

**FLUVIAL OVERPRINTING OF GLACIALLY INDUCED MICROTEXTURES
ON QUARTZ GRAINS DERIVED FROM THE CHITINA GLACIER,
ALASKA**

by

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ABSTRACT

Microtextures revealed through scanning electron microscopy (SEM) of quartz grain surfaces can be useful for interpreting sedimentary transport mechanisms, especially in eolian, fluvial, and glacial depositional environments. Few studies have applied SEM microtextural analysis with systematic sampling to assess the degree of surface modification when grains experience multiple episodes of transport style. Transport-induced microtextures can be grouped based on the process of fracturing into: (1) sustained high shear stress fractures created through grain-to-grain stylus contact (i.e. troughs, grooves and gouges), (2) percussion fractures created through grain-to-grain impacts during saltation or traction flow, and (3) polygenetic fractures that reflect fracturing under a wide variety of transport processes. This study attempts to ascertain the degree of fluvial modification of glacially derived grains within the Chitina River of SE Alaska. In total, 41 samples were collected in ~5km increments over the entire 188 km length of the river beginning at the Chitina Glacier terminus for a total analysis of 1,000 quartz grains.

Data shows that the number of grains exhibiting percussion microtextures generally increased (from ~1-31%) progressively downstream from the initially sampled glacial till (1%-percussion, 30% sustained high stress features). Percussion microtextures demonstrate a fairly strong positive correlation ($R^2 = 0.6535$) versus distance downstream. In contrast, percentage of grains exhibiting sustained high shear stress microtextures ranges from ~7-36% and negatively correlates ($R^2 = 0.6248$) with distance downstream. The reciprocal relationship suggests that grains exhibiting percussion microtextures increase with downstream transport at the expense of grains

exhibiting sustained high shear stress microtextures. This trend is supported since percussion textures positively correlate, sustained high stress textures negatively correlate, and polygenetic microtextures display no downstream transport correlation ($R^2=0.02$).

In this study, sustained high stress microtextures persisted for at least 188 km downstream indicating that the presence of such microtextures in an ancient coarse-grained fluvial system can be used to differentiate from proglacial and non-glacial fluvial systems. Additionally, minor increases in sustained high stress features can be corroborated with glacially fed tributaries, including the Barnard, Hawkins, and Kennicott Glaciers.

Finally, the ratio of percussion to sustained high stress (P/S) occurrence frequency was used to correlate surface feature changes relative to river morphology. Changes in the P/S ratio coincide with confluencing glaciers and the Tana and Nizina Rivers. P/S ratio decreases when proximal to glacial environments and increases with further transport distance from glacial headwaters or tributaries. The P/S ratio relationship was used to make conclusions concerning river morphology, linear regression application to downstream distance, and changes in microtexture occurrence frequency during downstream fluvial transport. Thus, the results of this study support the merits of using this method as proxy in ancient systems to determine a glacial influence on depositional systems and potentially as a proxy to predict extent of glacial advances.

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CHAPTER 1

INTRODUCTION

Scanning electron microscopy (SEM) analysis of quartz grain surface features has been used since the 1960's to ascertain grain transport history after liberation from provenance rock and prior to final deposition (e.g. Krinsley and Takahashi, 1962; Krinsley and Donahue, 1968; Krinsley and Doornkamp, 1973; Mahaney, 2002). Although SEM analysis of quartz grain surfaces is not a Rosetta stone to infer all styles of transport, a few environments can be defined by the surface microtexture character. For example, wet-based glaciers with high basal and internal shear impart a suite of microtextures reflecting grain-to-grain stylus contact through sustained high shear stress, whereas percussion transport produces grain-to-grain impact features on grain surfaces from saltation (Mahaney and Kalm, 2000; Mahaney, 2002, Whalley and Langway, 1980). However, no study to date has systematically assessed the overall abundance and survivability of glacially induced microtextures during progressive downstream fluvial transport.

Many SEM microtextures studies have documented multiple phases of transport history through first principle, cross-cutting relationships of grain surface microtextures. For example, Jackson (1996) observed v-shaped cracks attributed to fluvial saltation atop surfaces that exhibit grain-to-grain stylus microtextures within fluvial sands collected approximately 10 km from glacial till. In a later study, Mahaney and Kalm (2000), document grain-to-grain stylus microtextures with scarce saltation microtextures in Pleistocene till within, yet the associated proglacial fluvial deposits, approximately 100 km downstream from the till, saltation induced

microtextures were abundant whereas grain-to-grain stylus microtextures were absent. These two case studies indicate that fluvial transport modifies previous glacial transport history recorded on grain surfaces. To date, no systematic study has been performed in a modern system to determine the degree of fluvial modification on grain surfaces relative to distance. Thus, the following questions remain unanswered: 1) how far downstream can glacially induced microtextures survive in a fluvial system while undergoing percussion transport, 2) does dense fluvial modification of glacially derived grains correspond to distance downstream, and 3) can the relationship of fluvially induced to glacially induced microtextures be utilized to reconstruct real river physiographic changes in a modern proglacial system?

If glacially induced microtextures remain within a proglacial fluvial system, then SEM analysis of quartz grains can be administered to decipher between ancient proglacial and non-glacial coarse-grained fluvial strata. Facies models of coarse-grained fluvial systems do not differentiate well between non-glacial and proglacial systems. Indeed, some facies models of coarse-grained braided river systems are based entirely on glacially derived systems (Boothroyd and Ashley, 1975; Boothroyd and Nummendal, 1978) even though they are argued to apply to all coarse-grained braided river systems (e.g. Miall, 1978). More recent assessment of proglacial river systems have argued that large and abundant flood facies provide evidence to differentiate proglacial from non-glacial braided rivers (e.g. Maizels, 1993, 1997; Marren, 2002); however this argument is not necessarily diagnostic of ice because floods occur in rivers of all types and abundance is a matter of preservation.

If glacially induced microtextures are systematically modified downstream by fluvial saltation, then the relationship between distance downstream and relative abundance of glacially induced or fluvially induced microtextures could be used to predict distance downstream in ancient systems and accordingly the extent of past ice. Extent of ancient ice is most commonly assessed by the location of terminal moraines. However, glacial depositional successions are typically incomplete because the mechanism of advance often recycles and truncates previously deposited sediments (e.g. Johnson and Hansel, 1999). Thus, potential trends in microtextural modification versus distance downstream derived from modern proglacial systems may provide an alternative way to reconstruct ancient ice extent even in incomplete successions.

If glacially induced microtextures are modified by downstream fluvial transport, then the ratio of fluvially induced to glacially induced microtextures may potentially reflect real river physiography. Potential river physiography changes include glacial or fluvial confluences each of which should affect the ratio of fluvially to glacially induced microtextures. For example, tributary confluences should increase the number of grains that were subjected to fluvial transport and the ratio should increase. Alternatively, if valley glaciers are intersected, then more grains with solely glacial transport should be supplied to the river and the ratio should decrease. Therefore, applying this ratio to ancient rivers may help reveal specific paleogeographic components of past proglacial systems.

This study uses SEM to examine quartz grains recovered from the Chitina River of SE Alaska and seeks to answer these outstanding questions. To test downstream variation in microtextures, 1,000 quartz grains were analyzed from 40

samples, beginning at the terminal moraine of the Chitina Glacier and extending to the Chitina-Copper river confluence approximately 188 km downstream. The analysis documents change in the abundance of grain-to-grain stylus and grain-to-grain impact microtextures versus distance downstream. Results indicate that glacially induced quartz grain microtextures are liberated into the fluvial system and persist downstream, but are progressively modified by percussion bed load transport, such that frequency of grains exhibiting glacial stylus microtextures decreases with downstream transport.

CHAPTER 2

SEM BACKGROUND

2.1 Historical SEM Analysis Introduction

Theoretically, quartz grain surface features record surface modification resulting from grain-to-grain interaction during transport after initial liberation to final deposition. Accordingly, SEM analysis of grain surfaces has been used since the 1960's to correlate quartz grain topography with geologic processes (e.g. Krinsley and Takahashi, 1962; Krinsley and Doornkamp, 1973; Mahaney, 2002). Yet, extensive studies have demonstrated that only a few microtextural suites reflect distinct styles of sedimentary transport (e.g. Biederman, 1962; Porter, 1962; Campbell and Thompson, 1991; Mahaney and Kalm, 2000; Mahaney, 2002). Consequently, the majority of microtextures have similar characteristics produced from different transport processes, a principle known as equifinality. Similar microtextures imparted by dissimilar transport methods are of little significance for determining depositional environments; however, transport-unique microtextures can be used in conjunction with local geology and other sedimentologic observations to infer depositional environment (e.g. Campbell and Thompson, 1991; Mahaney, 2002; Sweet and Soreghan, 2010).

Specific styles of grain transport can modify grain surfaces in relatively unique ways such that Campbell and Thompson (1991) suggested that microtextures could be divided into suites based on imparted surface features. Sweet and Soreghan (2010) further argued that microtextures can be divided into three genetic categories of transport style defined as sustained high stress, percussion, and polygenetic (i.e. Equifinality; Table 2.1). Thus, the particular suite of microtextures observed on grain

surfaces may reflect the transport style subjected on the grains, and in conjunction with other geologic relationships, specific depositional environment can be assessed (e.g. Mahaney, 2002).

2.2 Sustained High Stress Microtextures

Sustained high stress microtextures are defined as those microtextures that reflect grain-to-grain contact while under high shear stress such that individual grains act as a stylus on other grains. Imparted microtextures assigned to this transport style include all grooves, troughs, and gouges (Mahaney, 2002; Sweet and Soreghan, 2010). Sustained high stress modification of grain surfaces has been reported most commonly from wet-based glaciers with abundant basal and internal shear (Whalley and Langway, 1980; Campbell and Thompson, 1991; Mahaney and Kalm, 2000; Mahaney, 2002). Other processes or environments appear to produce grain-to-grain contact under enough shear to stylize grain surfaces include structural shear zones (Hellend and Diffendal, 1993) and high viscosity debris flows (Mahaney, 2002). However, when sustained high stress microtextures have been observed in significant quantities, a glacial origin is the most common system studied or inferred especially if other corroborating geologic relationships exist (Krinsley and Takashi, 1962; Whalley and Langway, 1980; Campbell and Thompson, 1991; Mahaney et al., 1991; Mahaney and Kalm, 2000; Mahaney et al., 2001; Mahaney, 2002; Strand et al., 2003; Sweet and Soreghan, 2010; Kirshner and Anderson, 2011; Witus et al., 2014; Immonen et al., 2014). A study that assessed

Table 2.1: Classification of transport-induced microtextures on quartz grain surfaces

Microtexture Nomenclature	Characteristics ⁽¹⁾	Process of microtexture formation ⁽²⁾	Selected Reference(s)
Edge rounding	Rounded edges on grains	Percussion	Campbell and Thompson, 1991; Mahaney and Kalm, 1995, 2000; Mahaney, 2002
V-shaped cracks	V-shaped fractures of variable size and depth on grain surface	Percussion	Campbell and Thompson, 1991; Mahaney and Kalm, 1995, 2000; Mahaney, 2002
Abrasion features	Rubbed or worn down grain surfaces	Polygenetic	Mahaney and Kalm, 1995, 2000; Mahaney, 2002; Mazzullo and Ritter, 1991
Arc-shaped steps	Arcuate fractures on grain surfaces, typically depths greater than micrometers	Polygenetic	Campbell and Thompson, 1991; Mahaney and Kalm, 1995, 2000; Mahaney, 2002
Breakage blocks	Space represented by removal of block of variable size on grain surface	Polygenetic	Campbell and Thompson, 1991; Mahaney and Kalm, 1995; Mahaney, 2002
Conchoidal fractures	Smooth curved fractures with ribbed appearance	Polygenetic	Campbell and Thompson, 1991; Mahaney and Kalm, 1995; Mahaney, 2002
Fracture faces	Large, smooth, and clean fractures of at least 25% of grain surface	Polygenetic	Mahaney, 2002
Linear steps	Widely spaced ($> 5 \mu\text{m}$) linear fractures on grain surface	Polygenetic	Campbell and Thompson, 1991; Mahaney and Kalm, 1995; Mahaney, 2002
Sharp angular features	Distinct sharp edges on grain surface	Polygenetic	Campbell and Thompson, 1991; Mahaney and Kalm, 1995; Mahaney, 2002
Subparallel linear fractures	Linear fractures on grain surface, typically $< 5 \mu\text{m}$ spacing	Polygenetic	Hellend and Diffendal, 1993; Mahaney and Kalm, 1995, 2000; Mahaney, 2002
Crescentic Gouges	Crescent shaped gouges on grain, typically $> 5 \mu\text{m}$	Sustained High Stress	Campbell and Thompson, 1991; Mahaney et al., 1988, Mahaney, 2002
Deep Troughs	Groves $> 10 \mu\text{m}$	Sustained High Stress	Mahaney and Kalm, 1995, 2000; Mahaney, 2002
Mechanically Upturned Plates	Partially torn loose plates from the mineral surface. Linear grooves on mineral surface $< 10 \mu\text{m}$	Sustained High Stress	Mahaney and Kalm, 2000; Mahaney 2002
Straight Grooves	Linear grooves on mineral surface $< 10 \mu\text{m}$	Sustained High Stress	Hellend and Diffendal, 1993; Mahaney and Kalm, 1995, 2000; Mahaney, 2002
Curved Grooves	Curved grooves on mineral surface $< 10 \mu\text{m}$	Sustained High Stress	Hellend and Diffendal, 1993; Mahaney and Kalm, 1995, 2000; Mahaney, 2002

⁽¹⁾ Descriptions from Mahaney (2002)⁽²⁾ Descriptions from Sweet and Soreghan (2010)

microtextures on grains recovered from *in situ* tills and paraglacial debris flows found that the occurrence of microtextures within the two sample suites was statistically indiscernible (Curry et al., 2009). Thus, it seems that in this case, debris flow transport did not meaningfully overprint the original glacial transport microtexture signal. Nevertheless, the study provides a cautionary note on the need to incorporate other geologic relationships into environmental interpretations using sustained high stress microtextures.

2.3 Percussion Microtextures

Percussion transport produces edge rounding and v-shaped cracks indicative of grain-to-grain impacts during saltation (Table 2.1; Campbell and Thompson, 1991; Mahaney and Kalm, 1995, 2000; Mahaney, 2002; Mahaney and Dohm, 2011). Depositional environments that have been identified using grain-to-grain impact microtextures include fluvial (Hellend and Diffendal, 1993; Mahaney and Kalm, 2000; Sweet and Soreghan, 2010), eolian (Al-Saleh and Khalaf, 1982; Mazullo, 1987; Malhame and Hesse, 2015), and near-shore marine systems (Biederman, 1962; Pascoe, 1961; Campbell and Thompson, 1991; Mahaney and Dohm, 2011; Hossain et al., 2014). The diversity of environments with saltation transport of sand requires integration of other independent geologic evidence for depositional environmental interpretation (Campbell and Thompson, 1991; Mahaney, 2002). For example, to infer percussion induced microtextures resulting from transport in an ancient fluvial system, other geologic or sedimentologic observations must be inconsistent with eolian and near shore marine systems and consistent with fluvial deposition (Campbell and Thompson, 1991; Sweet and Soreghan, 2010; Malhame and Hesse, 2015).

2.4 Polygenetic Microtextures

The majority of transport-induced fractures observed on quartz surfaces have been observed in a variety of depositional systems under different styles and transport mediums (e.g. Mahaney, 2002). Resulting polygenetic microtextures (Table 2.1) include conchoidal fractures, step fracturing, and lineations (Sweet and Soreghan, 2010). A wide range of environments impart polygenetic microtextures onto grain surfaces, including burial or tectonic stress (Mazullo and Ritter, 1991), glacial stress (Mahaney and Kalm, 2000; Mahaney, 2002), mass-flow, matrix shearing (Mahaney, 2002), bed load grain contact during saltation (Mahaney and Andres, 1991,1996; Hellend and Diffendal, 1993; Mahaney and Kalm, 2000; Sweet and Soreghan, 2010; Mahaney and Dohm, 2011), comet impacts (Mahaney, 2002), and soil shrink-swelling (Mahaney et al., 2001a; Sweet and Soreghan, 2008). Thus, SEM polygenetic microtextures are of limited use for determining specific transport agents (Sweet and Soreghan, 2010).

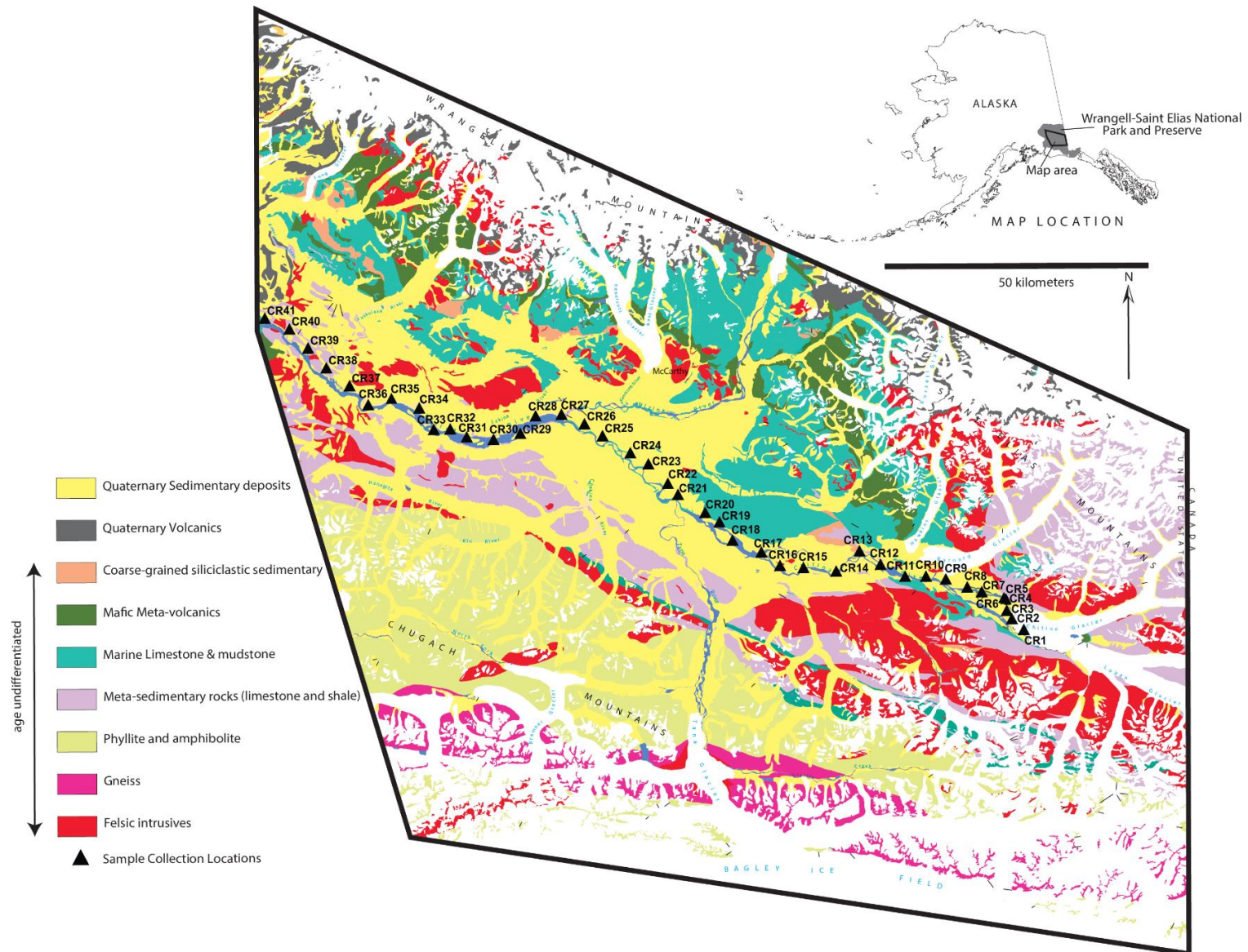
CHAPTER 3

GEOLOGIC BACKGROUND

3.1 Study Area Introduction

The Chitina River is located in the Wrangell-St. Elias National Park and Preserve in SE Alaska and is surrounded by the Chugach Mountains to the south and the Wrangell Mountains to the north (Fig 3.1). The Chugach and Wrangell mountains are primarily cored by metamorphic assemblages with minor sedimentary deposits ranging in geologic age from Permian to Quaternary (MacKevett, 1969). The region is primarily the product of accretion of allochthonous terranes along the continental margin resulting in a complex tectonic history (Nokleberg et al., 1985).

Figure 3.1: Simplified geologic map of the Chitina River, SE Alaska (modified from Richter et al., 2006). Black triangles indicate sampling locations along the Chitina River. Rock units are grouped into potential source lithotypes for sediment sampled from the Chitina River. Also, note locations of Tana and Nizina rivers and Barnard and Hawkins glaciers as they are often referred to in text.



3.2 Regional Tectonic History

The Wrangellia composite terrane (WCT) and Chitina arc compose the landscape bedrock being currently shaped by the Chitina River. Broadly, the St. Wrangell-Elias region has a complex tectonic history that includes the Wrangellia, Windy, Alexander, Yakutat, Chugach and Price William composite terranes (Nokleberg et al., 1994; Plafker and Berg, 1994). Yet, given this complex tectonic background, sediment entering the Chitina River can be isolated to the WCT and Chitina arc (Trop et al., 2002; Richter et al., 2006; Brannan and Sweet, 2014). The WCT is an allochthonous unit composed of the Wrangell Mountain and Nutozin basins that were deformed during terrane accretion (Plafker and Berg, 1994). The Wrangell Mountain Basin (WB) surrounds the Chitina River and contains fourteen lithologic units (Table 3.1) that provide sediment to the Chitina River watershed.

The Chitina arc formed along the southern margin of the WCT during the initial collision of the Chugach and Wrangellia terranes approximately 170-150 mya (Nokleberg et al., 1985; Plafker et al., 1994). Exposed units of Upper Jurassic plutonic and metaplutonic rocks comprise the Chitina arc and surround the headwaters of the Chitina River (Fig. 3.1). The Chitina arc is the main source of first-cycle sediment in the Chitina River and is the most likely dominant provenance for quartz sand in the watershed.

3.3 Stratigraphy

The surrounding Wrangell and Chugach mountains contain multiple sedimentary or meta-sedimentary formations within the Chitina River watershed that can potentially release second-cycle sediment into the Chitina River. Detailed

stratigraphic and sedimentologic data from the Wrangell Mountain Basin was collected by Trop et al. (2002) who grouped lithology into specific time intervals: Quaternary-Tertiary, Tertiary, Late Triassic-Early Cretaceous, Middle-Late Jurassic, Late Jurassic, Early-Late Cretaceous, and Late Cretaceous (Table 3.1). As the provenance column indicates, the majority of the units present were deposited on the WCT prior to accretion and are predominantly composed of mudstone and carbonate rocks. Coarse-grained, siliciclastic lithotypes that can liberate second-cycle quartz grains are restricted to Late Cretaceous and Early Jurassic strata, but are volumetrically minor and predominantly exposed in the lower reaches of the Chitina River (Fig. 3.1).

Table 3.1: Quaternary -Early Jurassic Wrangell Mountains Basin Formations Geologic Features

Age*	Formations†	Main Lithologies#	Inferred deposystems**	Provenance††
Tertiary	Frederika Formation	Nonmarine Sedimentary Rocks	Tuff and siltstone	Volcanic ash and glacial outwash
Latest Cretaceous	MacColl Ridge	Conglomerate, sandstone, and crystal-vitric tuff	Submarine Fan	Remnant arc (Chitina), active arc (Kluane) and recycled WB/WCT
Late Early to Late Cretaceous	Berg Creek, Kuskalana Pass, Kennicott, Schultze, Chittu, and Moonshine Creek Formations	Mudstone and Sandstone	Shoreface to outer marine shelf and submarine shelf	Remnant arc (Chitina) and recycled WB/WCT
Late Jurassic	Kotsina. Conglomerate and Upper Root Glacier Formation	Conglomerate and Sandstone	Fan delta and submarine fan	Remnant arc (Chitina) and recycled WB/WCT
Middle-Late Jurassic	Lower Root. Glacier and Nizina Mountain Formations	Mudstone and volcanic deposits	Muddy marine shelf and submarine slope	Active volcanic arc
Late Triassic to Early Jurassic	Chitistone and Nizina Limestones; McCarthy and Lubbe Creek Formations	Limestone, chert, and mudstone	Carbonate platform and submarine slope	Detrital input from remnant volcanic arc

*From marine megafossils (Jones and MacKevett, 1969; MacKevett, 1969). K-Ar age determinations (Grantz et al., 1966), palynology (Trop et al., 1999), and Ar/Ar age determinations (Trop et al., 1999, 2002).

†From Jones and MacKevett (1969) and MacKevett (1969).

#From Trop et al., (2002), Armstrong et al., (1969), and MacKevett (1978).

**From Trop et al., (2002)

††From Trop et al., (2002) in conjunction with regional mapping (Richter, 1976; MacKevett, 1978; Winkler et al., 1981), local tectonic models (Plafker and Berg, 1994; Nokleberg et al., (1998), and terrane plate reconstructions (Engelbreton et al., 1985).

3.4 Chitina River Pleistocene Deposits

Pleistocene deposits housed in the Chitina River watershed primarily record glacial outwash, till and glacio-lacustrine environs from previous glacial episodes (Fig. 3.1; McKeve, 1969). The glacio-lacustrine units are largely silt with minor sands and occur predominantly in the region where the Chitina River funnels into a single channel in the stretch between the Tana River confluence and the Nizina River confluence (Fig. 3.1). Pleistocene deposits are persistent and extensive throughout the entire length of the river and remain volumetrically similar downstream from the Chitina Glacier terminus.

3.5 Geomorphology

From the Chitina Glacier terminus to the Copper River confluence, the Chitina River is approximately 188 km long and can be divided into three different reaches based on physiographic characteristics. From the nose of the Chitina Glacier to the confluence of the Tana River (~ 80 km), the Chitina River is heavily braided with an average slope of 0.004 and channel depths during the sampling transect were commonly up to 2 m. However, note that annual flow can vary substantially and would result in variable channel depths throughout a given year. From the Tana River confluence to the Nizina River confluence (approximately 35 km), the Chitina River forms a single channel (approximately 250 m wide) that incises into Pleistocene glacio-lacustrine deposits (Fig. 3.1). This section of the Chitina River comprises almost exclusively transverse bars and has an average slope of 0.002 with channel depth up to 6 m. From the Nizina River confluence to the Copper River confluence (approximately 70 km), the Chitina River returns to braided channels with an average

slope of 0.002. Transverse bars become more abundant than longitudinal bars after the initial 20 km from the Chitina-Nizina confluence and transforms into a single dominant channel approximately 30 km upstream of the Copper River confluence.

3.6 Hydrology

The Chitina River is part of the larger Copper River basin watershed, which encompasses approximately 53,354 km². In the mid-1980's, approximately 17% of the drainage area was covered by glacial features (Emery et al., 1985). The Chitina River encompasses approximately one third of the Copper Basin watershed and drains high altitude snow- and glacier-melt from the surrounding Chugach and Wrangell mountains (Fig. 3.1). The Chitina River is therefore subject to seasonal freshets during the five month open water period from May–September during which approximately 88% of stream flow volume occurs (Emery et al., 1985). The absence of a hydrologic gauging station along the Chitina River makes estimating changes in mean annual flow challenging. However, a gauging station on the upper Copper from 1955-1985 recorded a mean annual discharge of 1,067 m³/s and 2846 m³/s peak annual discharge (Emery et al., 1985). Data from this gauging station also estimates that 69 million tons of sediment is transported annually in the Copper River. Emery et al. (1985) estimated that approximately half of the total discharge from the Copper River is sourced from the Chitina River. If this estimation is realistic, then the Chitina River contributes approximately 534 m³/s annually and 1423 m³/s during peak discharge. However, as discussed above, the Chitina River has three distinct stretches each defined by a major river confluence. Thus, the discharge of the Chitina River itself would decrease up river within each of the three reaches, on the order of a third for

each reach based on size of drainage area of the contributing tributary. Average slope over the entire transect is 0.0028, which is consistent with sand and gravel dominated bed load rivers (Blair and McPherson, 1994). Discharge and slopes of this magnitude produces high Froude and Reynolds numbers that produce sufficiently turbulent flow regimes to allow for energetic bed load transport.

CHAPTER 4

METHODS

The Chitina River provides an excellent natural laboratory to test fluvial modification of glacial transport microtextures because: 1) the bedrock geology is largely devoid of sedimentary, sand-sized, quartz grains eliminating the possibility of inherited transport-induced microtextures; 2) gneiss and granite provide abundant first-cycle quartz sand to the glacial system; and 3) the length of the river is sufficiently long to observe overprinting signals under a variety of hydraulic regimes. Samples were collected systematically downstream from till at the terminal moraine of the Chitina Glacier to the Copper River confluence with sample spacing approximately 1 km for the initial 5 km and 5-7 km thereafter (Fig. 3.1). In total, 41 samples were recovered along the Chitina River transect.

At each sample site, approximately 0.5 kg of sand was collected from surficial material on active longitudinal bars. Transverse bars were used as sampling sites if longitudinal bars were not present at a corresponding sample distance such as in the middle, single-channel section of the river. In the laboratory, sand was sieved into a 250-850 μm fraction and subjected to magnetic mineral separation and hydrogen peroxide treatment to remove heavy minerals and organics, respectively.

Numerous quartz grains were selected from the processed 250-850 μm fraction by hand with a binocular microscope; the 250-850 μm grain fraction was used due to being too large for eolian or wind based transport. In order to alleviate potential subjectivity and bias in collection of microtextural data, samples were assigned a random letter unassociated with collection site prior to processing so that the SEM

user was not aware of distance downstream during data collection. Randomly selected quartz grains were placed on carbon-taped, aluminum stubs for iridium sputter coating. Microscopy was conducted on a Hitachi S-4300 SEM with an accelerating voltage of approximately 15kV and working distance of 15 mm. All grains were verified as quartz with energy dispersive spectroscopy.

Collection of microtexture data followed guidelines outlined in Mahaney (2002) where individual textures are marked as present or not present. Collecting data in this manner yields occurrence frequency of each microtexture in per grain units. Thus, an occurrence frequency of 20% indicates that 20% of the grains exhibited at least one instance of that specific microtexture. Note this methodology does not differentiate between a grain that exhibits a single occurrence of microtexture versus another grain that may exhibit numerous examples of the same microtexture. In total, 1,000 quartz grains were randomly evaluated, the 1,000 grains analyzed had no numerical significance and were sampled from 40 different samples with each sample averaging about 25 grains. Sample CR-20 did not yield sufficient sand from the 250-850 μm fraction and thus is not included in subsequent discussions. Additionally, 65 grains exceeding 850 μm were also evaluated, but were only present in samples CR-1, CR-5, CR-10, CR-17, and CR-25, and were subsequently excluded from this study due to scarcity over the entire transect. Microtexture identification utilized the atlases produced by and Krinsley and Doornkamp (1973) and Mahaney (2002). Detailed microtexture descriptions are listed in Table 2.1. This study focuses predominantly on microtextures resulting from fracturing during transport. Those microtextures that

reflect surface modification from chemical weathering and precipitation were not recorded, but were also scarcely observed in this system.

Depths and velocities of various stretches of the Chitina River were measured within channel centers while rafting between various sample sites. Velocity was measured directly from instantaneous GPS readings and is a measure of boat speed. Velocity readings were variable due to wind friction on the boat, local channel variation and oar propelling, thus, only those taken with minimal wind and no oaring were used in Froude number calculations. Depths were taken within the estimated deepest part of the channel with a weighted rope off the bow of rafts between sample sites. Although the rope was weighted, faster and deeper channels likely inflated depth readings due to increased non verticality of the rope.

CHAPTER 5

RESULTS

5.1 SEM Microtextural Analysis

The results of SEM microtextural analysis are presented in full in Table 5.1. A summary of key results is presented below and organized into five main categories that correspond to sample location(s), namely, 1) glacial till at the terminal moraine of the Chitina Glacier is characterized for a baseline of glacial transport; 2) proximal Chitina River samples (CR-2 to CR-9) upstream of any major glacial or river confluences; 3) samples (CR-10 to CR-21) downstream from the Barnard and Hawkins glacier confluences, but upstream of the Tana River confluence; 4) samples (CR-22 to CR-27) recovered between confluences of the Tana River and Nizina River that also corresponds to a single channel section of river previously denoted; and 5) samples (CR-28 to CR-41) downstream from the Nizina River confluence to the Chitina-Copper river confluence. Unless otherwise notes, microtextural percentages reported in this section refer to the number of grains that exhibited that particular microtexture.

5.1.1 Glacier Terminus Sample Baseline (CR-1)

The Chitina River headwaters are proximally sourced by meltwater of the Chitina Glacier and runoff. Sample CR-1 was collected as a baseline sample of glacial till from the terminal moraine of Chitina Glacier (Fig. 5.1). In total, 52 quartz grains were analyzed from CR-1. Overall, grain surface relief was moderate and rounding of grains is angular to subangular (Fig. 5.2). Every grain examined exhibited at least one

type of fracture induced during transport with the overwhelming majority of these comprised of breakage blocks, conchoidal and linear fractures, and step fracturing.



Figure 5.1: Chitina Glacier till sampling location, CR-1. Note glacial imparted striations on the large boulder near the terminus top.

Table 5.1: Occurrence frequency of transport induced microtextures

Sample	Distance from Chitina Glacier terminus (km)	# of grains	Precipitation features	Adhering Particles	Low relief	Medim relief	High relief	Fracture faces	Subparallel linear fractures	Conchoidal fractures	Curved grooves	Straight grooves	Sharp angular features	Crescentric gouges	Arc shaped steps	Linear steps	Deep troughs	Mechanically- uptumed plates	V- shaped cracks	Edge rounding	Breakage blocks
CR-1	0	52	8	24	11	31	8	22	26	45	17	26	1	18	15	14	4	12	2	1	50
CR-2	0.14	72	15	36	14	43	13	21	36	52	29	20	8	21	29	28	10	19	4	15	67
CR-3	1.36	23	6	15	5	14	3	8	9	18	6	11	1	8	14	5	0	8	5	0	23
CR-4	2.52	21	2	10	6	10	3	12	7	14	11	12	2	9	8	8	1	5	1	0	16
CR-5	3.13	19	2	5	2	8	8	4	8	16	6	10	4	6	8	6	2	6	6	6	18
CR-6	3.61	22	2	7	2	11	7	6	11	21	6	12	2	6	6	5	0	7	3	0	22
CR-7	7.64	26	3	15	1	16	8	7	16	11	6	6	2	4	12	2	4	8	5	0	24
CR-8	12.65	21	11	16	4	11	6	7	7	15	10	1	3	4	3	3	2	4	9	1	20
CR-9	16.42	17	2	12	2	4	8	0	8	10	5	2	2	3	6	0	0	1	8	6	13
CR-10	21.8	20	1	8	2	6	1	3	3	3	5	4	0	1	2	1	0	0	3	1	6
CR-11	27.29	25	0	24	6	10	6	4	10	19	10	12	1	0	1	3	0	1	15	0	21
CR-12	32.81	16	5	14	2	7	3	2	5	4	11	7	5	0	6	5	0	5	11	3	15
CR-13	37.66	23	7	19	3	8	10	3	10	17	12	5	3	4	10	6	0	7	17	1	21
CR-14	43.74	25	1	20	3	10	8	5	9	9	10	8	0	1	9	5	1	3	9	0	19
CR-15	49.89	20	1	16	1	6	12	3	7	17	7	2	4	2	7	2	0	6	18	0	19
CR-16	55.23	47	1	33	8	20	17	12	13	21	23	14	7	2	22	10	3	13	25	0	33
CR-17	59.8	22	3	16	1	9	10	3	13	14	9	3	4	1	5	0	3	3	12	4	20
CR-18	65.35	25	2	18	0	10	13	2	11	15	12	11	0	5	4	1	1	9	15	0	25
CR-19	70.47	22	7	13	6	8	7	8	11	3	14	9	6	3	6	2	0	7	13	1	19
CR-20	73.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.1 Continued: Occurrence frequency of transport induced microtextures

Sample	Distance from Chitina Glacier terminus (km)	# of grains	Precipitation features	Adhering Particles	Low relief	Medim relief	High relief	Fracture faces	Subparallel linear fractures	Conchoidal fractures	Curved grooves	Straight grooves	Sharp angular features	Crescentric gouges	Arc shaped steps	Linear steps	Deep troughs	Mechanically- uptumed plates	V- shaped cracks	Edge rounding	Breakage blocks
CR-21	80.01	21	0	14	2	7	10	4	11	9	17	4	3	2	7	6	0	5	10	1	20
CR-22	85.8	23	0	15	4	8	9	5	10	9	13	6	2	2	13	1	1	3	13	0	19
CR-23	92.15	19	0	16	2	9	7	2	4	11	13	9	0	3	13	6	2	6	13	0	17
CR-24	98.24	20	0	18	1	12	6	4	5	9	10	2	2	3	4	8	1	2	19	1	19
CR-25	105.1	19	0	15	2	9	6	6	14	13	5	5	2	0	5	5	0	1	13	0	19
CR-26	110.33	22	1	17	2	8	10	7	19	11	5	2	5	1	2	3	1	3	18	9	19
CR-27	115.48	25	0	24	2	13	8	3	17	21	6	1	0	0	7	5	0	2	23	7	25
CR-28	120.85	21	0	17	3	8	9	4	11	17	4	1	2	2	9	8	0	1	15	0	21
CR-29	125.18	28	0	28	7	9	7	4	9	20	7	1	0	0	6	8	0	2	25	7	28
CR-30	130.77	22	2	19	4	7	10	8	11	11	6	4	4	0	4	7	0	3	10	4	21
CR-31	136.42	21	0	21	0	14	7	2	8	21	4	3	0	0	6	3	1	1	16	3	21
CR-32	139.64	22	0	21	2	8	9	3	12	15	2	3	6	1	3	11	2	4	15	3	22
CR-33	143.69	23	1	18	1	9	12	6	8	10	11	3	2	3	8	5	1	5	15	4	19
CR-34	148.91	21	0	21	1	5	15	3	10	16	6	0	1	0	4	6	3	2	19	0	21
CR-35	154.37	21	0	20	2	14	3	3	6	17	4	2	0	0	6	9	2	1	15	1	21
CR-36	160.74	34	1	25	5	18	10	11	11	19	11	2	2	0	11	4	2	2	27	7	30
CR-37	166.17	21	0	21	0	10	9	2	14	20	7	2	3	0	3	9	0	0	21	4	21
CR-38	171.45	26	0	19	0	13	7	5	15	19	7	2	0	0	5	8	0	0	23	11	26
CR-39	176.91	26	0	26	0	8	13	7	12	14	7	2	0	0	5	3	0	0	23	12	26
CR-40	181.96	25	0	24	2	11	12	5	10	15	8	3	1	0	12	8	1	4	24	4	24
CR-41	188.2	22	0	19	0	13	7	4	12	16	2	4	5	0	0	7	0	1	20	13	22

Figure 5.2: Binocular microscope images of sampled sediment from the Chitina River. All photos were taken after treatment with hydrogen peroxide and were magnetically separated; viewed grain sizes range from 250-850 μ m. A) Angular-subangular glacial till (CR-1) placed on aluminum stub. B) Unseparated CR-1 sample containing angular-subangular grains. C) Semiangular unsorted grains sampled from CR-2. D) Subangular-subrounded unsorted grains with medium to high relief sample collected from CR-8. E) Subrounded unseparated grains with medium to high relief collected from CR-10. F) Subrounded unseparated grains with medium-high relief collected from CR-15. G) Subrounded unseparated grains collected from CR-25 with medium relief. H) Subrounded unseparated medium relief grains collected from CR-33. I) Subrounded low-medium relief unseparated grains from sample CR-41.

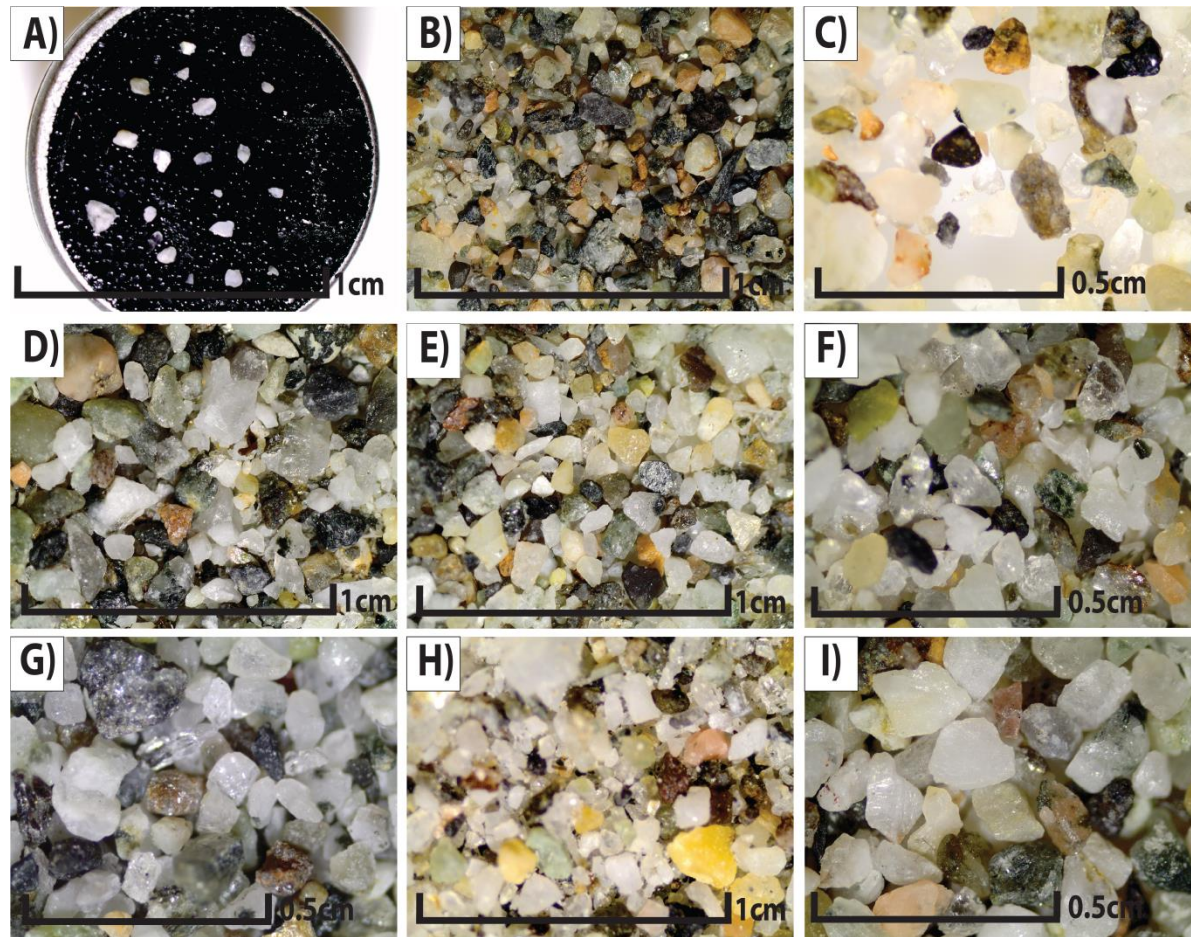
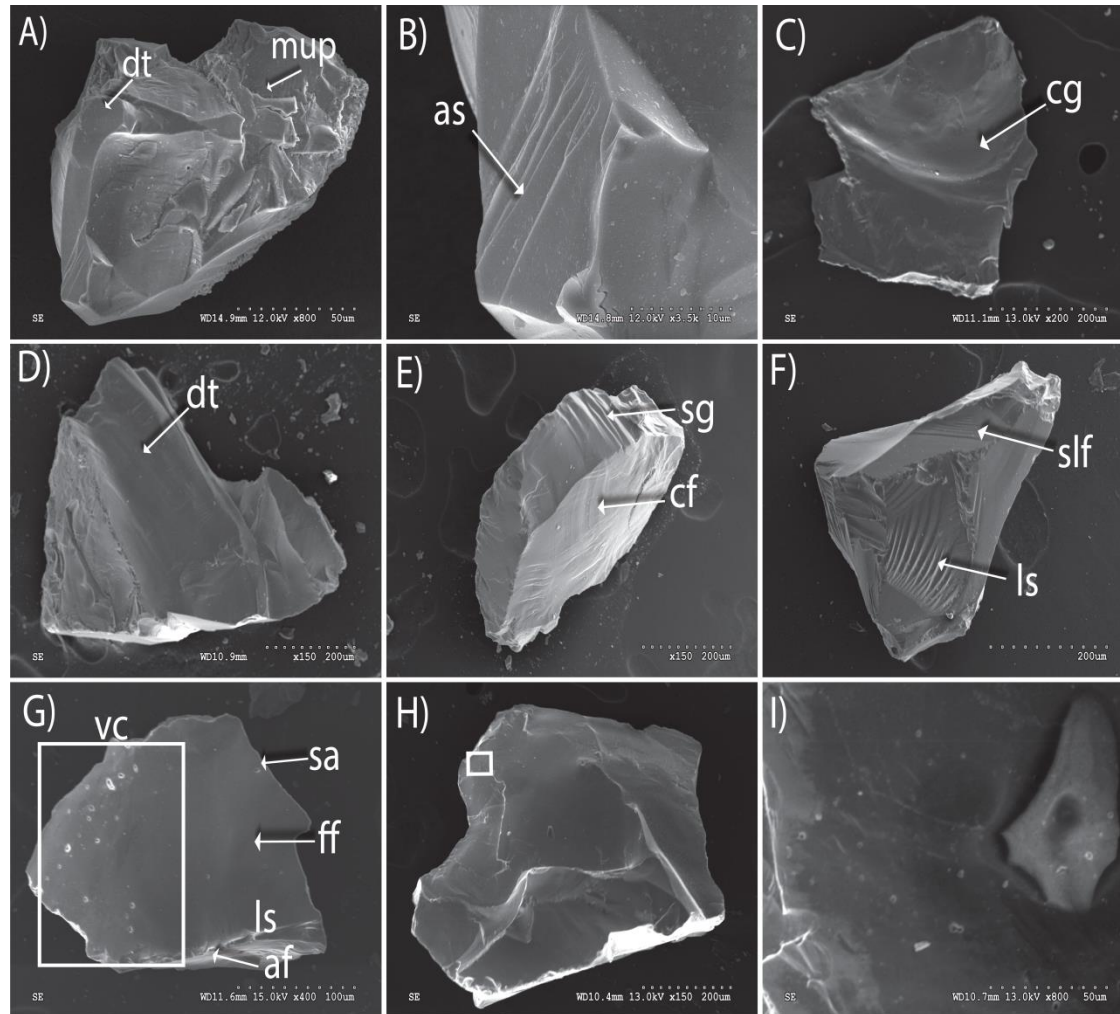


Figure 5.3: SEM images of a variety of microtextures from quartz sand grains from the Chitina River. A) Angular quartz grain displaying high relief, mechanically upturned plate (mup) and deep trough (dt). B) Angular quartz grain with arc-shaped steps (as). C) Curved groove (cg) across grain surface D) Irregular quartz grain with deep trough (dt). E) Angular quartz grain displaying straight grooves (sg) and conchoidal fracturing (cf). F) Subparallel linear features (slf) and linear steps (ls). G) Proximal (~20km from Chitina glacier terminus), semi-angular quartz grain with v-shaped cracks (vc) housed within white box, sharp angular features (sa), and fracture faces (ff). H) Distal quartz grain from the Chitina glacier terminus (~100 km) containing v-shaped cracks and transport abrasion. I) Magnified view (white box) of v-shaped cracks on grain H.



Grain-to-grain stylus fractures, i.e. grooves, gouges and troughs, occurred on all but four of the grains analyzed. The number of grains exhibiting individual microtextures representing this style of transport are straight grooves (50%), crescentic gouges (35%), curved grooves (33%), mechanically upturned plates (23%), and deep troughs (8%). Fractures that indicate grain-to-grain impacts, v-shaped cracks and edge rounding textures, occurred on only three of the grains examined.

5.1.2 Proximal Chitina River samples (CR-2 to CR-9)

Samples CR-2 to CR-9 were collected progressively downstream from the Chitina Glacier terminus to a point just upstream of influence from the Barnard Glacier (Fig. 2.1; 5.4). Analyzed quartz grains during this interval totaled 221 grains, with each sample ranging from 17-72 grains analyzed. Grain surfaces exhibited predominantly medium relief and demonstrated subangular to subrounded rounding (Fig. 5.2). Number of grains displaying stylus features include curved grooves ($\bar{X}$ =35%, range=23-52%), straight grooves ($\bar{X}$ =35%, range=5-57%), crescentic gouges ($\bar{X}$ =27%, range=15-43%), deep troughs ($\bar{X}$ =7%, range=0-15%), and mechanically upturned plates ($\bar{X}$ =26%, range=6-35%). However, occurrence frequency of grain-to-grain stylus microtextures decreases downstream over this stretch from > 28% of total microtextures observed proximally within 4 km of the terminal moraine to as low as 17% of the microtextures observed on samples from 4 to 17 km downstream. Grain-to-grain impact features, i.e. v-shaped cracks ($\bar{X}$ =23%, range=6-47%) and rounding of sharp edges ($\bar{X}$ =12%, range=0-35%), are only present on a total of 82 grains, yet this style of microtexture increases downstream from commonly <5% of the microtextures

observed proximally over the first 4 km downstream compared to as high as 22% at 16 km downstream. Nearly all grains display some form of fracturing features, including breakage blocks, conchoidal, step, and linear fractures.



Figure 5.4: Oblique low-elevation aerial photograph of the heavily braided, glacially proximal portion of the Chitina River, representative of river morphology from CR-2 to CR-9.

5.1.3 Barnard Glacier to Tana River Confluence (CR-10 to CR-21)

Quartz grain samples collected downstream from the Barnard Glacier (CR-10) to the Tana River confluence (CR-21) are subrounded to rounded with medium to high relief of grain surface topography (Fig. 5.2; Fig. 5.5). In total, 266 grains were analyzed from this stretch of river, with individual samples ranging from 16 to 47

grains. Microtextures such as breakage blocks, step fractures, and conchoidal and linear fractures are the most prevalent. Grain-to-grain stylus microtextures are present on all but 29 grains analyzed during this interval and includes curved grooves ($\bar{X}$ =53%, range=25-81%), straight grooves ($\bar{X}$ =28%, range= 10-48%), crescentric gouges ($\bar{X}$ =9%, range=0-20%), deep troughs ($\bar{X}$ =3%, range=0-14%), and mechanically upturned plates ($\bar{X}$ =26%, range=0-36%). The total number of stylus type microtextures observed demonstrate a large increase at the Barnard Glacier confluence (up to ~31%) that approaches the base line till values for this style of microtextures. However, over this entire stretch of river, the stylus microtextures slightly decrease downstream, from commonly high 20's % to low 20's %. Grain-to-grain impact microtextures are present on all but 78 grains but note that over the interval v-shaped cracks ($\bar{X}$ =60%, range=15-90%) and edge rounding ($\bar{X}$ =6%, range=0-19%) were relatively consistent from CR-10 to CR-21.



Figure 5.5: Downstream oriented photograph of the heavily braided Chitina River.

Photo was taken at CR-16, prior to the Tana River confluence.

5.1.4 Tana River to Nizina River Confluence (CR-22 to CR-27)

Samples collected downstream from the Tana River confluence (CR-22) and prior to the Nizina River confluence (CR-27) are subrounded and commonly exhibit medium surface relief (Fig. 5.2; Fig. 5.6). The number of grains analyzed from this interval is 128 with individual samples ranging from 19 to 25 grains. Stylus microtextures are absent from 49 grains while grain-to-grain impact microtextures are absent from 27 of the total grains. Over the entire interval, the number of grains exhibiting v-shaped cracks ($\bar{X}$ =77%, range=57-95%) and edge rounding ($\bar{X}$ =12%, range=0-41%) demonstrate an increase from samples collected upstream. Grains

exhibiting curved grooves ($\bar{X}$ =41%, range=23-68%), straight grooves ($\bar{X}$ =20%, range=4-47%), crescentric gouges ($\bar{X}$ =7%, range=0-16%), deep troughs ($\bar{X}$ =4%, range=0-11%), and mechanically upturned plates ($\bar{X}$ =14%, range=5-32%) are still quite common. Within the interval, substantial downstream trends occur from CR-22 to CR-27 with increasing abundance of v-shaped cracks and edge rounding, but decreasing abundance of stylus type microtextures.



Figure 5.6: Photograph of the single channel Chitina River. Photograph taken at CR-26, prior to the Nizina River confluence.

5.1.5 Nizina River to Copper River Confluence (CR-28 to CR-41)

Quartz grains analyzed between the Nizina and Copper River confluences are subrounded and exhibit predominantly medium surface relief (Fig. 5.2; Fig. 5.7). Downstream distance between CR-28 and CR-41 is approximately 65 km and examined grains have great variety in observed microtextures. Of the 333 grains analyzed, 284 and 167 displayed grain-to-grain impact and grain-to-grain stylus microtextures, respectively. Over the entire interval, the number of grains exhibiting curved grooves ($\bar{X}$ =25%, range=9-48%), straight grooves ($\bar{X}$ =10%, range=0-18%), crescentric gouges ($\bar{X}$ =2%, range= 0-13%), deep troughs ($\bar{X}$ =4%, range=0-14%), and

mechanically upturned plates ($\bar{X}$ =8%, range=0-22%) is lower than upstream stretches of river. However, the number of grains exhibiting v-shaped cracks ($\bar{X}$ =80%, range=45-100%) and edge rounding ($\bar{X}$ =21%, range= 0-59%) are increased from prior intervals. Within the interval, grains exhibiting v-shaped cracks and edge rounding microtextures increase downstream substantially from 71 to 91% and 0 to 59%, respectively.



Figure 5.7: Photograph of the mild to heavily braided Chitina River. Photograph taken at sample CR-40 prior to the Copper River confluence.

5.2 Transport-induced microtextural suites

The Chitina River dataset displays a range of microtextures that result from fracturing during transport. Yet, grains have experienced both glacial transport, under

sustained high shear stress, and fluvial transport, under bed load saltation. These two styles of transport produce different microtextures on grain surfaces, thus the data have been grouped into suites of microtextures that reflect similar style of transport as suggested by Sweet and Soreghan (2010) and modified from past studies (Krinsley and Doorncamp, 1973, Campbell and Thompson, 1991; Mahaney and Kalm, 2000). Microtextures that reflect grain-to-grain stylus engraving, i.e. all gouges, troughs, and upturned plates, are termed sustained high stress microtextures (Sweet and Soreghan, 2010) and are most commonly reflective of glacial transport (Table 3.1; e.g. Mahaney, 2002). Microtextures that reflect grain-to-grain impact, i.e. edge rounding and v-shaped cracks, are termed percussion microtextures (Sweet and Soreghan, 2010) and for this study must reflect saltation (e.g. Mahaney, 2002) from transport along the Chitina River or its tributaries. The remainder of transport induced microtextures yield little environmental information and are termed polygenetic microtextures (Table 3.1; Sweet and Soreghan, 2010). Henceforth, the data are compared as a function of distance downstream from the Chitina Glacier terminus using the triumvirate of sustained high stress, percussion and polygenetic microtextural groups. Note that percentages reported in this section represent the total number microtextures within one of the three genetic suites as a percentage of all three groups. For example, if a sample consisted of 20 analyzed quartz grains and three of those grains exhibited v-shaped cracks (i.e. percussion microtexture), yet the total number of microtextural observations was 30 (in other words those values given in Table 5.1), then the percussion percentage would be 10%.

5.3 Downstream trends in the three genetic microtextural groups

A reciprocal relationship between percussion and sustained high stress microtextures is observed over the entire distance (~188 km) of the Chitina River (Fig. 5.8). However, polygenetic microtextures appear to show no discernible trend with distance downstream. Sustained high stress microtextures are variable downstream ($\sigma=9\%$) but a modest negative correlation with distance downstream exists ($R^2=0.62$). In contrast, percussion microtextures demonstrate a positive correlation with distance downstream ($R^2=0.65$) and similar variability ($\sigma=8\%$). Polygenetic microtextures demonstrate no correlation with distance downstream ($R^2=0.02$) but are the most abundant microtexture frequency ranging from 50 to 75% with the least variability ($\sigma=5.5\%$) (Fig. 5.8; Table 5.1).

In addition to the long-distance trends, various short-distance trends are present within the data. For a baseline comparison, the till from the Chitina Glacier terminus exhibits 30 % sustained high stress, 1% percussion and 68% polygenetic microtextures. However, grains recovered progressively downstream over the first

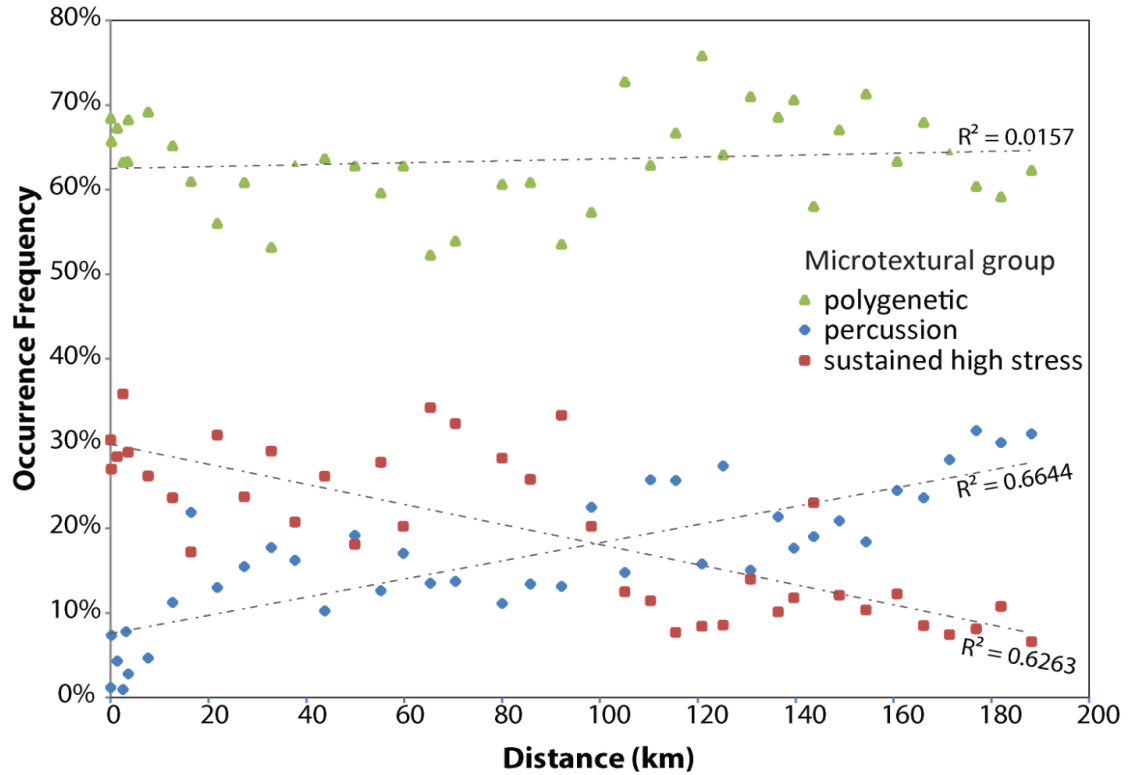


Figure 5.8: Occurrence frequency of percussion, sustained high stress, and polygenetic microtexture groups relative to distance downstream from the Chitina Glacier terminus.

~17 km (CR-2 to CR-9) demonstrate two important trends. Namely, sustained high stress microtextures negatively correlate ($R^2 = 0.64$) over total downstream distance, whereas percussion microtextures positively correlate ($R^2 = 0.58$). Polygenetic microtextures show no correlation ($R^2 = 0.07$) with distance downstream. These relationships indicate that the increase in percussion-induced microtextures is occurring at the expense of sustained high stress microtextures (Fig. 5.9).

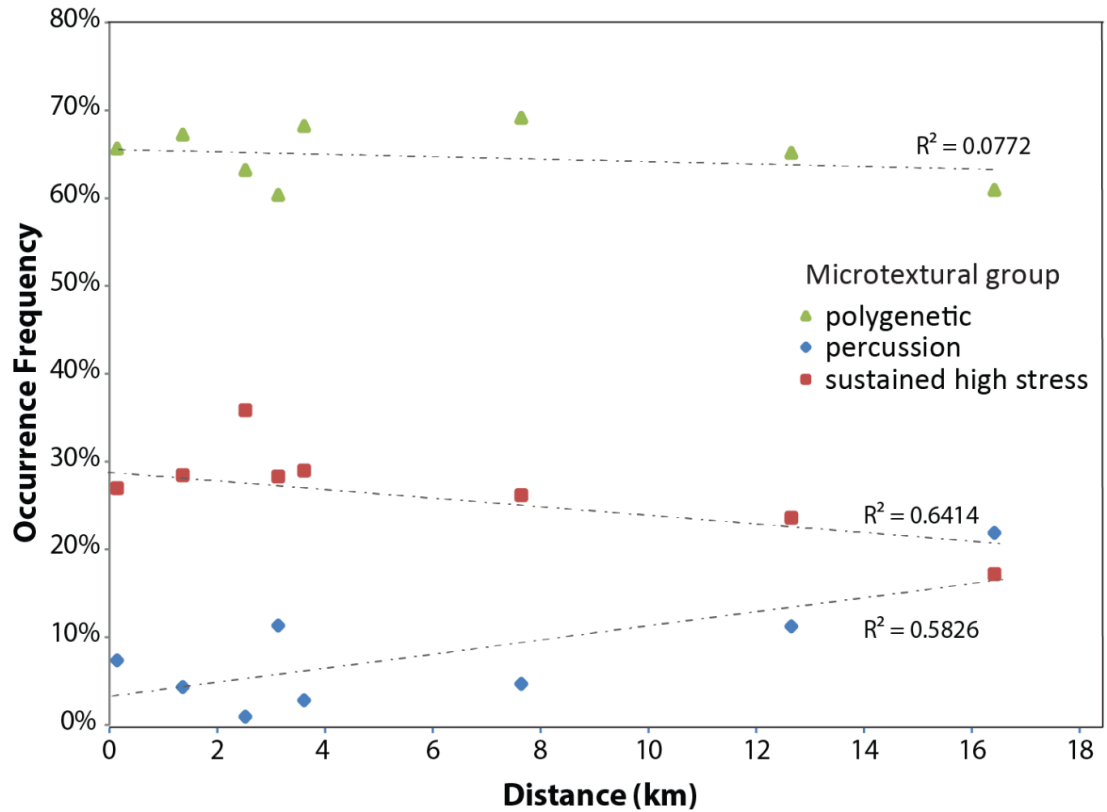


Figure 5.9: Occurrence frequency of percussion, sustained high stress, and polygenetic microtexture groups relative to samples CR-2 to CR-9 collected from near the terminal moraine of the Chitina Glacier to just upstream of the Barnard Glacier.

From ~17 km to 80 km downstream (CR-10 to CR-21; Fig. 5.10), the occurrence frequency of sustained high stress microtextures markedly increases back near the till baseline range of percentages with no discernible downstream trend over this river stretch. Percussion microtextures ($R^2 = 0.07$) and polygenetic microtextures ($R^2 = 0.005$) also do not display any discernible. However, even though neither of the microtextural groups show any trend over this interval (Fig. 5.10), the occurrence frequency magnitudes demonstrate marked differences from the section of the river upstream from the Barnard Glacier.

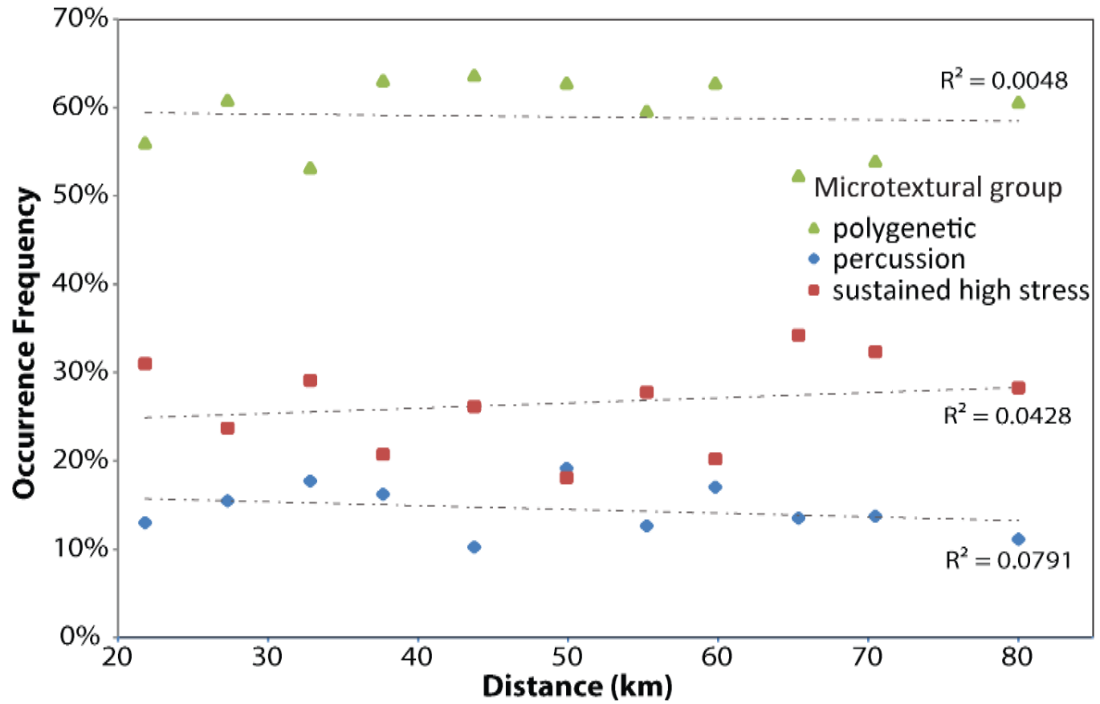


Figure 5.10: Occurrence frequency of percussion, sustained high stress, and polygenetic microtexture groups relative to samples CR-10 to CR-21 collected between Barnard Glacier and the Tana River confluence.

From ~ 80 km to 115 km distance downstream (CR-22 to CR-27), occurrence frequency demonstrates strong negative correlation in sustained high stress microtextures ($R^2=0.8$) and positive correlation in percussion textures ($R^2=0.6$) to distance downstream (Fig. 5.11). Incidentally, polygenetic microtextures demonstrate a weak positive correlation ($R^2=0.35$) within this interval. At ~ 100 km, the occurrence frequency of sustained high stress microtextures decreases in magnitude below the occurrence frequency of percussion microtextures. The long distance trends

previously discussed (Fig. 3.1) also intersect at approximately this distance downstream.

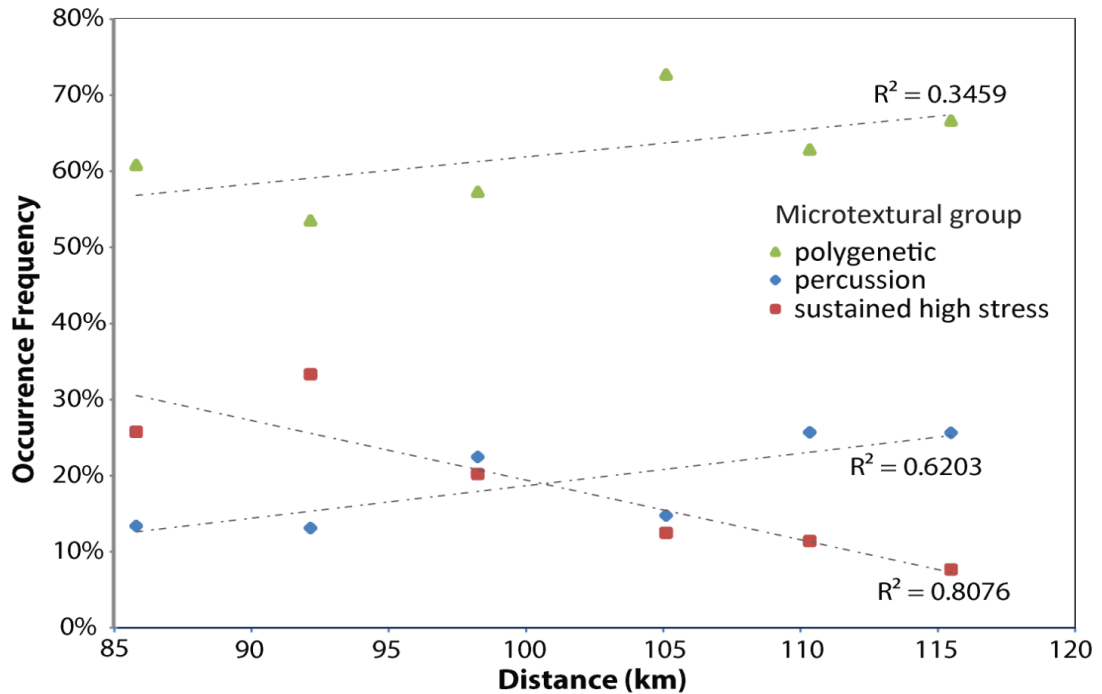


Figure 5.11: Occurrence frequency of percussion, sustained high stress, and polygenetic microtexture groups relative to samples CR-22 to CR-27 collected between the Tana and Nizina confluences.

The final segment of downstream transport, from ~115-188 km (CR-28 to CR-41; Fig. 5.12) sustained high stress microtextures continue to progressively decrease, but not substantially, and remain predominantly below percussion microtextural percentages. With the exception of CR-33 (23%), sustained high stress features are well below the till baseline (near 10%) and therefore demonstrate no correlation ($R^2=0.09$) to distance over the stretch. In contrast, occurrence frequency of percussion microtextures demonstrate positive correlation ($R^2=0.6$) to distance downstream, and progressively increase from less than 20% at CR-28 to more than 30% of observed

textures at CR-41. These percussion values are well above the till baseline and represent some of the highest values of all samples. Occurrence frequency of polygenetic microtextures demonstrate weak negative correlation ($R^2=0.37$) to distance downstream.

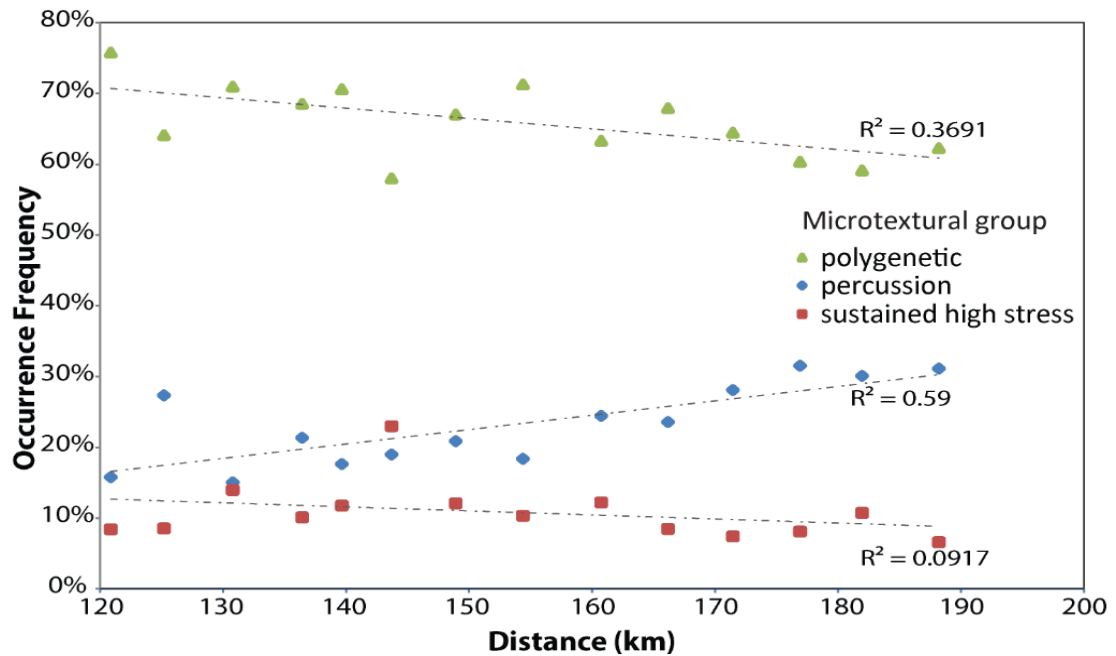


Figure 5.12: Occurrence frequency of percussion, sustained high stress, and polygenetic microtexture groups relative to samples CR-28 to CR-41 collected between the Nizina River and Copper River confluences.

CHAPTER 6

DISCUSSION

6.1 Percussion to Sustained High Stress Microtextures Ratio

The long- and short-distance downstream trends of percussion and sustained high stress microtextures are nearly always reciprocal, yet polygenetic microtexture downstream trends are weak or not present. Thus, the ratio of percussion to sustained high stress microtextures versus distance downstream should demonstrate the relative importance of those styles of transport induced microtextures. Overall, the percussion to sustained high stress ratio (P/S ratio) increases downstream with some localized river stretches that demonstrate decreasing values (Fig. 6.1). A 5-point running average of the ratio was calculated to smooth the data and potentially reveal inflection points in the slope of the ratio.

The P/S ratio increases relatively steadily over the first ~ 17 km of transport, and then demonstrates a slight decrease until ~ 80 km (Fig. 6.1). The ~17 km and ~80 km distances correspond to important geomorphic variations in the watershed. From Chitina Glacier to ~17km, the Chitina River is heavily braided with no meaningful tributary, thus the only influence on grain surface modification is transport from the Chitina River. However, from ~17 to ~33 km downstream, the Barnard and Hawkins glaciers are intersected by the Chitina River. Grains sampled (CR-10 to CR-12) in this stretch of river exhibit an increase in occurrence frequency of sustained high stress

microtextures (Fig. 6.1) and a corresponding decrease in the P/S ratio (Fig. 6.1). A reasonable cause

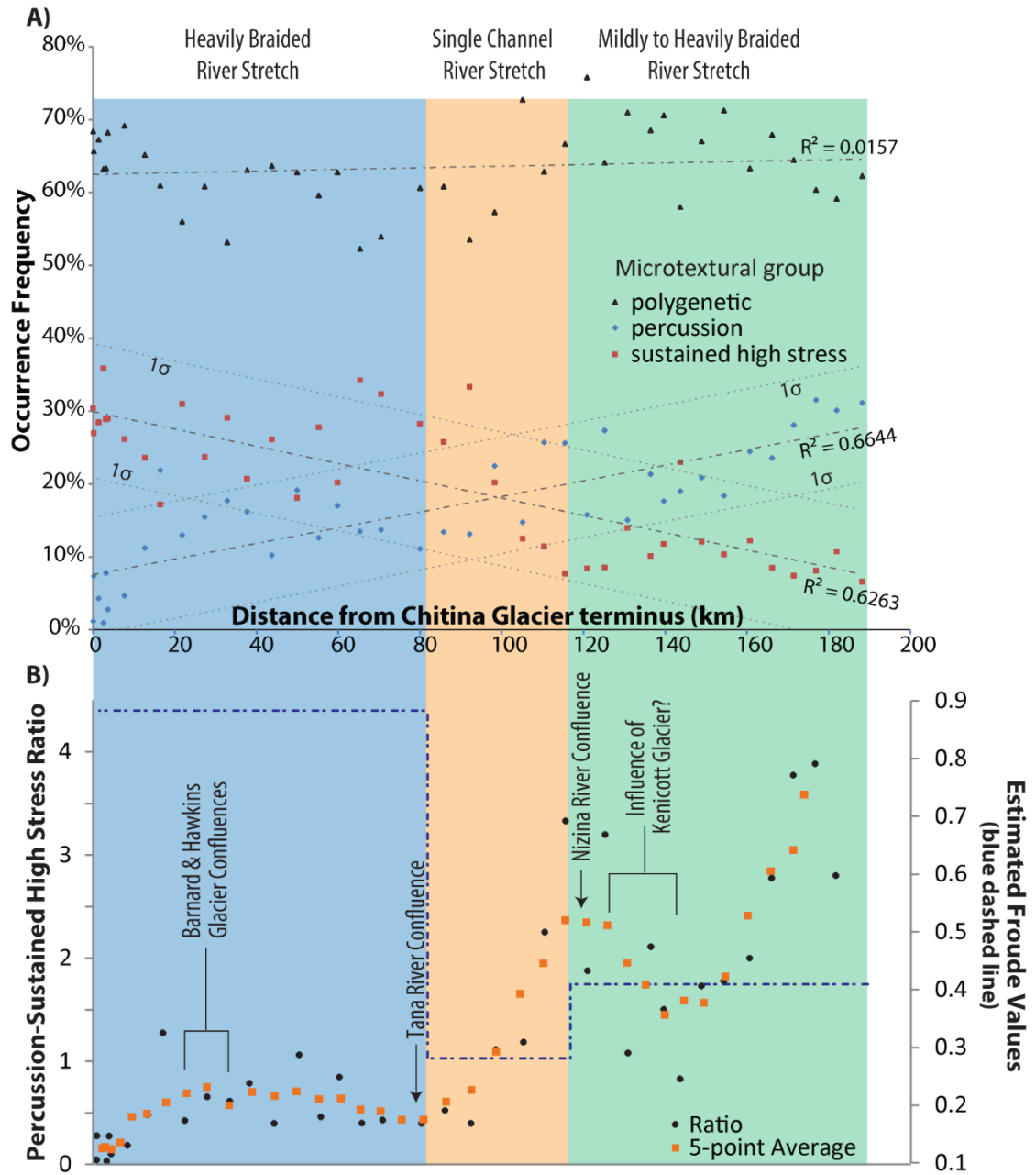


Figure 6.1: **A)** Occurrence frequency of genetic group relative to downstream distance with indicated changes in river physiography. **B)** P/S ratio (black squares) and 5-point running average (orange squares) shown relative to changes in river physiography.

of both of these changes is an influx of grains from both the Barnard and Hawkins glaciers. The glaciers provide material to the Chitina River that experienced predominantly glacial transport with little to no fluvial transport, thus the microtextural baseline from these glaciers likely resembles till from the Chitina Glacier (CR-1). This influx of new material with a predominant glacial transport history should suppress the P/S ratio and thus seems to be a reasonable cause for the P/S ratio decrease observed in this stretch of the river.

However, after the Barnard and Hawkins glaciers and prior to the Tana River confluence (~33 to 81 km of transport), the P/S ratio continues to decrease slightly. In theory, grains along this stretch of river should be modified by fluvial transport such that the percussion microtextures increase relative to the sustained high stress microtextures yielding the opposite trend in the P/S ratio than observed. The reason for this discrepancy in theory and observation is not clear, but one contributor may be degree of turbulence during channel transport. While sustained high stress microtextures remain fairly constant, over this stretch of river, percussion microtextures were observed on fewer grains towards the end of the interval, thus the slight ratio decrease is a function of decreased occurrence frequency of percussion microtextures. River morphology along this stretch is extensively braided, yet slope steadily decreases from ~0.004 to 0.002. Averages of water depth and instantaneous velocity indicate Froude values that approach 1 or supercritical flow. This style of turbulence may have resulted in longer periods of suspension during saltation which would result in fewer chances to impart percussion microtextures on grains.

Alternatively, the relatively constant sustained high stress microtextural trend along this stretch of the river may be the product of periodic isolated outbursts from the Barnard or Hawkins glaciers that resulted in substantial glacial grains falling from suspension 10-15 km from the source. In short, a solid interpretation is difficult due to the lack of hydrology data and the unpredictable nature of a fluvial system, but it seems quite probable that influence of the Hawkins and Barnard glaciers and/or hydrology of the system had some control in suppression of the P/S ratio along this stretch of the river.

After the Tana River confluence, the Chitina River converges into a single channel river. Downstream from the Tana River to the Nizina River confluence (~81 to 115 km) the P/S ratio more than doubles (Fig. 6.1). Two factors are potentially contributing to this increase. First, quartz grains supplied by the Tana River have experienced ~ 50 km of transport after liberation from the respective upstream glacier (Fig. 3.1). This distance of fluvial transport should have imparted significant component of percussion microtextures atop sustained high stress microtextures. However, the P/S ratio continues to increase steadily after the confluence suggesting another control. The second factor is likely more important and related to this particular stretch of river. The average Froude value for this stretch, using the same style of measurements as previously stated, is much lower (< 0.3) which may have resulted in shorter saltation distances and more chances to impart percussion microtextures.

The Chitina River transforms back into a moderately-to-heavily braided system after the Nizina River confluence. This change in river morphology also coincides

with an increase in sediment delivery and discharge from the Nizina River. Even with increasing discharge and sediment supply, the P/S ratio decreases by nearly a factor of 1 after the Nizina River confluence (Fig. 6.1). These results are unclear because the Nizina River should have supplied grains with up to 60 km of percussion transport (Fig. 2.1). However, approximately 20 km upstream of the Nizina River confluence, terminal moraines of the Kennicott Glacier are sourcing grains into the Nizina River system. Thus, if these grains resemble the baseline percentages of the Chitina Glacier till (CR-1), then the sustained high stress microtextures should increase and drive the ratio downward. Occurrence frequency of sustained high stress microtextures do generally increase just downstream of the Nizina River confluence, although not immediately at the confluence. However, after an additional 50 km of transport from the Nizina River confluence the P/S ratio begins to increase such that by the end of Chitina River three to four grains exhibited percussion microtextures for every grain that exhibited sustained high stress microtextures. This solid and progressive increase is likely attributable to increasing downstream distance from glacial termini. Overall, although heavily braided at times, the average water depth of channels is much deeper in this stretch of river, which results in lower Froude values and likely shorter saltation distances thus also potentially contributing to such strong surface modification.

6.2 Linear Regression Analysis

Linear regression was utilized to determine potential relationships between calculated and actual downstream distance. Equations from these trendlines were calculated for distance relative to three potential proxies (i.e. sustained high stress microtextures, percussion microtextures, and the P/S ratio) to assess potential

suitability and applicability to ancient systems. In addition, two different distance intervals were used for each proxy, the entire river (~188 km) and the initial ~17 km of transport (Table 6.1). The shorter distance interval was utilized because no outside influence other than fluvial saltation of grains derived directly from the Chitina Glacier could result in grain surface modification. The longer distance was utilized to assess if the trends observed in the modern were applicable to predict the ancient despite wide physiographic and hydrologic variations downstream. Calculated standard error (SE) is overall quite low, the P/S ratio (SE= ± 2.17 km), sustained high stress (SE= ± 0.96 km), and percussion (SE= ± 0.64 km), for the less than 17 km transport interval. In contrast, the P/S ratio (SE= ± 7.75 km), sustained high stress (SE= ± 4.79 km), and percussion (SE= ± 3.23 km) values had higher error values when calculated for the entire Chitina River. Yet, when SE is taken as a percentage of the total distance of the longer and shorter trend lines, the longer distance SE's are much lower. For example, the 188 km regression predicts a distance to ancient ice that ranges from 2-4% (range dependent on which of the three proxies is utilized) of the total distance, compared to 4-13% range for the shorter trends. Regardless, each of the

Table 6.1: Linear regression formulas calculated from ratio, sustained high stress, and percussion microtextures relative to traveled distance

	Ratio (~188km)	Ratio (~ 17 km)	Sustained High Stress (~188 km)	Sustained High Stress (~17 km)	Percussion (~188 km)	Percussion (~17 km)
Regression Equation	$x=(y-0.0324)/0.0146$	$x=(y-0.0126)/0.0562$	$x=-(y-0.2989)/0.0012$	$x=(y-0.3107)/0.0071$	$x=(y-0.0782)/0.0011$	$x=(y-0.0249)/0.0091$
Coefficient of Determination (R^2)	0.6417	0.7085	0.6248	0.658	0.6535	0.6256
Standard Deviation (SD)	48.39	6.5	30.33	2.893	20.44	1.92
Standard Error (SE)	± 7.75	± 2.17	± 4.79	± 0.96	± 3.23	± 0.64

proxies appear to show enough correlation with distance downstream in the Chitina River watershed that meaningful information could likely be predicted for ancient systems. However, these results need to be tested against a fairly well-known ancient system and corroborated by additional modern proglacial systems to assess if the Chitina River results are normal for a glacial system.

6.3 Application to Ancient Proglacial Systems

Data presented suggests that this tool may be applicable to ancient depositional systems. Questions of this study include; 1) how far downstream can glacially induced microtextures remain in a fluvial system while undergoing percussion modification; 2) does fluvial modification of glacially derived grains correspond to distance downstream; and 3) can the relationship of fluvially induced to glacially induced microtextures be utilized to reconstruct real river physiographic changes in a modern proglacial system? Cumulatively, data collected from the Chitina River supports the above hypotheses, and thus supports potential applications to ancient systems.

Currently, ancient coarse grained braided systems are separated into glacial or non-glacial on the basis of extensive flooding episodes. Extensive flooding episodes are currently thought to be indicative of glacial release during melting periods (eg. Maizels, 1993, 1997; Marren, 2002), however, extensive flooding in a coarse grained braided system could be caused by natural variation in seasonal flow from other means than glacial melt. The presence of sustained high stress features is presented as a proxy to establish glacial influence on ancient fluvial strata. Glacial influence could be established with the presence of sustained high stress microtextures in ancient

deposits. The presence of sustained high stress microtextures may then be used with more detailed proxy applications, including the occurrence frequency of microtextures, and the corresponding P/S ratio and sustained high stress texture survivability. Results of the data collected from the Chitina River in SE Alaska indicate the applicability of all the hypotheses initially stated in this study. However, further refinement for application to ancient strata requires these methods to be calibrated in additional modern proglacial systems.

CHAPTER 7

CONCLUSION

SEM analysis of quartz grains from the Chitina River, SE Alaska demonstrates that sustained high stress microtextures decrease with distance of fluvial transport, percussion microtextures increase with downstream fluvial transport, and polygenetic microtextures show no relationship to distance of transport. Results of this study were used to determine fairly consistent conclusions; however, the applicability of this study will require future modern analogs to corroborate these conclusions. Evaluated questions include; 1) how far downstream can glacially induced microtextures remain in a fluvial system while undergoing surface modification during percussion transport; 2) does fluvial modification of glacially derived grains correspond to distance downstream; and 3) can the relationship of fluvially induced to glacially induced microtextures be utilized to reconstruct real river physiographic changes in a modern proglacial system. Results that bear on these hypotheses are concluded below.

Glacially induced microtextures are observed in all samples collected from the Chitina River. Results of this study support that glacially liberated grains can survive at least ~188 km of fluvial transport if conditions are/were similar to the Chitina River. This conclusion is due to the persistence of glacially derived grains from the Chitina Glacier terminus to immediately prior to the Chitina-Copper River confluence. It is unclear if the dominant source of grains exhibiting sustained high stress microtextures at the end of the sampling transect are still sourced directly from the Chitina Glacier because multiple glacial origins are possible along the entire stretch of river. However, the persistent presence of sustained high stress microtextures indicates if

this style of microtextures is observed in ancient fluvial strata, then the best interpretation is proglacial.

Fluvial transport modifies the surface of glacially derived grains. The most common modifications suggested by this study are in the form of edge rounding and v-shaped percussion cracks (i.e. percussion microtextures). These percussion features overprint glacially imparted surface textures and become progressively more common with distance downstream. The P/S ratio, sustained high stress microtextures, and percussion microtexture occurrence frequency demonstrate modest to strong correlation with distance downstream. Linear regression of those relationships may be applicable to reconstruct the extent of past glacial events. Applying a linear regression equation to estimate transport distance from glacial termini requires further calibration and comparison with additional modern proglacial systems, but is a promising tool for future application to ancient systems.

The P/S ratio appears to record real physiographic changes within the Chitina River. The most direct response in the P/S ratio is when the Chitina River intersected the toes of glaciers. In these instances, the P/S ratio decreased in the sample directly downstream from the intersection and the decrease is attributable to an increase of grains with solely glacial transport introduced into the river. Additionally, the P/S ratio appears to record the addition of grains from main tributaries. For example, grains delivered by the Tana River substantially increase the ratio as would be expected if grains supplied to the Chitina River had experienced significant fluvial modification.

Overall, data collected from the Chitina River support the argument that this tool can be used as a proxy to determine the presence and extent of ancient ice in systems that are lacking sedimentologic features that are historical hallmarks of ice presence. For example, proglacial braided river facies models are only differentiated from nonglacial braided river facies by the presence of large and abundant floods (e.g. Maizels, 1993, 1997; Marren, 2002) which is limited since all braided systems can experience flooding events. Therefore, utilizing microtextures on quartz grains from ancient braided rivers can significantly augment current facies models.

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PLATE 1
CHITINA TOPOGRAPHIC MAP

Plate 1: Chitina River topographic map with sampling locations

