Two types of water comprise this system, glacial meltwater and saline Taku Inlet water (Fig. 15). A meltwater lake flanks much of the Norris Glacier terminus (Fig. 14). A subglacial stream emerges from under the ice just north of the lake and flows eastward into Taku Inlet. Some of the lake water is undoubtedly derived from this stream. A distinct boundary between sediment-laden stream water and relatively sediment-free lake water has been observed at the junction of these water bodies, suggesting mixing is minimal and the lake is the product of melting ice at the terminus. Chemical data presented below supports this conclusion. Ground water flows from the ice front, through the outwash gravel (designated outwash ground water), then through the tide flat sediment (designated tide flat ground water). Because the outwash fan slopes eastward, some outwash ground water emerges as surface streams (Streams I-III in Fig. 14) which flow from the eastern edge of the forest across the mud flat to Taku Inlet. Stream IV (Fig. 14) is also derived from outwash ground water, but flow of bog water is impeded within the bog. Stream V (Fig. 14) is a dry stream channel which is filled largely with inlet water on the flood tide and which receives some ground water seepage on the ebb tide. Water from Streams I-V is collectively designated as tide flat surface water. Taku Inlet water is a two layer system; a thin layer of slightly saline (salinity less than 1⁰/.) surface water overlying slightly diluted sea water (salinity approximately 27⁰/.) (Hood and others, 1966). Aside from Norris Glacier meltwater, Taku River water and Taku Glacier meltwater also flow into the inlet.

The diurnal tidal range is approximately 5 m (17 ft) in this area (Department of Commerce, 1966), so much of the tide flat is covered twice daily during

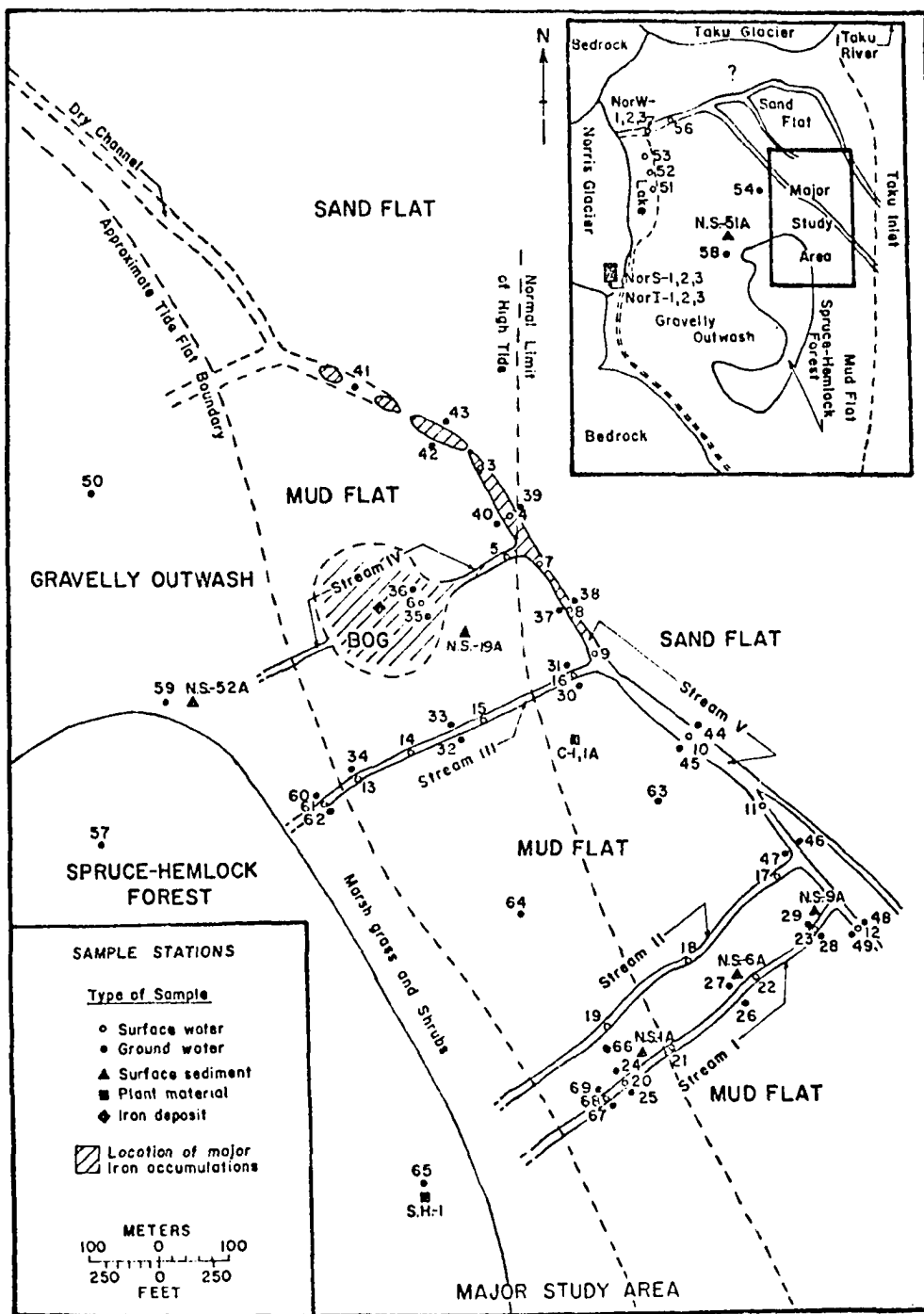


Fig. 14 - Location and types of samples in the Norris Glacier area. Locations of major iron accumulations are also shown.

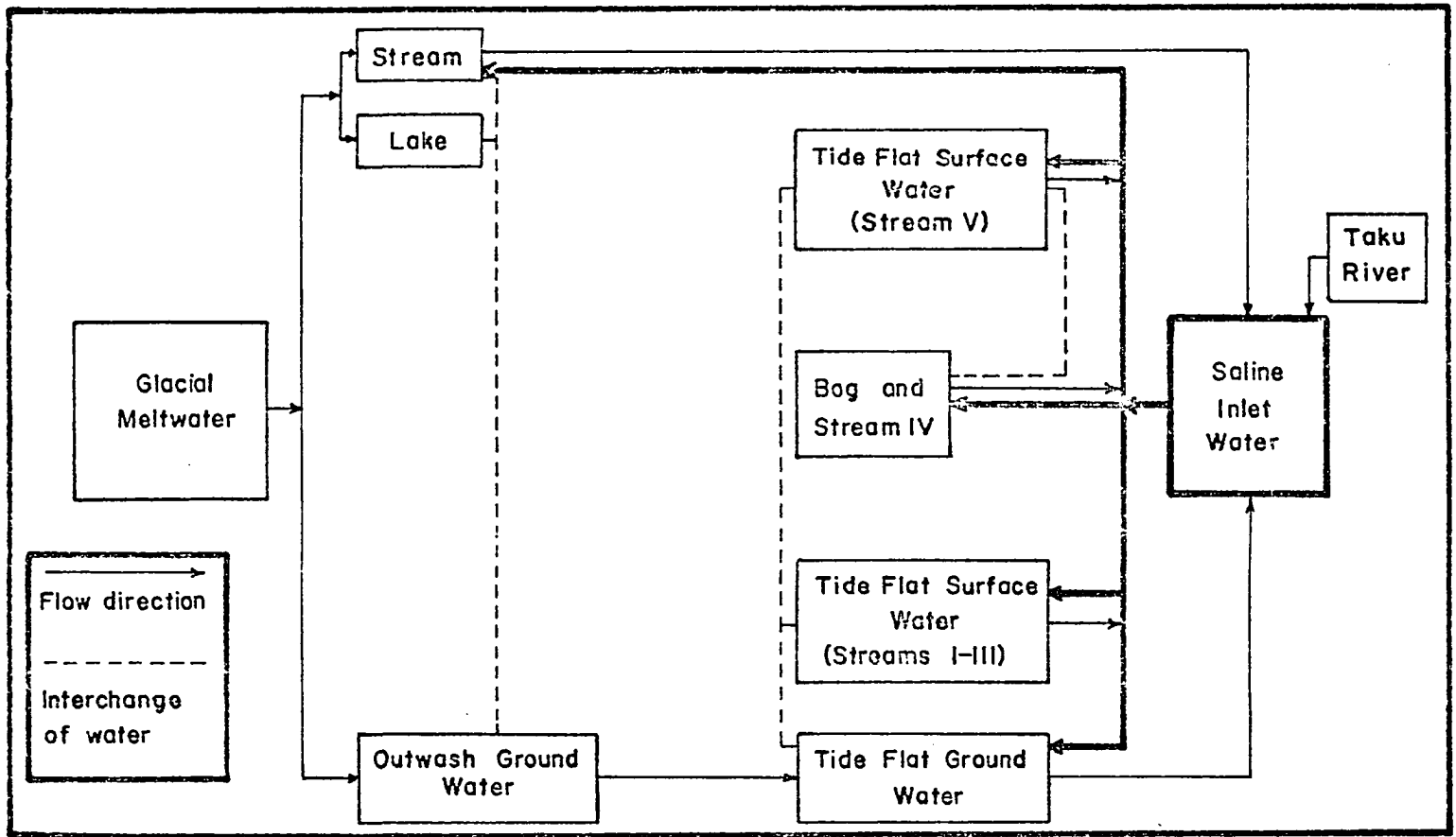


Fig. 15 - Diagram showing water flow directions and interchange of water among the various hydrologic environments in the Norris Glacier area.

flood tides. The outwash ground water table is at a depth of approximately 1m whereas the water table in the tide flat is approximately 0.3m deep; the latter presumably varies with tidal stage.

A flocculent orange iron deposit is abundant in the bog and in the upper half of Stream V (Fig. 14). Scattered small patches of this precipitate are found on parts of the mud flat, but none is found on the sand flat. Iron staining on sediment grains is also common at the outwash and mud flat ground water tables, but not at the sand flat ground water table. Iron staining is also found in the beds of streams I-III.

Methods of Investigation

Sample collection

During May and June, 1967, surface and ground water samples from the various waters were obtained in new, acid-washed polyethylene bottles at locations shown in Fig. 14. Surface water was collected in the same manner as the meltwater stream samples, which were described in Chapter IV. Ground water from near the water table was collected by first digging a pit to below the water table, pumping the hole dry with a hand-vacuum pump attached to an Erlenmeyer flask and rubber hose, then allowing the hole to refill; this procedure was repeated until clear water was obtained. All samples except those from the subglacial stream, lake, Taku Inlet, and Taku River were clear, thus filtering was not necessary. Sediment in these latter samples was allowed to settle, then the water was decanted into a clean bottle. As much of the tide flat is covered during flood tide, samples were necessarily collected at times when sites were exposed.

Samples of surface sediment and the iron deposit were obtained from various sedimentary environments, as were samples of marsh grass, identified as Carex sp. (R. Hadley, personal communication, 1969), from the mud flat, and spruce-hemlock litter from the forest floor (Fig. 14). Three ice samples from near the sole of Norris Glacier also were obtained (Fig. 14). Locations of the three superglacial sediment samples, described in Chapter III, are also shown in Fig. 14.

Methods of analysis

Water. Measurements of pH, Eh, and temperature were made immediately upon collection at most of the sites, using the same techniques and instruments as described previously. Chlorinity (Cl) was determined in the laboratory by titrating with silver nitrate standardized against IAPO sea water (Cl = 19.373⁰/...) (U. S. Hydrographic Office, 1969): replicate analyses gave equivalent results. Concentrations of Na, K, Ca, and Mg were determined by the methods previously described except that, prior to analysis, water samples were diluted considerably to eliminate any analytical error due to the greater viscosity of sea water (Angino and Billings, 1967). Total iron concentrations (Fe_T) in water and ice (melted) were also analyzed by atomic absorption spectrophotometry after adding 10% HCL in a ratio of 1/1 v/v to the samples, diluting, and allowing this solution to stand for at least 24 hours. Percent error in the determination of Na, K, Ca, and Mg are given in Table 6. Analytical error in the Fe_T determination is +5.0% of the reported value. Physio-chemical data for the water is presented in Appendix D. Subglacial stream samples, which were collected in July, 1969, and described in Chapter IV, were also analyzed for Fe_T.

Iron deposit. The sample was air-dried, then gently ground to a powder in an agate mortar. Structural analysis was performed by X-ray diffraction, using a Norelco Type 12045 spectrometer and by electron microscopy, using a Jem Model G-A instrument. Chemical composition was determined by X-ray spectrography, using the Norelco instrument with a W tube, LiF crystal and scintillation detector and by emission spectrography using a Jarrell-Ash 1.5 Meter Wadsworth Grating Spectrograph.

Sediment. Superglacial, outwash, and mud-flat sediment samples were air-dried, gently disaggregated in an agate mortar, then sieved through a 2mm screen from which representative aliquots of the less than 2mm fraction were removed for analysis.

Clay content was determined by pipetting (Folk, 1968). After determining that the samples were free of carbonate, the organic matter content was estimated by weight loss upon heating to 650⁰ C for four hours in a Lindberg muffle furnace.

Cation exchange capacity (CEC) at pH 7 was determined using a method modified from Chapman (1965). Ten gm samples in 50 ml of 1.0N NH_4OAc were heated on a steam bath for 30 minutes rather than allowing them to stand overnight. Exchangeable iron (Fe_E) concentrations were determined by atomic absorption spectrophotometry rather than colorimetrically.

The Fe_T content of one superglacial sediment and one mud flat sample was determined by the silicate analysis method described previously. Mineralogy of the mud-sized fraction of the superglacial sediment is presented in Table 4. Qualitative mineralogical analysis of tide flat mud revealed a similar assemblage except for the lack of carbonate. More detailed mineralogy of tide flat and out-wash sediments are presented by Slatt and Hoskin (1968).

Organic material. Carex sp. was separated into leaves and roots and these and the spruce-hemlock litter were ground in a Wiley mill. Representative aliquots were split and analyzed for CEC, and Fe_E concentrations were determined by the same method as for sediments. The Fe_T content of these organic samples was determined by atomic absorption spectrophotometry after HClO_4 digestion (Olsen and Dean, 1965).

Results and Interpretation

Characteristics of the water and ice

Chlorinity distribution and fresh-saline water mixing. The tide flat is the zone of mixing of meltwater and saline inlet water (Fig. 15). Ground water chlorinity in the mud flat decreases progressively toward the meltwater source (Fig. 16). The anomalously low chlorinity of ground water near the bog is apparently due to the greater quantity of fresh water stored here which may migrate through the mud and to the ground water table. The lower chlorinity of ground in the sand flat suggests rapid and almost complete drainage and flushing out of saline water through the permeable sand during ebb tide (Slatt and Hoskin, 1968) as opposed to slower and incomplete flushing through the mud.

Stream V is saline, as are the lower reaches of most of the other streams

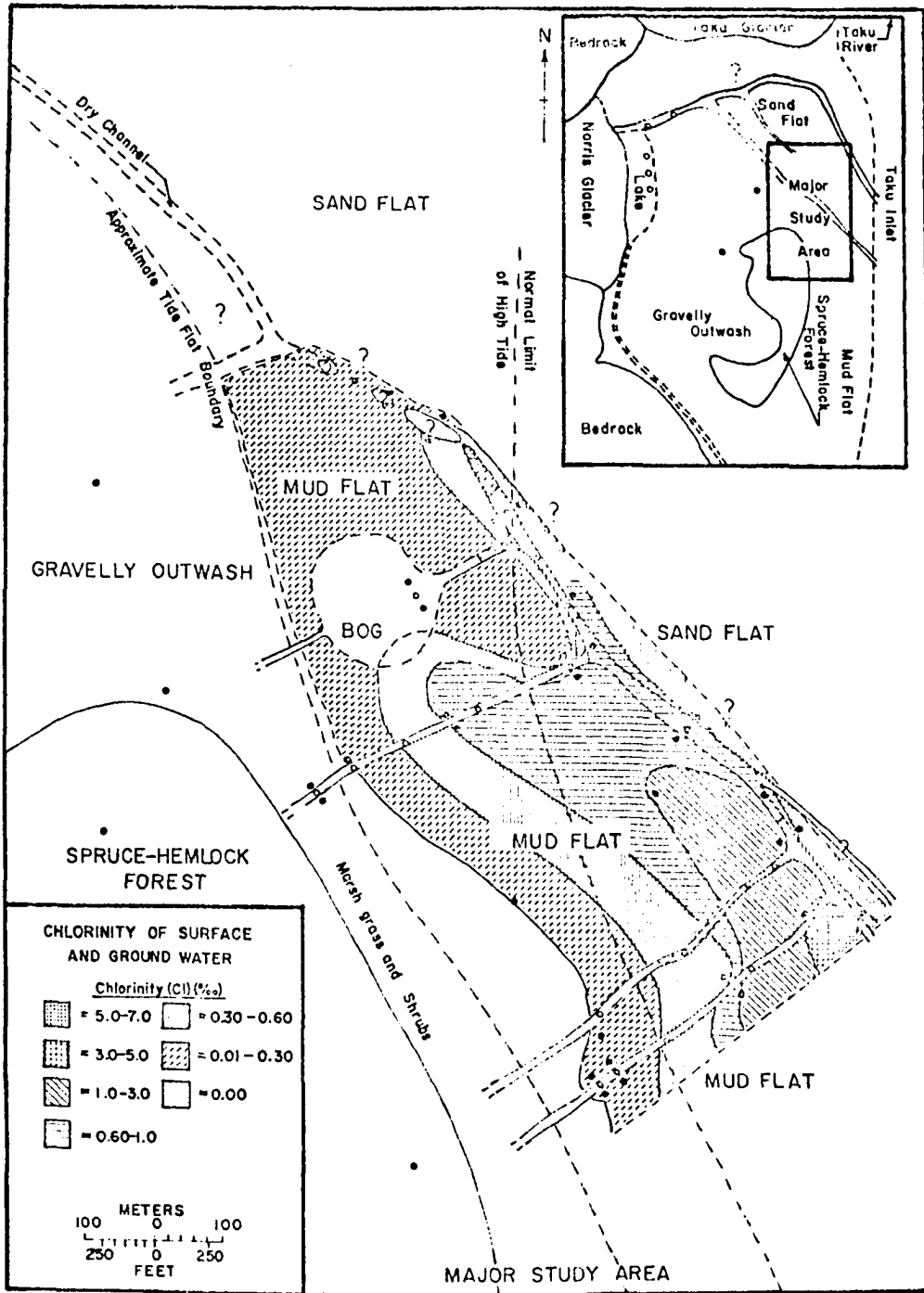


Fig. 16 - Chlorinity distribution map for surface and ground water in the Norris Glacier area.

(Fig. 16). This is due to some mixing. As much of these streams are inundated on the flood tide, the chlorinity of this water should change constantly.

Undoubtedly the ground water chlorinity distribution presented in Fig. 16 is not constant, but varies somewhat with tidal position. The higher chlorinity values here, however, suggest that this ground-water body fluctuates more slowly than surface water. This is particularly evident because most ground water samples were collected on the ebb tide, when sites were exposed and when fresh water would exert maximum influence upon the mixing process.

Measurements of pH, Eh, and water temperature. The pH ranges from slightly acidic to slightly basic. The subglacial stream is most basic with pH = 9.1, followed by lake water which ranges from 8.1 to 8.2. The pH range of outwash ground water is 5.9 to 7.8, that of tide flat surface water is 6.6 to 8.2, and that of tide flat ground water is 6.2 to 9.0.

The Eh measurements indicate highly oxidizing environments. Eh measurements of surface water are usually considered valid because an equilibrium state has been attained with atmospheric oxygen. Ground water measurements, on the other hand, are subject to question due to the possibility of oxygen contamination during sample collection and analysis (Hem, 1960a). In normal ground water systems, the oxidation potential is higher near the upper surface of the water table than at depth due to the greater availability of oxygen (Hem, 1960b), so iron oxides may accumulate here which are stable under oxidizing conditions (Hem and Cropper, 1959). Because these ground water samples were collected from near the water table and iron staining was present here, Eh measurements are thought to be valid. The Eh ranges of outwash ground water, lake water, and subglacial stream water are similar; these are +0.49v. to +0.59v., +0.47v. to +0.48v., and +0.45v., respectively. Tide flat surface water has a slightly lower Eh, with values ranging from +0.37v. to +0.52v. Tide flat ground water has the lowest Eh, with values ranging from +0.22v. to +0.48v.

Meltwater is colder toward the ice. The temperature of the subglacial stream is 2.0° C, that of the lake ranges from 3.5 to 12.0° C, and that of the outwash ground water ranges from 8.0 to 13.0° C. Tide flat ground water is slightly colder than tide flat surface water; these ranges are 6.0 to 21.0° C and 8.0 to 25.0° C, respectively.

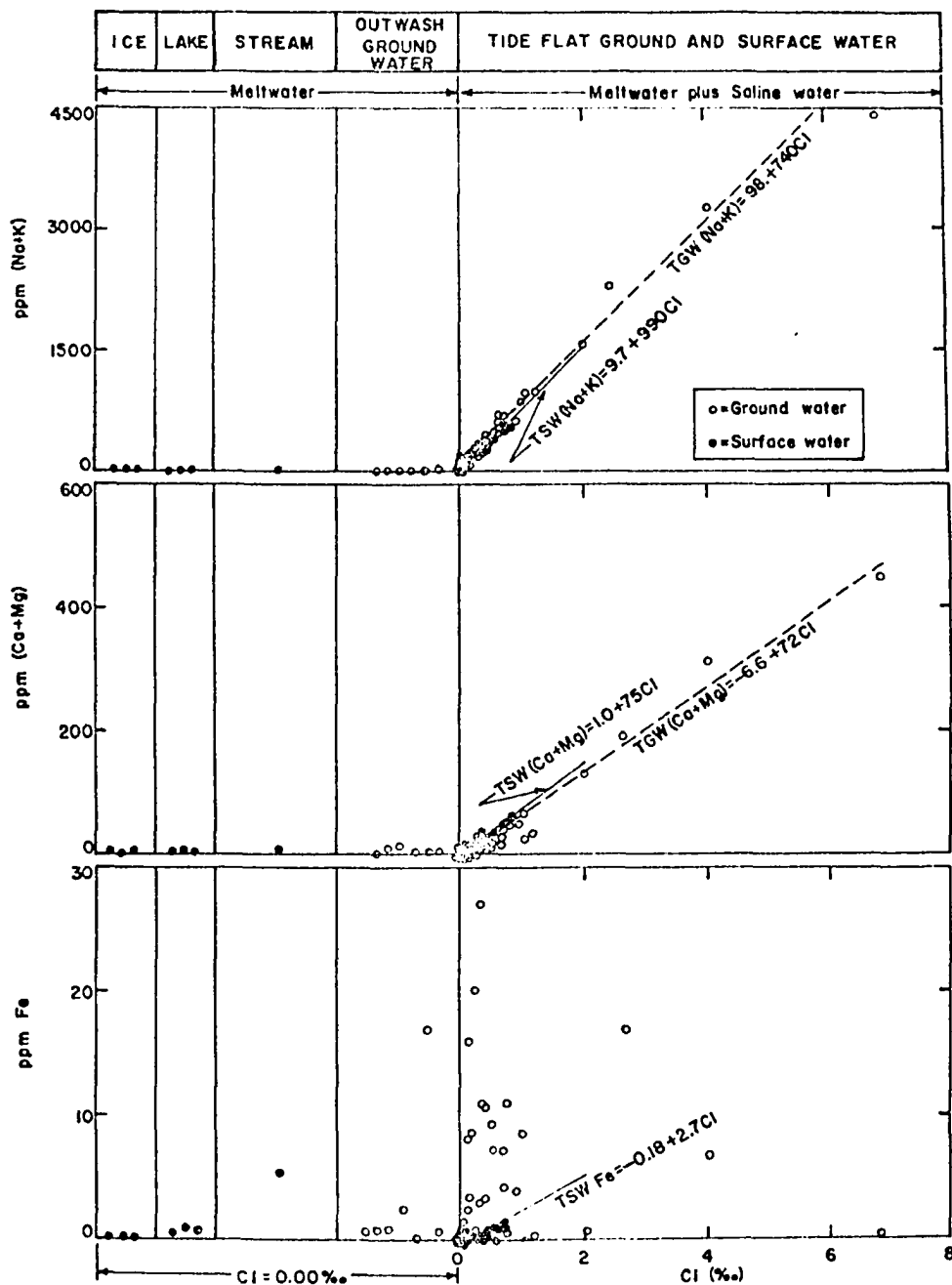


Fig. 17 - Relationships between cation concentrations and chlorinity in Norris Glacier ice and water. Linear regression equations for tide flat ground water (TGW) and tide flat surface water (TSW) are also shown.

Table 12. Mean concentrations of chemical constituents in water in the Norris Glacier area.

	Ice	Lake	Sub-glacial Stream	Outwash Ground Water	Tide Flat Surface (TSW) & Tide Flat Ground (TGW) Water (range of values)	Taku Inlet Surface Water	Taku River
No. of Samples	3	3	1	6	TSW = 22 TGW = 33	2	1
Chlorinity (Cl) (0/00)	0.00	0.00	0.00	0.00	TSW - 0.00 to 0.82 TGW - 0.00 to 6.8	0.03	0.00
Sodium (Na) + Potassium (K) (ppm)	0.3	2.7	7.4	8.3	TSW (Na + K) = 9.7 + 990 Cl, r = 0.991 TGW (Na + K) = 98. + 740 Cl, r = 0.987	6.4	4.2
Calcium (Ca) + Magnesium (Mg) (ppm)	3.1	1.3	7.6	5.2	TSW (Ca + Mg) = 1.0 + 75 Cl, r = 0.948 TGW (Ca + Mg) = -6.6 + 72 Cl, r = 0.987	15.	14.
Iron (Fe) (ppm)	0.0	0.7	5.5	3.6	TSW (Fe) = -0.18 + 2.7 Cl, r = 0.793 TGW (Fe) = 100. - 120. Cl, r = 0.038	6.4	6.3

r = Correlation coefficient

Water and ice chemistry. The chemical composition of the water and ice is presented in Fig. 17 and summarized in Table 12. Na, K, Ca, and Mg have been grouped as Na+K and Ca+Mg. Ice from the sole of Norris Glacier is not pure, probably because there has been some sediment-meltwater interactions in this zone of freeze-thaw. Na, K, Ca, and Mg in the subglacial stream are derived from suspended sediment dissolution (Chapter IV). Since the stream sample was collected from near the terminus, its chemical composition here is considered representative of glacial meltwater prior to travel through the various environments.

Lake water has a chemical composition more closely related to glacial ice than subglacial stream water, thus much of this water is probably derived from melting ice. During the sampling period, several large bergs were in the lake, and calving at the terminus was observed.

There are no major differences between the chemical composition of the subglacial stream and that of the outwash ground water. Once the meltwater travels through the outwash and into the tide flat, where it mixes with Taku Inlet water, Na+K and Ca+Mg concentrations increase rapidly with increasing chlorinity (Fig. 17 and Table 12). Regression equations and correlation coefficients (r) relating Cl to the dissolved constituents in both tidal surface and tidal ground water are presented in Fig. 17 and Table 12. The correlation coefficients indicate a good linear relationship for Na+K and Ca+Mg in both surface and ground water. The fact that the intercept values for these equations indicate higher Na+K and lower Ca+Mg in non-saline tide flat ground water than non-saline tide flat surface water suggests exchange reactions might be important in the tide flat. This could be the case if the ground water were in contact with sediment for a long period of time so that Ca+Mg in the ground water could exchange with Na+K on the sediments. These reactions probably would not take place in the constantly fluctuating surface water.

The chemical composition of tide flat surface and ground water varies with Cl (the degree of fresh and saline water mixing). Therefore cation concentration distribution patterns would be similar to that for Cl (Fig. 16).

The correlation coefficient of the Fe_T concentration equation for tide flat surface water is relatively low (Table 12), however, it is a significant correlation for the number of samples used (Freund, 1967). This significant correlation

Table 13. Physio-chemical data for sediments and organic material in the Norris Glacier area.

Sample No.	Sample Type	% Clay (of less than 2 mm fraction)	% Loss on Ignition	Cation Exchange Capacity (CEC) (me/100 gms)	Exchangeable Iron (Fe) (me/100 gms)	Total Iron (Fe) (% as Fe ⁺²)
N. S. -1A	Mud Flat Sediment	34	6.4	14.	0.00	
N. S. -6A	Mud Flat Sediment	27	4.8	12.	0.00	
N. S. -9A	Mud Flat Sediment	13	2.8	5.7	0.00	
N. S. -19A	Mud Flat Sediment	-	-	-	-	4.7
N. S. -51A	Outwash Sediment	0.5	0.5	0.56	0.00	
N. S. -52A	Outwash Sediment	2	0.4	1.3	0.00	
NorS-1	Ice-contact Sediment	20	1.2	12.	0.00	4.4
NorS-2	Ice-contact Sediment	6	0.8	2.1	0.00	
NorS-3	Ice-contact Sediment	2	0.5	1.2	0.00	
S. H. -1	Litter	-	-	100.	0.09	0.77
C. -1	<u>Carex sp.</u> leaves	-	-	47.	0.03	0.11
C. -1A	<u>Carex sp.</u> roots	-	-	39.	0.00	0.87

suggests some iron is transported to the tide flat by Taku Inlet water. The low correlation coefficient of the Fe_T concentration equation for tide flat ground water (Table 12) indicates there is no significant relationship between iron and chlorinity in the ground water. This lack of correlation plus the large variation in Fe_T concentrations (Fig. 17) suggest the influence of one or more other processes. For this reason iron is treated in more detail in a separate section.

Based on two analyses, the Na+K and Ca+Mg concentrations of Taku Inlet surface water and Taku River water are quite similar. Much of the inlet surface water may therefore be derived from Taku River. The contribution of Norris Glacier meltwater could be relatively small.

Characteristics of the sediments

Sediment data are presented in Table 13. Mud flat samples N. S. -1A, 6A, and 9A constitute a traverse across the flat (Fig. 14). Both clay and organic matter content increase toward the high tide line. Increase in clay is apparently due to the progressive decrease in depositional energy of the tidal water as it moves across the flat. The higher organic content is due to the greater abundance of marsh grass toward the upper tide flat. Apparently the grass has a low tolerance for the saline environment. Of particular interest is the increase in CEC toward the high tide line (Table 13). The CEC of a sediment is a function of clay (Hathaway and Carroll, 1955) and organic matter (Schnitzer, 1965) contents, and these apparently control the CEC of the tide flat muds. It is not known which of the two plays the dominant role. The important point is that the relative distance the tidal waters move up the tide flat (relative influence of the marine environment) controls the physical properties of the sediments. These in turn control CEC. Similarly, CEC of ice-contact and outwash sediment appears to be related to clay and/or organic matter content (Table 13).

Iron in the system

Major iron accumulations occur in the bog and in the upper, more

quiescent reaches of Stream V (Fig. 14). Emission and X-ray spectrographic analyses indicated iron was the only major element present in the sample and X-ray diffraction and electron microscopy analyses indicated a non-crystalline structure. Individual particles were usually less than a micron in size. The precipitate therefore is considered to be $\text{Fe}(\text{OH})_3$.

Most ground and surface waters have rather high Fe_T concentrations (Fig. 17 and Table 12). These high concentrations are somewhat anomalous because Eh and pH of these waters fall within Hem and Cropper's (1959) ferric hydroxide stability field. Because of the high concentrations and the large variation in Fe_T content of tide flat ground water, the distribution of iron cannot simply be explained by one process operative in the entire meltwater system. Iron in water systems is found in many forms, such as Fe^{+2} , particulate $\text{Fe}(\text{OH})_3$, and iron-organic complexes (Fe-R). The mobilization, transport, and accumulation of iron in any of these forms is a function of the nature of the environment and the physical, chemical, and biological processes that are operative. Since numerous distinct environments occur in the Norris Glacier area, the behavior of iron is best explained on an environmental basis. Close examination of the data revealed apparent contradictions when relating water and sediment characteristics with the distribution of iron if the entire area were considered as one environment. These contradictions were resolved, however, by considering each environment separately.

Iron in Norris Glacier ice and the subglacial stream. As ice contains no iron (Fig. 17 and Table 12), it would at first appear that iron in the subglacial stream is derived from suspended sediment dissolution. Because of the high Eh and pH, iron would be transported as colloidal or larger-sized particles. The sample of subglacial stream water collected in 1967 was not filtered. Water samples collected in July, 1969, which were filtered immediately upon collection, were also analyzed for Fe_T . The 1967 samples contains 5.5 ppm Fe_T (Table 12). No iron is present in the 1969 filtered samples, and after 120 days none was dissolved from the suspended sediment (Table 14). To insure that the lack of iron dissolution during 120 days was not a result of prior removal of all the readily available iron from the suspended sediment, samples of iron-free Norris Glacier ice were mixed with superglacial sediment and allowed to stand for several

Table 14. Iron and suspended sediment concentrations of superglacial stream water collected in 1969. See Chapter IV for more detailed sample descriptions.

Sample No.	No. of Days before Filtration	Iron (Fe) (ppm)	Sediment Concentration (ppm)
NorWF-1	0	0.00	1,471±191
NorWU-1	62	0.00	1,358±177
NorWF-2	0	0.00	1,431±186
NorWU-2A	15	0.00	1,400±182
NorWU-2B	30	0.00	1,464±191
NorWU-2C	60	0.00	1,305±170
NorWU-2D	90	0.00	1,503±196
NorWU-2E	120	0.00	1,709±222
NorWF-3	0	0.00	1,391±181
NorWU-3	60	0.00	1,382±180
NorIF-1	0	0.00	-
NorIU-1	22	0.00	2,518±327
NorIF-2	0	0.00	-
NorIU-2	22	0.00	2,178±283
NorIF-3	0	0.00	-
NorIU-3	23	0.00	3,926±510

Nor = Norris Glacier.

F = Samples filtered at time of collection.

U = Samples not filtered for several days.

W = Water sample.

I = Ice sample

± Values are for two standard deviations.

days before filtration. Again, no iron was detected (Table 14). Assuming the conditions in the subglacial stream were similar in 1967 and 1969, these data indicate that (1) iron is not derived from suspended sediment dissolution and (2) the iron present in the subglacial stream is in a particulate form, and (3) particles were large enough to be retained on the filter paper.

Bedrock and superglacial sediment are rich in biotite which is undergoing vermiculitization. Grain surfaces are golden-yellow, have a scaly texture, exhibit considerable relief in the form of undulations and humps, and contain numerous cracks along which granular coatings of orange iron oxide are concentrated. Vermiculitization of biotite involves, among other things, oxidation of Fe^{+2} and subsequent migration of Fe^{+3} from the lattice (Walker, 1949). It seems in the present case much of the oxidized iron becomes concentrated near the most easily accessible exits, i. e. cracks in the grains. The granular iron-oxide coatings probably provide the most likely source of iron to the subglacial stream. Iron oxide particule disaggregation and subsequent transport are physical rather than chemical processes. In the high energy subglacial environment, these particles would be easily disengaged and subsequently transported by the subglacial stream. No further addition of iron to the water by suspended sediment dissolution would occur during transport.

Iron in the meltwater lake. The mean Fe_T concentration in the lake water is 0.7 ppm (Table 12). Some of the iron is probably transported to the meltwater lake by partial mixing with the subglacial stream. Some may also be derived by disaggregation of iron-oxide coatings from biotite grains in sediments near the lake. The iron would be subsequently transported to the lake by meltwater. The high Eh and pH of the lake water suggests iron is in a particulate form. Because the lake is relatively quiescent and the iron content low, it could remain in suspension for a long time.

Iron in outwash ground water. Iron is less abundant in outwash ground water than in subglacial stream water (Fig. 17 and Table 12). The high Eh and pH of the ground water and presence of iron staining near the water table suggest the loss of iron is due to precipitation.

All outwash ground water samples were clear when collected. A flocculent

orange precipitate soon formed in the sample bottle, however, indicating iron was in the dissolved, rather than the particulate, state, either as Fe^{+2} or Fe-R. Fe^{+2} is favored for several reasons. When in sufficient quantities, organic acids impart a brownish-yellow color to water. This color was not observed in outwash ground water. Hem (1960c) has found that appreciable quantities of tannic acid must be present for much Fe^{+2} complexing to occur and that this situation is analogous to the behavior of iron in water containing other organic acids. Iron-organic complexes are much more stable than Fe^{+2} , therefore they should remain in solution for longer periods of time than was observed.

Attempts were made in the field to determine the Fe^{+2} concentration of outwash ground water, as well as water from other environments, using Lee and Stumm's (1960) method. Although high Fe^{+2} concentrations were indicated, the results were not considered valid due to possible analytical errors in the technique. These errors are discussed by Shapiro (1966) and McMahon (1967).

High Eh, pH and Fe^{+2} are essentially incompatible under equilibrium conditions, however, in natural systems, iron is not usually in equilibrium with ground water (Hem and Cropper, 1959). Non-equilibrium conditions appear to prevail in the Norris Glacier outwash ground water.

The presence of Fe^{+2} in outwash ground water seems to contradict the assumption that iron is supplied to this water in a particulate form. The oxidation potential of ground water, however, usually decreases with depth due to lack of oxygen (Hem, 1960b). Particulate iron transported to the ground water system therefore probably would be reduced to Fe^{+2} at depth if reducing conditions prevailed.

The presence of iron staining at the outwash ground water table indicates some Fe^{+2} is oxidized and subsequently precipitated here as $\text{Fe}(\text{OH})_3$ as the ion travels through the outwash. Progressive oxidation and precipitation probably accounts for the higher Fe_T content of sample 58 (Fig. 17 and Appendix D) which is outwash ground water nearest the ice front (Fig. 14).

Aside from horizontal movement of iron through the outwash ground water, precipitation near the water table could result in the establishment of a concentration gradient. Fe^{+2} could therefore continually migrate upward where it is oxidized and precipitated at the water table.

Outwash sediment contains no Fe_E , however, some is present in the spruce-

hemlock litter (Table 13) which suggests some iron may be mobilized from the litter during decomposition. Since the forest is within the confines of the outwash fan, iron mobilized in this area could migrate downward to the outwash ground water. A pit dug to the water table in this area revealed downward-penetrating stringers of iron stain, which indicates this is the case. Among the products of plant decomposition are organic acids which are capable of mobilizing iron and transporting it as Fe-R (DeLong and Schnitzer, 1955a, 1955b; Bloomfield, 1952; Weinstein and others, 1954). Iron in plants may be made available through decomposition (Oborn, 1960). The Fe_T content of the spruce-hemlock litter is considered relatively high (Table 13) (K. VanCleve, personal communication, 1970) for plant material. Upon decomposition, appreciable quantities of iron are probably mobilized and transported to the outwash ground water as Fe-R. The transporting medium in this case would be percolating rain water, thus the amount of Fe-R reaching the water table would vary as a function of rainfall.

Iron in tide flat surface water and Taku Inlet surface water. The presence of Fe_T (0.1 ppm) in only one of ten non-saline tide flat surface water samples (Appendix D) and the intercept value for the tidal surface water Fe_T equation (Table 12) indicate iron has been oxidized and precipitated from outwash ground water by the time, or immediately after, the water becomes exposed as surface flow. Precipitation is supported by the presence of iron staining in the stream beds. The linear relation between Fe_T and Cl, however, suggests transport of iron from inlet waters to the tide flat. The high Eh and pH suggest this iron would be in a particulate form. Similar Fe_T concentrations in Taku Inlet surface water and Taku River water (Table 12) suggest the river is the major source of iron to the inlet, even though some would undoubtedly be derived from the Norris Glacier subglacial stream. The iron deposit in the upper reaches of Stream V (Fig. 14) probably is at least in part due to physical transport of particulate iron upstream on the flood tide and subsequent deposition. Deposition may be enhanced by the coagulating effect of seawater (Oborn and Hem, 1961). The proximity of the bog to the upper reaches of Stream V suggests some of the iron deposit is also derived from the bog.

Iron in tide flat ground water and bog water. The relatively high Fe_T concentrations but lack of correlation between Cl and Fe_T in tide flat ground water (Fig. 17 and Table 12) suggest the presence of a more complex mechanism(s). Some of the iron is undoubtedly Fe^{+2} and Fe-R derived from outwash ground water and some may be particulate iron from Taku Inlet water.

Although Eh and pH of tide flat ground water are high, a reducing environment appears to prevail within the muddy tide flat. Evidence for a reducing environment is abundant decaying vegetation, lack of iron staining, emission of an H_2S odor, and the presence of a black coloration imparted to the mud, particularly surrounding pieces of decaying vegetation. This coloration is generally attributed to the reaction of dissolved iron with H_2S produced during anaerobic plant decay by sulphate-reducing bacteria (Berner, 1967). These observations suggest in situ mobilization in the muddy tide flat is another source of iron. The Fe_T content of surface water flowing into the bog was not determined, however bog water and water draining the bog contain appreciable Fe_T (water samples 6 and 5, Appendix D). The upper reaches of Streams I, II, and III contain no iron, therefore it may be assumed that no iron is contributed to the bog from the upper half of Stream IV. The presence of iron in the bog as well as the accumulation of $Fe(OH)_3$ further indicate in situ mobilization.

Two possible iron sources in the muddy tide flat are mineral and organic matter. Tide flat mud contains more Fe_T than either the Carex sp. roots or leaves (Table 13). The two most abundant minerals in the clay-size fraction of these muds (the most potentially reactive fraction), are biotite and iron-rich chlorite (Slatt and Hoskin, 1968). Possible mobilization of iron during vermiculitization has already been discussed. Iron is mobilized during initial breakdown of clay-sized chlorite (Murray and Leininger, 1956). In addition, organic acids, which should be present here, are particularly effective in leaching iron from biotite (Boyle and others, 1967). Both these minerals probably are contributors of iron in the mud flat. The relatively high Fe_T content in Carex sp. roots as opposed to leaves (Table 13) is due to the capability of soil-rooted aquatic plants to store iron in their root systems (Oborn, 1960). The Fe_T content in both Carex sp. roots and leaves is lower than that of the tide flat mud (Table 13). The Fe_T content in the roots, however, is considered relatively high for plant material (K. VanCleve, personal communication, 1970). Although

minerals constitute the original source of iron for these plants, the observed active decay of this plant material probably provides a much more readily available and immediate source of iron in the mud flat.

The lack of Fe_E in the tide flat mud and Carex sp. roots, and only small amount in the leaves (Table 13) suggests iron is not made available through ion exchange during in situ mobilization. Release from plant material is direct and rapid.

The dispersion of iron in the mud flat ground water can best be described by considering the processes operative in the bog. Under the prevailing anaerobic conditions, iron probably is mobilized as Fe^{+2} or Fe-R.

Once mobilized, iron would first migrate to the pore water, then eventually reach the surface bog water or tide flat ground water. This might be accomplished by: (1) establishment of a concentration gradient and/or (2) periodic upward diffusion and drainage of pore water. The first situation is similar to one of the models presented by Berner (1969). Applying his description to the present situation, mobilized iron would be precipitated at the sediment-oxygenated bog water interface. Precipitation would lead to the establishment of a concentration gradient which would enhance continual upward diffusion of dissolved iron. This mechanism readily accounts for the observed accumulation of $Fe(OH)_3$ in the bog bottom. Furthermore, if any of the iron occurs as Fe-R, some might mix with the bog surface water. This would account for the Fe_T in the bog water. As the bog is above the normal high tide line, probably little, if any iron is contributed from saline tidal surface water.

The second mechanism could also account for the distribution of Fe_T in the ground water, as well as that in the bog water. In this instance, upward diffusion or drainage of iron-bearing pore water would be controlled by tidal action. On the flood tide a rise in the ground water table might enhance upward diffusion of interstitial water by capillary action, and during ebb tide a lowering of the water table would promote drainage to the ground water table. The anomalously low chlorinity of ground water near the bog (Fig. 16) suggests drainage does occur.

A thin bacterial film was observed on the surface of the bog water. Filamentous bacteria, similar in morphology to iron bacteria (Pringsheim, 1949) were also found associated with the iron deposit. Iron bacteria, which thrive

under the Eh and pH conditions observed in the bog water (Appendix D) (Baas Becking and others, 1960), are capable of accumulating relatively large quantities of $\text{Fe}(\text{OH})_3$ on their sheaths which accumulate on bog bottoms upon death of the organisms (Harder, 1919). Although there is some disagreement in the literature as to the precise role iron-bacteria play in iron transformations, it generally is believed they utilize energy during oxidation of Fe^{+2} or organic matter (Alexander, 1961). In this instance, they probably act: (1) as a catalyst (Hem, 1960b) in the oxidation of Fe^{+2} or the organic fraction of Fe-R, thus leaving the iron available for precipitation and/or (2) to accumulate $\text{Fe}(\text{OH})_3$ on their sheaths which subsequently is deposited in the bog. Rankama and Sahama (1950) attribute precipitation of bog iron to breakdown of Fe-R by bacterial action.

Mud flat sediment exhibits the same characteristics as mud in the bog. Reducing conditions apparently prevail, thus iron also presumably is mobilized. The lack of a depositional site however, accounts for the absence of large surficial accumulations. Any iron mobilized probably is transported to the ground or inlet water. Because the sand flat is well drained and lacks vegetation, aerobic conditions presumably prevail, and in situ iron mobilization probably does not occur.

To summarize, the distribution of iron in tide flat ground water is a result of in situ mobilization in the mud flat as well as transport from outwash ground water and perhaps Taku Inlet water. Accumulation of $\text{Fe}(\text{OH})_3$ in the bog is a result of its precipitation after migration and oxidation of Fe^{+2} or Fe-R from pore water. Precipitation may be aided by bacterial action.

The presence of iron staining at the water table indicates some iron in the tide flat ground water is precipitated, but this is expectable due to the high Eh and pH of the water. Precipitation could then result in the establishment of a concentration gradient in the water, similar to that described for outwash ground water. A concentration gradient might also promote upward migration of iron if conditions are suitable for iron mobilization at depth.

Summary of iron in the system. $\text{Fe}(\text{OH})_3$ is accumulating in the bog and in the upper reaches of a presently inactive distributary of the subglacial stream. The presence of this deposit and the complex distribution of iron in surface and ground water cannot be explained in terms of a single process operative in the

entire Norris Glacier area. Different physical, chemical, and biological processes are operative in the various environments. The behavior of iron in the Norris Glacier area can only be explained by studying these processes and environments individually.

Physical disaggregation of particulate iron from vermiculitized biotite and subsequent transportation accounts for the presence of iron in the subglacial stream and lake. Some of the iron in the upper reaches of the inactive distributary is due to physical deposition of particulate iron. Some of the deposited iron in this distributary is also derived from the bog.

Chemical processes account for iron in the outwash ground water. Here, particulate iron from glacial meltwater and iron in outwash sediment are dissolved and transported as Fe^{+2} . During progressive transport some Fe^{+2} is oxidized and precipitates at the water table. Precipitation might result in the establishment of a concentration gradient so that continual supply to the water from depth could be accomplished. In addition, during rainy periods, iron which has been mobilized from decomposing (presumably biological) spruce-hemlock litter may migrate as Fe-R to the outwash ground water.

Iron in outwash ground water eventually reaches the tide flat where some is oxidized and precipitated at the water table. Precipitation and deposition are apparently quite rapid when outwash ground water becomes exposed as surface streams, however, physical mixing with relatively iron-rich Taku Inlet water supplies iron to these streams.

Aside from iron transported to the tide flat ground water from outwash ground water, biochemical processes within the tide flat muds account for a further source of iron through in situ mobilization. Once mobilized, physical and/or chemical processes account for dispersion of the Fe^{+2} or Fe-R to the tide flat ground water or to the surface where it is chemically or biochemically oxidized and precipitated in the bog and flushed out from the rest of the mud flat during flood tide. Other chemical processes in the mud flat might further complicate the distribution of iron. Some iron is oxidized and precipitated at the water table, therefore any Fe^{+2} that is mobilized at depth could migrate upward through the establishment of a ground water concentration gradient. No iron is mobilized in the sand flat.

The sources of iron are both inorganic and organic material. As organic

matter decomposition generally proceeds at a faster rate than chemical weathering of minerals, the major immediate sources of iron in this water system, aside from iron in the original meltwater supply and iron in Taku River, are probably marsh grass and spruce-hemlock litter.

Conclusions

1. The tide flat is the zone of mixing of meltwater and saline Taku Inlet water. Chlorinity of water in the mud flat decreases progressively toward the meltwater source. Water in the upper reaches and further west of the tide flat is non-saline. Saline ground water is rapidly flushed out of the sand flat during ebb tide, but movement of ground water in the mud flat is probably slow.

2. There are no major changes in Eh and pH, and dissolved Na+K and Ca+Mg concentrations as meltwater flows from its source through the outwash. Upon mixing with saline inlet water in the tide flat, cation concentrations increase as a function of chlorinity (degree of mixing with saline water).

3. The relative distance Taku Inlet water moves up the tide flat controls the clay and organic matter contents of tide flat muds. These physical properties control cation exchange capacity of the sediments.

4. The behavior of iron in the Norris Glacier area cannot be explained on the basis of a single process or by assuming the entire area constitutes a single environment. The area consists of a number of distinct environments. Different physical, chemical, and biological processes are operative in these environments.

5. The research approach employed in the present study provided a satisfactory explanation for the behavior of iron in the Norris Glacier water system. It is suggested that this approach may be useful for determining the behavior of iron in other natural water systems.

CHAPTER VI

SUMMARY

Superglacial sediment from ten active Alaskan valley glaciers in five different types of bedrock terrane exhibit certain similar textural and mineralogical characteristics. Suspended sediments from different glacial streams also exhibit certain similar textural characteristics. General descriptions of superglacial sediment and suspended stream sediment have been presented based on these characteristics. The following geologically significant conclusions have been reached from grain-size distribution analyses of superglacial sediments and suspended stream sediments: (1) the environment of transport has a much greater effect on the grain-size characteristics of transported valley glacier sediment than does the source material (bedrock and unmodified sediments); (2) the concept of the presence in nature of three basic particle-size populations cannot be applied to valley glacier sediment because particles of all sizes are produced by the extraordinarily intense physical weathering process involved; (3) some outwash-like sediment may have been deposited during glacier recessions without the aid of glacial streams and some till-like deposits could result from mixing of proglacial sediments with more recently exposed, unmodified valley glacier sediments; the classical explanations for the origin of till and outwash should therefore be used cautiously when interpreting the origin of these types of deposits.

Different glacial meltwater streams exhibit certain similar characteristics. A general description of glacial meltwater has been presented based on these characteristics. Results of the present investigation indicate dissolved constituents in glacial meltwater are derived from dissolution of suspended stream sediment. Initial dissolution probably occurs soon after sediment comes in contact with meltwater. By the time meltwater emerges at a glacier's terminus its chemical composition has largely been established. Further dissolution is slow enough that the chemical composition is probably not altered along the typical course of these streams. Variations in the relative proportions

of dissolved constituents in different meltwater streams has been related to chemical and mineralogical variations in respective superglacial sediments. These relationships are a reflection of the ultimate bedrock control of meltwater chemistry.

The physio-chemical characteristics of the Norris Glacier meltwater system have been described. It has been determined that the degree of mixing of fresh glacial meltwater with saline Taku Inlet water largely controls the water's chemical composition. Some physical and chemical properties of tide flat sediments have been related to the relative influence of the marine environment.

The Norris Glacier area consists of several distinct environments. The behavior of iron in each environment is governed by various physical, chemical, and biological processes. The research approach employed in the present study provided a satisfactory explanation for the behavior of iron in the Norris Glacier water system. It is suggested that this approach may be useful for studying the behavior of iron in other natural water systems.

APPENDICES

Appendix A. Grain size data for superglacial sediment.

Sample No.	Weight %			Clay	Mean Size	Standard Deviation	Skewness	Kurtosis	Normalized Kurtosis	Textural Class
	Gravel	Sand	Mud							
WorS-2	84	10	6	2	-6.17	4.13	+0.95	1.11	0.53	G
"	52	29	19	7	-0.20	4.34	+0.41	0.95	0.49	msG
WorS-7	62	21	17	6	-1.99	5.28	+0.35	1.18	0.54	msG
"	42	32	26	9	0.71	4.64	+0.32	0.82	0.45	msG
WorS-9	59	24	17	6	-1.27	4.87	+0.31	1.80	0.64	msG
"	48	30	22	8	1.38	4.43	+0.38	0.91	0.48	msG
MatS-1	45	34	21	3	0.19	4.05	+0.13	0.72	0.42	msG
MatS-2	45	32	23	2	0.22	4.07	+0.12	0.68	0.41	msG
MatS-3	26	39	35	4	1.98	3.90	-0.20	0.80	0.45	gms
CasS-1	65	25	10	2	-1.97	4.18	+0.24	1.26	0.56	msG
"	56	31	13	2	-0.80	3.54	+0.36	0.84	0.46	msG
CasS-4	70	21	9	2	-2.97	4.59	+0.30	0.96	0.49	msG
"	53	32	15	3	-0.60	3.80	+0.34	0.78	0.44	msG
CasS-13	59	27	14	2	-1.01	3.73	+0.46	0.74	0.43	msG
FelS-1	77	16	7	1	-2.62	2.74	+0.51	1.34	0.57	msG
FelS-2	75	19	6	1	-2.47	2.76	+0.50	1.14	0.53	msG
FelS-3	72	19	9	1	-2.12	3.07	+0.53	1.23	0.55	msG
GulS-3	62	26	12	3	-1.23	3.45	+0.47	1.03	0.51	msG
GulS-4	59	28	13	4	-1.00	3.70	+0.47	1.02	0.50	msG
GulS-5	62	24	14	4	-1.16	3.81	+0.51	1.04	0.51	msG
ColS-2	69	19	12	2	-1.75	3.44	+0.58	1.04	0.51	msG
ColS-3	60	21	19	2	-0.90	4.11	+0.50	0.75	0.43	msG
ColS-4	71	20	9	1	-1.85	2.94	+0.54	1.16	0.54	msG
RenS-1	61	23	16	1	-2.06	4.68	+0.42	0.66	0.40	msG
"	38	37	25	2	0.39	3.95	+0.12	0.66	0.40	msG
RenS-4	60	32	8	2	-1.65	3.20	+0.36	0.89	0.47	msG
RenS-5	65	28	7	2	-2.04	3.10	+0.40	0.94	0.49	msG
ReiS-1	50	36	14	6	-0.47	3.54	+0.28	0.82	0.45	msG

Appendix A, cont. Grain size data for superglacial sediment.

Sample No.	Weight %					Mean Size	Standard Deviation	Skewness	Kurtosis	Normalized Kurtosis	Textural Class
	Gravel	Sand	Mud	Silt	Clay						
CarS-1	72	24	4	3	1	-3.06	3.56	+0.21	0.88	0.47	msG
* "	61	33	6	4	2	-0.56	2.88	+0.35	0.89	0.47	msG
NorS-1	37	30	33	17	16	1.66	5.55	+0.23	0.76	0.43	mG
NorS-2	26	49	25	19	6	1.34	3.97	+0.13	0.95	0.49	gmS
NorS-3	43	41	16	14	2	-0.05	3.78	+0.01	0.72	0.42	msG

*Re-calculated for the less than -5.25 phi fraction.

Sample designations are coded according to the first three letters of each glacier.

Appendix B. Grain size data for suspended stream sediment.

Sample No.	Weight %					Mean Size	Standard Deviation	Skewness	Kurtosis	Normalized Kurtosis	Textural Class	Stream Velocity (cms./sec.)
	Gravel	Sand	Mud	Silt	Clay							
WorS-3*	-	24	76	45	31	6.08	3.55	-0.11	1.13	0.53	sM	67
WorS-13**	1	3	97	34	63	8.87	2.31	+0.21	1.16	0.54	(g)M	94
MatS-4	-	39	61	45	16	5.01	2.88	+0.16	0.90	0.47	sM	116
CasS-2***	1	9	90	69	21	7.43	3.05	+0.21	1.56	0.61	(g)M	31
CasS-6	-	43	57	41	16	4.94	3.13	+0.29	1.17	0.54	sM	214
CasS-10	1	50	50	37	13	4.42	3.17	+0.29	1.12	0.53	(g)sM	180
FelS-4	3	31	66	49	17	5.18	3.40	-0.02	1.26	0.56	(g)sM	107
GulS-2	1	49	50	32	18	4.57	3.52	+0.28	0.94	0.49	(g)sM	183
ColS-1	1	46	53	41	12	4.39	2.88	+0.21	1.07	0.52	(g)sM	183
RenS-3	-	16	84	53	31	6.72	3.21	+0.01	1.54	0.61	sM	82
NorS-4	-	32	68	48	20	5.61	2.89	+0.39	1.09	0.52	sM	64

* = Subglacial stream sample

** = Composite stream sample downstream from lake

*** = Sample from meltwater flowing from base of ice-covered sediment mound

Sample designations are coded according to the first three letters of each glacier.

Appendix C. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms. /sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
<u>Location: Worthington Glacier - lake</u>														
WorWF-1	6-21-68 12 a. m.	-	-	7.7	0.58	2.0	-	152	1.1	0.35	8.0	0.52	0.61	11.
WorWF-3	6-21-68 3 p. m.	-	-	7.6	0.59	3.0	-	141	1.4	0.40	8.0	0.26	0.41	10.
WorWF-4	6-21-68 4 p. m.	-	-	7.7	0.59	2.0	-	130	0.69	0.40	8.0	0.26	0.47	11.
WorWF-5	6-21-68 5:30 p. m.	-	-	7.7	0.58	2.0	-	131	0.53	0.35	6.1	0.26	0.35	7.6
WorWF-6	6-21-68 6:15 p. m.	-	-	7.5	0.57	4.0	-	137	0.60	0.31	8.0	0.26	0.47	9.6
<u>Location: Worthington Glacier - outflow stream</u>														
WorWF-7	6-24-68 2:15 p. m.	-	34	7.3	0.54	2.0	-	142	0.69	0.35	8.0	0.26	0.75	10.
WorWU-7	6-24-68 2:15 p. m.	16	-	-	-	-	-	120	1.1	0.35	7.1	0.52	0.99	10.
WorWF-8	6-24-68 4:30 p. m.	-	68	7.6	0.54	2.0	-	126	0.53	0.27	8.0	0.26	0.61	9.7

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)						
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations	
	<u>Location: Worthington Glacier - outflow stream, cont.</u>														
WorWU-8	6-24-68 4:30 p. m.	16	-	-	-	-	-	112	1.2	0.31	8.0	0.52	0.89	11.	
WorWF-9	6-25-68 1:30 p. m.	-	79	7.7	0.53	2.0	-	143	0.53	0.31	8.0	0.26	0.21	9.3	
WorWU-9	6-25-68 1:30 p. m.	15	-	-	-	-	-	132	0.97	0.35	8.0	0.52	0.70	11.	
WorWF-10	6-25-68 4:30 a. m.	-	92	7.6	0.51	3.0	-	160	0.60	0.31	8.0	0.26	0.21	9.4	
WorWU-10	6-25-68 4:30 a. m.	15	-	-	-	-	-	146	0.97	0.40	8.8	0.52	0.99	12.	
WorWF-11	6-25-68 7:45 p. m.	-	101	7.6	0.53	2.0	-	134	0.62	0.35	8.0	0.26	0.47	9.7	
WorWU-11	6-25-68 7:45 p. m.	15	-	-	-	-	-	154	0.84	0.31	8.8	0.52	0.85	11.	
WorWF-12	6-25-68 1 p. m.	-	101	7.7	0.52	3.0	-	149	0.53	0.31	8.8	0.52	0.21	10.	
WorWU-12	6-25-68 1 p. m.	14	-	-	-	-	-	153	1.2	0.35	8.0	0.52	0.75	11.	

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature ($^{\circ}$ C)	Specific Conductance (micromhos at 25 $^{\circ}$ C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentration (ppm)						
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations	
Location: Worthington Glacier - outflow stream, cont.															
WorWF-13	6-26-68 5 p. m.	-	92	7.5	0.54	3.0	-	-	0.53	0.27	8.0	0.52	0.28	9.6	
WorWU-13	6-26-68 5 p. m.	14	-	-	-	-	-	134	1.1	0.35	8.0	0.52	1.1	11.	
WorWF-14	6-28-68 11:15 a. m.	-	85	7.4	0.52	3.0	-	191	0.57	0.27	7.1	0.26	0.28	8.5	
WorWU-14	6-28-68 11:15 a. m.	12	-	-	-	-	-	191	0.97	0.31	8.0	0.52	0.99	11.	
WorWF-17A	6-28-68 6 p. m.	-	101	7.5	0.56	3.0	-	189	0.62	0.27	8.0	0.26	0.21	9.4	
WorWU-17A	6-28-68 6 p. m.	12	-	-	-	-	-	163	1.1	0.31	7.1	0.52	0.89	9.9	
WorWF-17B	6-29-68 12 p. m.	-	101	7.6	0.55	1.0	-	227	0.84	0.31	7.1	0.26	0.41	8.9	
WorWU-17B	6-29-68 12 p. m.	11	-	-	-	-	-	218	1.3	0.35	7.1	0.52	0.89	10.	
WorWF-17C	6-29-68 11 a. m.	-	128	7.6	0.52	2.0	-	195	0.40	0.19	6.1	0.26	0.21	7.2	
WorWU-17C	6-29-68 11 a. m.	11	-	-	-	-	-	183	0.97	0.31	7.1	0.26	0.80	9.4	

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature ($^{\circ}$ C)	Specific Conductance (micromhos at 25 $^{\circ}$ C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentration (ppm)						
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations	
Location: Worthington Glacier - outflow stream, cont.															
WorWF-17D	6-29-68 5 p. m.	-	128	7.7	0.51	3.0	-	235	0.35	0.23	6.1	0.26	0.35	7.3	
WorWU-17D	6-29-68 5 p. m.	11	-	-	-	-	-	198	0.77	0.27	6.1	0.26	0.56	8.0	
WorWF-21	8-16-68 6 p. m.	-	151	7.5	0.50	2.0	-	80	0.20	0.13	4.2	0.30	0.00	4.8	
WorWU-21	8-16-68 6 p. m.	41	-	-	-	-	23	148	0.88	0.27	4.6	0.30	0.07	6.1	
WorWF-22	8-17-68 6 p. m.	-	151	7.5	0.46	3.8	-	114	0.35	0.13	4.6	0.30	0.00	5.4	
WorWF-23	8-18-68 5:30 p. m.	-	151	7.5	0.50	2.7	-	139	0.29	0.13	4.6	0.30	0.00	5.3	
WorWF-24	8-21-68 3:30 p. m.	-	151	7.7	0.50	2.6	-	144	0.09	0.09	4.6	0.30	0.26	5.3	
WorWF-25	8-23-68 6 p. m.	-	151	7.5	0.50	2.2	-	98	0.11	0.04	5.0	0.30	0.13	5.6	
WorWU-25	8-23-68 6 p. m.	34	-	-	-	-	-	127	0.51	0.18	5.0	0.30	0.13	6.1	

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	Ph	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentration (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
<u>Location: Worthington Glacier - outflow stream, cont.</u>														
WorWF-26	8-25-68 6 p. m.	-	151	7.7	0.48	3.0	-	122	0.15	0.09	5.0	0.30	0.00	5.5
WorWU-26	8-25-68 6 p. m.	32	-	-	-	-	-	165	1.2	0.22	5.4	0.30	0.20	7.3
<u>Location: Worthington Glacier - subglacial stream</u>														
WorWF-27	8-26-68 9:30 a. m.	-	68	8.2	0.42	1.0	-	880	0.57	0.36	7.7	0.30	0.33	9.3
<u>Location: Worthington Glacier - lake</u>														
WorWF-29	8-26-68 12 a. m.	-	-	7.3	0.49	3.2	-	106	0.09	0.09	5.0	0.30	0.13	5.6
<u>Location: Worthington Glacier - outflow stream</u>														
WorWF-30	8-26-68 5 p. m.	-	125	7.4	0.45	2.1	-	116	0.09	0.13	5.0	0.30	0.06	6.1
WorWF-31	8-28-69 12:30 p. m.	-	82	7.7	0.51	2.8	-	100	0.16	0.16	5.5	0.42	0.18	6.4
WorWU-31	8-28-69 12:30 p. m.	23	-	-	-	-	39	96	0.16	0.16	4.8	0.25	0.23	5.6

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
<u>Location: Worthington Glacier - outflow stream, cont.</u>														
WorWF-32	8-28-69 12:30 p. m.	-	82	7.4	0.51	2.8	-	92	0.14	0.14	5.0	0.25	0.23	5.8
WorWU-32	8-28-69 12:30 p. m.	48	-	-	-	-	35	99	0.13	0.16	4.9	0.42	0.33	5.9
WorWF-33	8-28-69 12:30 p. m.	-	82	7.4	0.51	2.8	-	110	0.13	0.16	5.8	0.48	0.33	6.9
WorWU-33	8-28-69 12:30 p. m.	48	-	-	-	-	33	101	0.16	0.22	5.1	0.59	1.2	7.3
<u>Location: Matanuska Glacier - stream</u>														
MatWF-1	6-10-69 3 p. m.	-	116	9.0	-	1.0	-	5,142	1.5	0.39	8.9	0.65	1.6	13.
MatWU-1	6-10-69 3 p. m.	49	-	-	-	-	109	4,559	1.3	0.77	17.	0.83	1.2	21.
MatWF-2	6-11-69 11 a. m.	-	-	8.6	-	1.0	-	2,415	1.3	0.40	10.	0.76	1.3	14.
MatWU-2A	6-11-69 11 a. m.	15	-	-	-	-	70	2,590	1.2	0.54	17.	1.0	1.4	21.

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms. /sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
<u>Location: Matanuska Glacier - stream, cont.</u>														
MatWU-2B	6-11-69 11 a. m.	30	-	-	-	-	70	2,360	1.1	0.50	17.	0.97	1.1	21.
MatWU-2C	6-11-69 11 a. m.	60	-	-	-	-	114	2,402	1.1	0.54	21.	1.0	1.2	25.
MatWU-2D	6-11-69 11 a. m.	90	-	-	-	-	141	2,378	1.1	0.57	23.	1.1	1.2	27.
MatWU-2E	6-11-69 11 a. m.	120	-	-	-	-	122	2,188	1.2	0.58	24.	1.6	2.2	30.
MatWF-4	6-11-69 3 p. m.	-	-	8.7	-	2.0	-	3,883	1.2	0.39	8.2	0.55	0.94	11.
MatWU-4	6-11-69 3 p. m.	48	-	-	-	-	79	3,574	1.3	0.43	17.	0.90	0.99	21.
<u>Location: Castner Glacier - stream</u>														
CasWF-1	7-30-68 8 p. m.	-	-	8.4	0.43	0.5	-	2,221	0.93	0.65	15.	3.8	0.28	21.
CasWU-1	7-30-68 8 p. m.	12	-	-	-	-	182	2,441	0.93	0.90	24.	4.2	0.99	31.

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)										
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations					
Location: Castner Glacier - stream, cont.																			
CasWF-2	7-31-68 5:30 p. m.	-	-	8.6	0.44	0.5	-	2,021	1.3	0.65	16.	4.4	0.52	23.					
CasWF-3	8-1-68 8 p. m.	-	156	8.7	0.44	0.2	-	2,292	2.1	0.78	13.	3.5	0.47	20.					
CasWF-4	8-2-68 5:30 p. m.	-	189	8.7	0.44	1.5	-	1,972	3.5	0.99	16.	4.3	0.41	25.					
CasWU-4	8-2-68 5:30 p. m.	9	-	-	-	-	162	2,278	1.4	0.71	17.	4.3	1.3	25.					
CasWF-6	8-4-68 6 p. m.	-	183	9.0	0.42	1.0	-	3,182	2.9	1.2	13.	3.1	0.35	21.					
CasWF-7	8-6-68 7 p. m.	-	214	9.0	0.42	1.5	-	5,530	1.7	1.1	14.	3.0	0.52	20.					
CasWF-8	8-7-68 5:30 p. m.	-	223	8.8	0.43	1.2	-	7,445	3.5	1.2	15.	3.5	0.56	24.					
CasWF-9	8-8-68 7:30 p. m.	-	262	9.0	0.43	0.6	-	5,455	3.5	1.1	15.	3.5	0.40	24.					
CasWF-10A	8-9-68 9 a. m.	-	214	8.4	0.45	1.0	-	3,750	4.0	1.3	22.	5.8	0.56	34.					

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
Location: Castner Glacier - stream, cont.														
CasWU-10A	8-9-68 9 a. m.	2	-	-	-	-	214	3,035	4.0	1.5	23.	5.8	1.3	36.
CasWF-10B	8-9-68 4 p. m.	-	180	8.9	0.43	0.8	-	4,120	2.0	0.90	15.	3.6	0.41	22.
CasWF-11	8-27-68 11 a. m.	-	143	8.3	0.43	1.0	-	1,086	3.5	1.2	25.	7.8	0.52	38.
CasWU-11	8-27-68 11 a. m.	30	-	-	-	-	238	1,058	3.5	1.2	25.	7.8	0.70	38.
CasWF-20	6-15-69 1 p. m.	-	-	8.6	-	1.0	-	2,157	1.2	1.1	20.	5.2	0.75	28.
CasWU-20A	6-15-69 1 p. m.	15	-	-	-	-	155	2,451	1.4	1.2	21.	6.0	0.94	31.
CasWU-20B	6-15-69 1 p. m.	30	-	-	-	-	154	2,167	1.2	1.3	23.	6.0	0.94	32.
CasWU-20C	6-15-69 1 p. m.	60	-	-	-	-	162	2,147	1.2	1.2	24.	6.5	0.94	34.
CasWU-20D	6-15-69 1 p. m.	90	-	-	-	-	158	2,362	1.2	1.2	25.	6.4	0.94	35.

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
Location: Castner Glacier - stream, cont.														
CasWU-20E	6-15-69 1 p. m.	120	-	-	-	-	186	2,136	1.2	26.	6.9	1.3	37.	
CasWF-21	6-15-69 6 p. m.	-	-	8.6	-	1.0	-	2,891	1.0	18.	4.5	0.61	25.	
CasWU-21	6-15-69 6 p. m.	43	-	-	-	-	144	3,094	1.0	22.	5.5	0.75	30.	
CasWF-22	8-22-69 9:30 a. m.	-	98	8.2	0.49	1.0	-	306	3.7	36.	15.	0.94	57.	
CasWU-22	8-22-69 9:30 a. m.	39	-	-	-	-	316	241	3.7	36.	15.	1.4	58.	
CasWF-23	8-22-69 9:30 a. m.	-	98	8.0	0.49	1.0	-	267	3.7	37.	15.	1.2	58.	
CasWU-23	8-22-69 9:30 a. m.	39	-	-	-	-	308	230	3.7	38.	15.	1.8	60.	
CasWF-24	8-22-69 9:30 a. m.	-	98	8.0	0.49	1.0	-	237	3.8	37.	15.	0.94	58.	
CasWU-24	8-22-69 9:30 a. m.	39	-	-	-	-	310	205	3.7	36.	16.	1.8	59.	

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms. /sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
<u>Location: Fels Glacier - stream</u>														
FelWF-1	6-23-69 11 a. m.	-	104	8.3	-	2.0	-	9,898	1.4	2.5	24.	6.6	1.0	36.
FelWU-1	6-23-69 11 a. m.	37	-	-	-	-	211	10,894	1.4	2.7	31.	8.3	2.0	45.
FelWF-2	6-23-69 11 a. m.	-	104	8.3	-	2.0	-	9,992	1.5	2.4	23.	6.5	1.1	35.
FelWU-2	6-23-69 11 a. m.	37	-	-	-	-	217	9,840	1.4	2.8	32.	8.0	1.6	46.
FelWF-3	6-23-69 11 a. m.	-	104	8.4	-	2.0	-	9,598	1.7	2.4	27.	6.6	1.0	39.
FelWU-3	6-23-69 11 a. m.	38	-	-	-	-	220	11,445	1.5	2.7	29.	8.4	1.5	43.
<u>Location: Gulkana Glacier - stream</u>														
GulWF-1	6-19-69 4:30 p. m.	-	183	8.4	-	2.0	-	1,547	0.47	0.39	7.8	0.50	0.99	10.
GulWU-1	6-19-69 4:30 p. m.	40	-	-	-	-	44	1,396	0.47	0.68	10.	0.70	0.85	13.

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature ($^{\circ}$ C)	Specific Conductance (micromhos at 25 $^{\circ}$ C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)						
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations	
<u>Location: Gulkana Glacier - stream, cont.</u>															
Gu1WF-2	6-20-69 1 p. m.	-	-	9.3	-	1.5	-	1,642	0.50	0.40	7.9	0.76	0.94	11.	
Gu1WU-2	6-20-69 1 p. m.	40	-	-	-	-	63	1,695	0.50	0.73	11.	0.72	0.94	14.	
Gu1WF-3	6-20-69 1 p. m.	-	-	9.1	-	1.5	-	1,810	0.66	0.39	8.4	0.87	0.89	11.	
Gu1WU-3	6-20-69 1 p. m.	40	-	-	-	-	66	1,679	0.61	0.73	11.	0.72	1.1	14.	
<u>Location: College Glacier - stream</u>															
Co1WF-1	6-20-69 1 p. m.	-	183	8.8	-	3.0	-	4,758	1.5	1.3	14.	1.4	0.94	19.	
Co1WU-1	6-20-69 1 p. m.	39	-	-	-	-	96	5,388	1.4	2.4	16.	1.3	1.3	22.	
Co1WF-2	6-20-69 1 p. m.	-	183	8.9	-	3.0	-	5,118	1.1	1.3	14.	1.4	1.0	19.	
Co1WU-2	6-20-69 1 p. m.	40	-	-	-	-	101	4,839	1.1	2.3	17.	1.4	1.3	23.	

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
<u>Location: College Glacier - stream, cont.</u>														
Co1WF-3	6-20-69 1 p. m.	-	183	8.9	-	3.0	-	5,089	1.5	1.4	13.	1.4	1.0	18.
Co1WU-3	6-20-69 1 p. m.	41	-	-	-	-	87	5,046	1.2	2.4	17.	1.6	1.4	24.
<u>Location: Rendu Glacier - stream</u>														
RenWF-2	9-10-69 3:30 p. m.	-	-	-	-	1.0	-	7,784	1.3	0.81	9.3	0.83	0.80	13.
RenWU-2	9-10-69 3:30 p. m.	45	-	-	-	-	77	8,014	1.5	1.3	14.	1.2	2.7	21.
RenWF-3	9-10-69 3:30 p. m.	-	-	-	-	1.0	-	7,541	1.3	0.78	9.4	0.75	0.80	13.
RenWU-3	9-10-69 3:30 p. m.	45	-	-	-	-	87	7,940	1.5	1.3	13.	0.96	2.6	19.
RenWF-4	9-10-69 3:30 p. m.	-	-	-	-	1.0	-	7,289	1.3	0.88	11.	0.72	0.94	15.
RenWU-4	9-10-69 3:30 p. m.	46	-	-	-	-	95	7,484	1.5	1.3	14.	1.0	2.8	21.

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Total Five Cations
<u>Location: Carroll Glacier - stream</u>														
CarWF-2	9-10-69 8:30 a. m.	-	-	-	-	0.5	-	14,504	1.8	1.1	9.1	1.5	0.85	14.
CarWU-2	9-10-69 8:30 a. m.	38	-	-	-	-	116	11,988	2.2	2.3	15.	2.1	3.0	25.
CarWF-3	9-10-69 8:30 a. m.	-	-	-	-	0.5	-	12,182	1.7	1.2	8.9	1.3	0.94	14.
CarWU-3	9-10-69 8:30 a. m.	38	-	-	-	-	99	13,363	2.0	2.3	18.	2.5	3.0	28.
CarWF-4	9-10-69 8:30 a. m.	-	-	-	-	0.5	-	11,722	1.8	1.2	9.5	1.5	0.94	15.
CarWU-4	9-10-69 8:30 a. m.	38	-	-	-	-	117	12,859	2.1	2.3	14.	1.9	2.7	23.
<u>Location: Norris Glacier - stream</u>														
NorWF-1	7-18-69 12 a. m.	-	64	9.5	0.44	1.0	-	1,471	2.4	0.54	4.4	0.60	0.75	8.7
NorWU-1	7-18-69 12 a. m.	62	-	-	-	-	70	1,358	2.5	1.7	9.5	1.2	1.2	16.

Appendix C, cont. Physio-chemical data for glacial meltwater.

Sample No.	Collection Time and Date	No. of Days before Filtration	Stream Velocity (cms./sec.)	pH	Eh (+ volts)	Temperature (°C)	Specific Conductance (micromhos at 25°C)	Suspended Sediment Concentration (ppm)	Dissolved Cation Concentrations (ppm)					Total Five Cations
									Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	
Location: Norris Glacier - stream, cont.														
NorWF-2	7-18-69 12 a. m.	-	64	9.3	0.44	1.0	-	1,431	2.4	0.65	5.7	0.71	0.52	10.
NorWU-2A	7-18-69 12 a. m.	15	-	-	-	-	38	1,400	2.0	0.94	8.4	0.67	0.85	13.
NorWU-2B	7-18-69 12 a. m.	30	-	-	-	-	50	1,464	2.5	1.6	9.6	1.2	1.6	17.
NorWU-2C	7-18-69 12 a. m.	60	-	-	-	-	86	1,305	2.6	1.7	10.	1.3	1.6	18.
NorWU-2D	7-18-69 12 a. m.	90	-	-	-	-	85	1,503	2.4	1.9	9.7	1.4	1.4	17.
NorWU-2E	7-18-69 12 a. m.	120	-	-	-	-	86	1,709	2.4	1.9	10.	1.2	2.1	18.
NorWF-3	7-18-69 12 a. m.	-	64	9.3	0.44	1.0	-	1,391	2.5	0.72	8.5	0.44	0.52	13.
NorWU-3	7-18-69 12 a. m.	60	-	-	-	-	80	1,382	2.5	1.8	10.	1.6	1.1	17.

F = Samples filtered at the time of collection. U = samples not filtered until several days after collection. Sample designations are coded according to the first three letters of each glacier.

Appendix D. Physio-chemical data for water and ice in the Norris Glacier area. Samples collected in 1967.

Sample No.	Stream No.	pH	Eh (+ volts)	Temperature (°C)	Chlorinity (0/00)	Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Iron (Fe)	Total Major Cations
3	V	7.5	0.46	19.	0.24	250.	6.7	4.2	4.6	0.2	270.
4	V	7.8	0.44	19.	0.33	320.	7.8	6.8	9.2	0.4	340.
5	IV	7.3	0.48	22.	0.05	54.	1.7	3.0	2.4	1.1	61.
7	V	8.2	0.43	25.	0.38	300.	9.2	9.4	11.8	1.2	330.
8	V	7.2	0.40	20.	0.41	340.	12.	5.4	12.6	0.2	370.
9	V	6.6	0.37	15.	0.82	570.	16.	24.	44.	1.2	650.
10	V	7.4	0.45	21.	0.71	600.	17.	18.	36.	1.2	670.
11	V	7.1	0.45	19.	0.72	560.	16.	17.	34.	1.7	620.
12	V	7.1	0.47	14.	0.53	370.	11.	12.	23.	1.4	420.
13	III	7.4	0.52	8.	0.00	9.7	1.3	4.2	0.2	0.1	15.
14	III	7.2	0.49	10.	0.00	4.0	0.9	4.2	0.0	0.0	9.1
15	III	6.9	0.44	11.	0.00	18.	1.0	4.2	0.2	0.1	24.
16	III	7.1	0.44	14.	0.00	13.	1.8	4.2	0.2	0.0	20.
17	II	7.0	0.49	9.	0.34	250.	7.2	9.4	32.	0.0	300.
18	II	7.1	0.47	8.	0.05	28.	1.5	5.4	0.2	0.0	35.
19	II	7.2	0.46	8.	0.00	8.6	1.3	4.2	0.0	0.0	14.
20	I	7.7	0.48	11.	0.00	8.6	1.3	4.2	0.0	0.0	14.
21	I	7.5	0.48	11.	0.00	4.9	1.0	4.2	0.0	0.0	10.
22	I	7.4	0.47	11.	0.00	8.6	1.6	4.2	0.0	0.0	14.

Water Type: Tide Flat Surface Water

Appendix D, cont. Physio-chemical data for water and ice in the Norris Glacier area. Samples collected in 1967.

Sample No.	Stream No.	pH	Eh (+ volts)	Temperature (°C)	Chlorinity (0/00)	Cation Concentrations (ppm)					Total Major Cations
						Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Iron (Fe)	
<u>Water Type: Tide Flat Surface Water, Cont.</u>											
23	I	7.1	0.46	12.	0.30	220.	6.0	9.4	12.	0.2	250.
61	III	-	-	-	0.00	2.7	0.3	5.2	0.0	0.0	8.2
68	I	-	-	-	0.00	4.2	0.6	4.2	0.0	0.0	9.0
<u>Water Type: Tide Flat Ground Water</u>											
24		6.8	0.38	7.5	0.21	150.	6.7	5.4	8.2	20.	20.
25		7.1	0.33	6.0	0.09	120.	4.7	3.0	4.0	16.	130.
26		6.2	0.48	9.0	1.0	1,000.	30.	6.8	24.	0.0	1,100.
27		6.4	0.27	8.8	0.44	410.	17.	5.4	10.	7.2	440.
28		6.6	0.34	12.	4.0	3,300.	66.	85.	230.	6.9	3,700.
29		6.7	0.31	9.8	2.6	2,300.	52.	58.	140.	17.	2,600.
30		6.9	0.41	12.	0.65	660.	26.	6.8	19.	4.6	710.
31		7.1	0.40	11.	0.04	40.	6.3	2.0	5.2	8.3	54.
32		6.8	0.26	10.	0.60	620.	19.	4.2	12.	7.2	660.
33		6.7	0.23	9.0	0.67	690	19.	5.4	13.	11.	730.
34		6.4	0.38	7.0	0.00	37.	1.5	0.6	0.4	1.6	40.
35		6.8	0.30	9.5	0.26	280.	6.4	0.6	1.0	3.0	290.
36		7.0	0.25	8.5	0.13	220.	5.6	0.6	1.2	8.6	230.

Appendix D, cont. Physio-chemical data for water and ice in the Norris Glacier area. Samples collected in 1967.

Sample No.	Stream No.	pH	Eh (+ volts)	Temperature (°C)	Chlorinity (0/00)	Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Iron (Fe)	Total Major Cations
37		7.1	0.42	14.	0.30	330.	19.	5.4	8.8	11.	360.
38		8.2	0.37	14.	0.68	500.	16.	24.	30.	0.7	570.
39		9.0	0.35	15.	0.30	240.	9.7	12.	14.	1.4	280.
40		6.9	0.30	14.	0.38	410.	15.	6.8	12.	3.6	440.
41		7.0	0.24	13.	0.28	180.	11.	12.	17.	27.	220.
42		6.8	0.24	12.	0.32	350.	11.	12.	9.2	11.	380.
43		7.8	0.41	21.	0.28	300.	12.	15.	9.8	0.2	340.
44		7.9	0.40	18.	0.51	440.	13.	13.	17.	0.0	490.
45		7.1	0.22	14.	0.93	870.	24.	18.	37.	8.7	950.
46		8.5	0.35	14.	0.49	500.	21.	14.	22.	9.3	550.
47		7.0	0.38	20.	2.0	1,600.	40.	38.	93.	0.7	1,800.
48		8.2	0.37	-	0.83	640.	20.	28.	44.	4.0	730.
49		7.4	0.17	15.	6.8	4,300.	140.	150.	300.	0.3	4,900.
60		-	-	-	0.00	4.2	0.5	0.0	0.0	0.1	4.7
62		-	-	-	0.00	3.3	0.6	1.0	0.0	0.0	4.9
63		-	-	-	1.1	1,000.	34.	9.2	26.	0.3	1,100.
64		-	-	-	0.00	59.	1.7	0.0	0.0	0.3	60.
66		-	-	-	0.04	13.	0.9	0.0	0.4	2.5	15.
67		-	-	-	0.00	17.	0.7	0.0	0.0	1.1	18.
69		-	-	-	0.05	36.	2.2	2.0	1.6	3.6	42.

Water Type: Tide Flat Ground Water, Cont.

Appendix D, cont. Physio-chemical data for water and ice in the Norris Glacier area. Samples collected in 1967.

Sample No.	Stream No.	pH	Eh (+ volts)	Temperature (°C)	Chlorinity (0/00)	Cation Concentrations (ppm)					Total Major Cations
						Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Iron (Fe)	
<u>Water Type: Outwash Ground Water</u>											
50		7.2	0.49	13.	0.00	3.3	1.3	6.4	0.6	2.5	12.
54		7.8	0.56	8.8	0.00	7.7	2.2	7.8	1.6	0.8	19.
57		6.4	0.59	8.3	0.00	2.0	0.6	4.2	2.4	0.0	9.2
58		6.0	0.58	8.0	0.00	7.7	3.2	3.0	2.4	17.	16.
59		5.9	0.57	8.5	0.00	8.6	1.8	0.0	0.0	0.7	10.
65		-	-	-	0.00	10.	0.9	2.0	1.0	0.7	14.
<u>Water Type: Bog Water</u>											
6		6.8	0.38	17.	0.00	21.	1.2	3.0	0.6	1.5	26.
<u>Water Type: Lake Water</u>											
51		8.2	0.48	12.	0.00	2.7	0.9	2.0	0.0	0.7	5.6
52		8.1	0.47	3.5	0.00	2.7	0.4	1.0	0.0	0.8	4.1
53		8.1	0.48	4.0	0.00	1.1	0.3	1.0	0.0	0.7	2.4
<u>Water Type: Subglacial Stream Water</u>											
56		9.1	0.45	2.0	0.00	5.5	1.9	6.4	1.2	5.5	15.

Appendix D, cont. Physio-chemical data for water and ice in the Norris Glacier area. Samples collected in 1967.

Sample No.	Stream No.	pH	Eh (+ volts)	Temperature (°C)	Chlorinity (0/00)	Sodium (Na)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Iron (Fe)	Total Major Cations
<u>Water Type: Taku Inlet Surface Water</u>											
70	-	-	-	-	0.06	8.6	1.4	13.	2.8	6.5	25.
71	-	-	-	-	0.00	4.2	0.9	12.	2.0	6.3	19.
<u>Water Type: Taku River Water</u>											
72	-	-	-	-	0.00	3.3	0.9	12.	1.8	6.3	18.
<u>Water Type: Norris Glacier Ice</u>											
NorIF-1	-	-	-	-	-	0.22	0.11	3.9	0.17	-	4.4
NorIF-2	-	-	-	-	-	0.14	0.09	1.5	0.08	-	1.8
NorIF-3	-	-	-	-	-	0.17	0.06	3.7	0.12	-	4.0

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