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Quartz Grain Microtextures and Sediment Provenance: Using Scanning Electron Microscopy to Characterize Tropical Highland Sediments from Costa Rica and the Dominican Republic

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To the Graduate Council:

I am submitting herewith a thesis written by Sarah Marie Deane entitled "Quartz Grain Microtextures and Sediment Provenance: Using Scanning Electron Microscopy to Characterize Tropical Highland Sediments from Costa Rica and the Dominican Republic." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Kenneth H. Orvis, Major Professor

We have read this thesis and recommend its acceptance:

Sally P. Horn, Carol P. Harden

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Thesis Presented for the
Master of Science Degree
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Sarah Marie Deane
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ABSTRACT

Microtextures recorded on quartz sand grain surfaces provide evidence of past environment. Environmental processes, such as transport by glacial ice, create unique microtextures on sand grain surfaces that can be observed under high magnification with a scanning electron microscope. These microtextures and their proportions tend to be unique to environment type, allowing investigators to infer the environmental conditions to which sediments have been exposed, for example to distinguish sediments from fluvial versus mass-wasted environments. Microtextural evidence also allows inferences about the history of sediments of unknown origin.

This thesis determines the qualitative and quantitative microtextural fingerprint of glacigenic quartz sand grains deposited by small tropical alpine glaciers in Costa Rica, and compares that fingerprint to the fingerprints of highland Dominican Republic sediments of uncertain genesis, to gauge whether those, individually or grouped, resemble the Costa Rican glacigenic samples.

I selected 18 samples (9 each from Costa Rica and the Dominican Republic) and analyzed a minimum of 100 quartz sand grains per sample using a scanning electron microscope. My sample sizes were dictated by the scale of empirical 99% confidence intervals that would allow meaningful comparison of samples. Analysis using literature-recommended numbers of quartz sand grains would entail such large confidence intervals that practically any results would have been indistinguishable. I recorded the presence or absence of 25 microtextures on each grain, and calculated the percentage of each microtexture's occurrence in the sample. The percentages constituted the sample's microtextural fingerprint. As a whole, the Costa Rican fingerprints were very similar to each other, and so were the Dominican Republic fingerprints.

Further comparison led me to conclude that the Dominican Republic samples are statistically indistinguishable from the Costa Rican glacierized samples.

This thesis is part of a larger project establishing protocols for distinguishing glacigenic from non-glacigenic sediments, and testing for glacigenicity of sediments in Costa Rica, the Dominican Republic, and elsewhere. My results can be applied in other studies distinguishing tropical highland glacigenic and non-glacial samples. My contribution will hopefully contribute toward completion of the project's goals, specifically determining the presence or absence of past glaciers in the Dominican Republic.

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CHAPTER 1. INTRODUCTION

1.1 Subject of the Thesis

Scanning electron microscopy of quartz sand grain microtextures can provide evidence of sediment genesis and transport (henceforth "environmental provenance"). Sand grains are sculpted by the kinds of forces and processes that typify the environments that generate them, and that sculpting remains until overwritten by new events. The environmental conditions in which a sand grain forms, typically by separation from parent rock as with glacial grains from fracture of bedrock clasts, are recorded in surficial microtextures. Eolian, fluvial, mass-wasting, glacial, and other processes all create combinations of microtextures on sand grain surfaces that are unique in the types exhibited and their statistical frequency. These combinations of microtextures record the paleoenvironmental history of the area from which the grains were derived; the various forms of fractures and post-fracture surface alterations found on sand grain surfaces should therefore provide useful evidence of climate and other environmental aspects of the sand grain's history.

Physical and chemical processes that modify sand grain surfaces vary from environment to environment. For example, the quarrying and grinding and transport by glacial ice that create U-shaped valleys, eskers, kettle lakes, and lateral and terminal moraines at the landscape scale also generate distinctive microtextures on the surfaces of micrometer-scale quartz sand grains. The presence, or absence, of certain diagnostically glacigenic microtextures is thought to serve as a test for past glaciation (Krinsley and Doornkamp 1973; Mazullo and Ritter 1991; Mahaney 1995; Mahaney et al. 1996; Helland et al. 1997; Mahaney 1998; Mahaney and Kalm 2000; Mahaney et al. 2001; Mahaney 2002; Strand et al. 2003; Mahaney et al. 2004; Bernet and Bassett 2005). In fluvial environments, water velocity affects both grain shape and the frequency of surface fractures found on sediments; v-shaped percussion fractures are considered indicative of water transport (Mahaney 2002). Sediments that share a particular series of provenance histories should exhibit similar, diagnostic patterns of surface microtextures; therefore one should be able to determine environmental provenance by identifying such patterns at sufficiently high magnification with a scanning electron microscope (SEM).

While it is true that a proportion of sand grains can pass through an environment, such as a glacial system, without being physically affected, those grains that are affected will tend to display the characteristic microtextures caused by the unique environmental processes that occur within it. According to one school of thought, the mere presence of diagnostic microtextures, whether glacial, fluvial, or littoral, on a single quartz grain within a sample equates to evidence of the environmental provenance of the sample; however, it seems doubtful that evidence from a single grain can so unequivocally represent a large sample. To robustly provide evidence of environmental provenance, diagnostic microtextures should occur on a reasonable proportion of all sand grains within the larger sample. A "one grain diagnosis" is not sufficient to determine the environmental provenance of a body of sediment; nor should the mere presence of any single type of microtexture be used to infer environmental provenance (Culver et al. 1983). For example, certain microtextures have been described as typically glacial in origin (paired curved grooves, sharp edges, and step-like features), but the presence of a single "diagnostic" microtexture cannot be considered sufficient enough evidence to determine glacigenesis (Mahaney et al. 1996). V-shaped percussion fractures are identified as diagnostic of fluvial environments, but this fracture type alone should not be considered sufficient to confirm environmental provenance of an entire sediment sample. Rather, the totality of microtextures identified on a representative number of sand grains should be used.

William Mahaney has published a number of studies on the use of SEM to analyze quartz microtextures. His *Atlas of Sand Grain Surface Textures and Applications* (2002) gives detailed descriptions of the microtextures found on quartz grains from various environmental settings: eolian, mass-wasted, fluvial, glacial, and others. Mahaney also discusses typical sample preparation methods for SEM analysis. Quartz (SiO_2) provides an ideal substrate for microtextural study because of its durability, hardness (7 on the Moh scale), and lack of cleavage. Textures resulting from environmental pressures, such as fractures that occur during transport by ice, are not easily eroded (Mahaney 2002). The effects of glacial weathering on quartz sand grains have been explored in numerous studies (e.g., Krinsley and Doornkamp 1973; Doornkamp 1974; Mazullo and Ritter 1991; Mahaney 1995; Mahaney et al. 1996; Mahaney 1998; Mahaney and Kalm 2000; Mahaney et al. 2001; Mahaney 2002; Strand et al. 2003; Mahaney et al. 2004; Bernet and Bassett 2005). Quartz is found in almost all environments, which also increases its value as an indicator: its microtextures can easily be compared site-to-site.

If specific environmental processes generate microtextures distinct in type and frequency on the surfaces of sand grains, it follows that sediments of similar provenance should display similar microtextural signature patterns. These patterns should be unique to environmental provenance. That said, if one can characterize the microtextural signature patterns of sediments with known origins, then it may be possible to classify sediments of unknown origin by comparing signatures. For example, the tropical highlands of Costa Rica are known to have supported alpine glaciers in the past. Other tropical highland locations, such as the Cordillera de Talamanca in the Dominican Republic, are purported to have been glaciated, but this has not been definitively proven. Should SEM analysis reveal a common microtextural signature among

Costa Rican glacierized tropical highland sediments, this pattern could be used to test sediments from similar locations in the Dominican Republic for glacigenicity. In that way one could make inferences about the past climate of the Dominican Republic tropical highlands based on the degree of similarity or contrast between microtextural signature patterns. I therefore propose to test the usefulness of scanning electron microscopy as a tool for characterizing sediments as to environmental provenance by analyzing and comparing samples of quartz sand grains from the tropical highlands of Costa Rica and the Dominican Republic.

In an effort to characterize the microtextural signature of known glacigenic sediments and to then classify purportedly glacigenic sediments as to provenance, I will address the following questions:

1. What is the qualitative and quantitative microtextural fingerprint of glacigenic quartz sand grains produced by small tropical-highland alpine valley-glacier systems?
    a. Do Costa Rican samples that should be similar—that are from the same sediment deposit or class of sediment—resemble each other?
    b. Do Costa Rican samples that are known to be glacial in origin resemble each other?
2. Is the glacigenic microtextural fingerprint information from (1) above useful in characterizing deposits of uncertain provenance and gauging whether samples and groups of samples are distinguishable from known glacigenic samples?
    a. Do downslope diamict deposits collected in the Río Chirripó valley appear to differ from upslope glacial deposits?
    b. Do putative Dominican Republic glacial samples appear to differ from known glacigenic samples from Costa Rica?

1.2 Purpose

The intent of this thesis is to first discern a common microtextural signature pattern of known glacierized sediments from Costa Rica, and, then, apply this fingerprint to sediments whose origins are less certain, in an attempt to infer environmental provenance. These will include Costa Rican sediments that appear to be translocated glacial till, and Dominican Republic samples of unknown origin. The degree of similarity between samples from the different locations will direct any conclusions that I can make regarding glacigenicity of the Dominican Republic samples. My thesis is one part of a larger project whose aim is to establish protocols to distinguish between glacigenic and non-glacigenic sediments, and to eventually test for glacigenicity among diverse sediments in Costa Rica, the Dominican Republic, and elsewhere. If the methods proposed in this thesis prove reliable, those methods can then be used to classify other field sediment samples as to provenance (e.g., eolian vs. littoral, fluvial vs. glacial) based on microtextural fingerprints. For the larger project, my thesis will aid future research on distinguishing tropical highland glacigenic field sediment samples from those of non-glacial provenances from the same region. The Costa Rican upland sites studied in the thesis are known to have been glaciated (Orvis and Horn 2000). The samples from the Dominican Republic were collected at sites which would yield englacial grains if there were in fact glaciers in the past. In that way, field sediment samples collected from the Dominican Republic could be analyzed for evidence in support of or rejection of glacigenicity. My contribution to the project should allow the completion of these remaining goals and allow the project to make suitable inferences about the past climate of the Dominican Republic, specifically the presence or absence of glaciers within the last 45,000 yr B.P.

Reconstructing past climate using scanning electron microscopy of quartz grain microtextures, specifically by distinguishing climatically marginal continental and alpine ice presence versus absence in the last glacial period, would also further paleoclimatological and glaciological research. Researchers agree that the microtextures found on sediment surfaces record the environmental conditions under which sediments were modified, and reliable SEM analytical techniques to identify surface microtextures have long been established. The ability to robustly determine environmental provenance based on microtextural signature patterns, specifically inferring provenance of unknown samples, will confirm the value of SEM to paleoenvironmental research. The purpose of this thesis is to lay the groundwork for the larger project, the end product of which will hopefully be the ability to answer questions of glacial environmental provenance based on microtexture signature patterns. I will discuss further the implications of my findings and the recommended final steps of the project later in this thesis.

1.3 Sample Locations

The sand grains analyzed were separated from field sediment samples that had been previously collected from diamictons and other deposits in the mountains of Costa Rica and the Dominican Republic, at elevations ranging from 1700–3700 m (Figures 1 and 2). This thesis focuses on field sediment samples from the last 45,000 yr B.P., and includes some that are less than 10,000 years old. These cover both the late Pleistocene and Holocene epochs of the Quaternary period. The field sediment samples were collected from Costa Rican and Dominican Republic sites that Orvis and Horn and collaborators either know (in the case of controls) or hypothesize (in the case of test samples) represent glacial sediments. The samples analyzed were chosen out of a larger body of work of the research of Orvis and Horn; I examined particle size

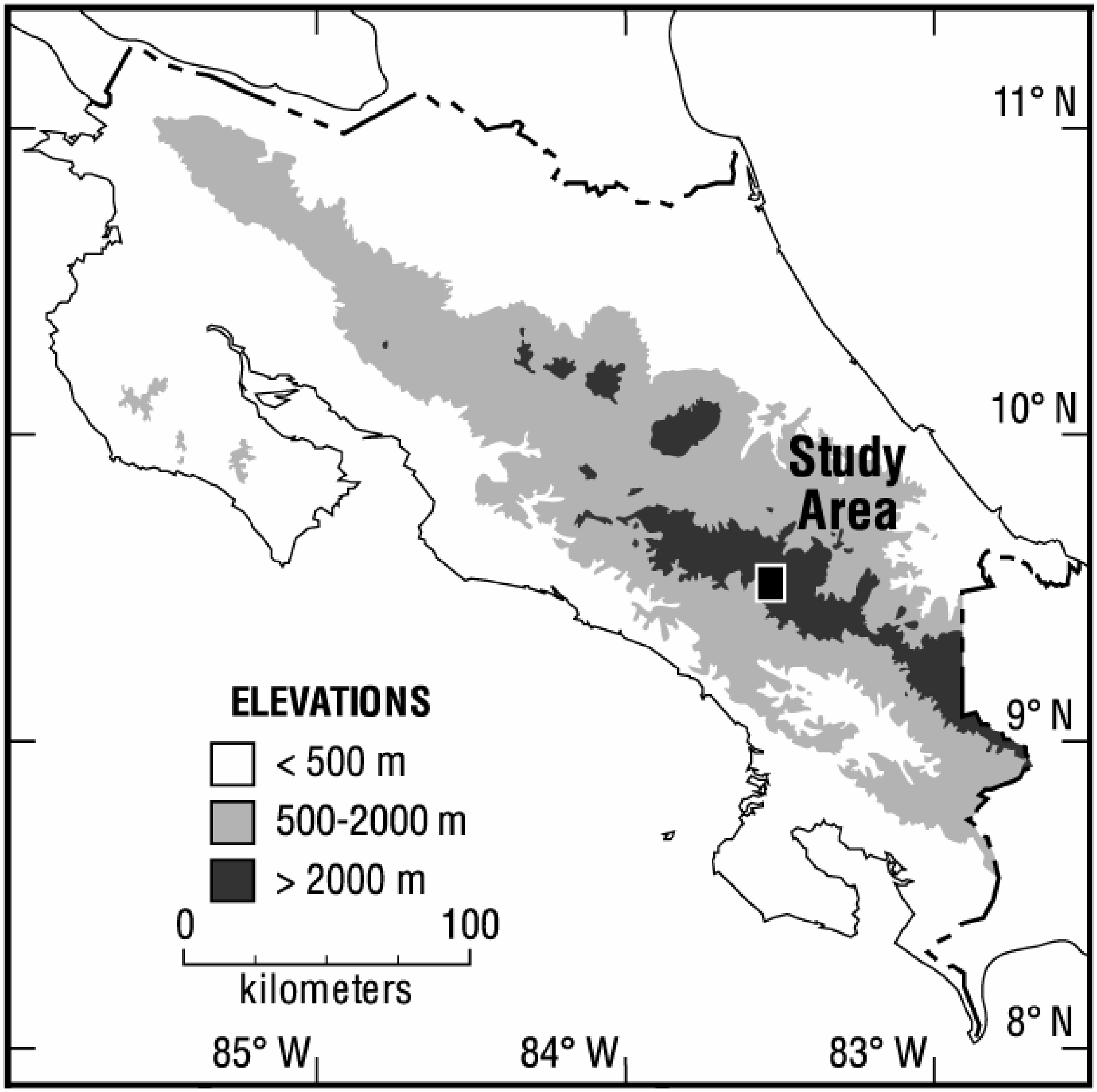

Figure 1. Location of the Chirripó highlands in the Cordillera de Talamanca of southern Costa Rica, source of glacigenic sediment samples analyzed in this thesis; from Orvis and Horn (2000).

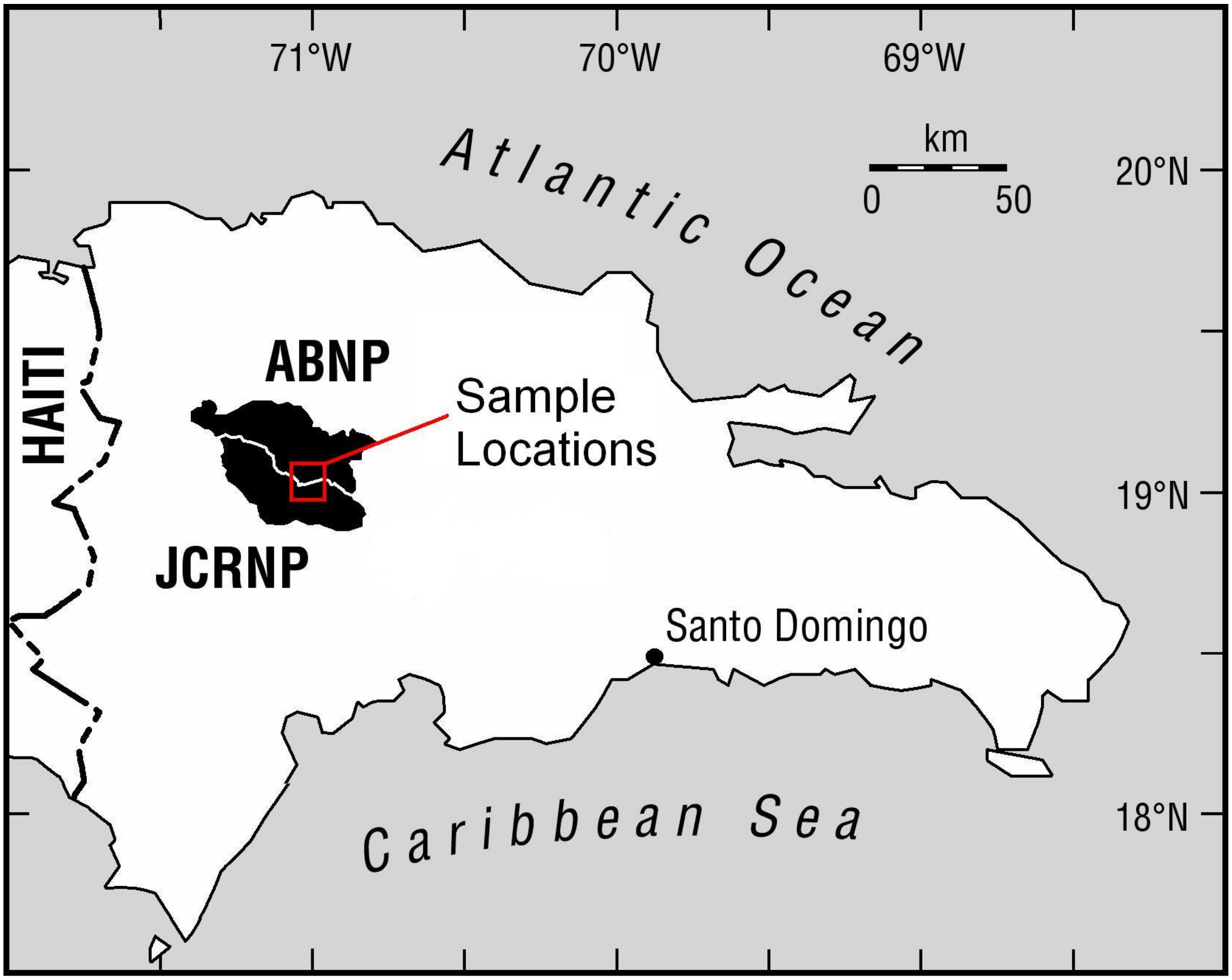

Figure 2. Location of the Macutico and El Valle de Bao sampling sites in the Cordillera Central of the Dominican Republic, modified from Horn et al. (2000). Macuticó (samples 11–17) is located in José del Carmen Ramírez National Park (JCRNP); el Valle de Bao (sample 18) is in Armando Bermúdez National Park (ABNP).

analysis records from those and selected candidates that I deemed would best provide a test for microtextural fingerprinting.

1.3.1 Cerro Chirripó, Cordillera de Talamanca, Costa Rica

Costa Rica is located on the Central American isthmus, bordered by Nicaragua in the north and Panama in the south. The Cordillera de Talamanca is a non-volcanic mountain range that trends north-northwest to south-southeast along the southern portion of Costa Rica's Central Highlands and into Panama. It is the highest and largest mountain range in that area of Central America. During the last glacial maximum, the higher peaks of the Cordillera de Talamanca supported small ice caps and alpine glaciers. The high elevations cooled enough to support ice at elevations above 3300 m. The present-day landscape is a mixture of glacial landforms (cirques, moraines, and lakes) amidst open slopes with a few highland bogs (Horn 1990).

Cerro Chirripó (3819 m, 9°29'08" N, 83°29'27" W) is the highest peak of the Chirripó massif of the Cordillera de Talamanca in Costa Rica (Orvis and Horn 1999). Treeless páramo vegetation covers elevations from approximately 3300 to 3800 m on Cerro Chirripó, while oak trees are the dominant taxon in the sub-alpine forests (3100–3400 m) and the montane forests (2100–3200 m), as described by Horn (1993). Páramo ecosystems are grasslands, characterized by the absence of trees and the presence of various grasses, shrubs, sedges, mosses, and other non-arboreal taxa. The Chirripó páramo, which is the largest of the many pockets of páramo vegetation in the Cordillera de Talamanca, is dominated by a dwarf bamboo, *Chusquea subtessellata*, as well as a variety of evergreen shrubs (Horn 1993; League and Horn 2000). Climate on the Chirripó páramo has a marked seasonality; the dry season, which occurs during northern hemisphere winter, lasts between 4 and 5 months (League and Horn 2000). Between

1971 and 1984, mean rainfall in the wet season (May through November) was 2260 mm, whereas the dry season (December–April) averaged 270 mm. Mean annual temperature during 1971–1979 was 7.6 °C at the Cerro Páramo meteorological station (3475 m) (Orvis and Horn 2000; League and Horn 2000). The Costa Rican sites that this thesis focuses on include tills in the glacial valley abutting Cerro Chirripó to the north, Valle de las Morrenas, and debris flow deposits forming a series of Pleistocene terraces in the canyon of the Rió Chirripó Pacifico at San Gerardo de Rivas, a town at the western base of the Chirripó massif.

Valle de las Morrenas

Valle de las Morrenas ("valley of the moraines") is an alpine glacial valley located within the Chirripó páramo on the north face of Cerro Chirripó (Orvis and Horn 2000). Orvis and Horn (2000) described this as a well developed glacial trough with a compound cirque headwall, numerous ponds and lakes, various moraines, and several rock thresholds. Cerro Chirripó is in fact a glacial horn that defines part of the southwestern headwall of the valley (Orvis and Horn 2000). Based on lake sediments, Horn (1990) determined a deglaciation date for Valle de las Morrenas of ~10,000 ^{14}C yr B.P. My SEM sample 1 is from a glaciolacustrine field sediment sample from that study, taken immediately below the deglaciation horizon in the lake sediments. Samples 2–5 and 8 are from field sediment samples collected from ground moraines and lateral moraines in Valle de las Morrenas, Costa Rica (Table 1).

San Gerardo

Samples 6, 7, and 9 are from field sediment samples that were collected in the San Gerardo de Rivas area of Costa Rica (Table 1). San Gerardo is a small town at the base of the Chirripó massif, and is often the starting point of Chirripó expeditions. The San Gerardo field sample sites are located in the Río Chirripó Pacifico valley, from Pleistocene terraces within the

Table 1. Sample locations and descriptions, Costa Rica

Sample	Site Area	Region	Elev. (m)	Coordinates	Site Description
Sample 1	Valle de las Morrenas	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	3477	9º29'35" N, 83º29'7" W	Collected from Lake 1 (Lago de las Morrenas 1), 596–600 cm below the sediment-water interface
Sample 2	Valle de las Morrenas	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	3455	9º29'35" N, 83º29'7" W	Collected from the distal side of the till exposure in the small outlet canyon below Lake 4
Sample 3	Valle de las Morrenas	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	3455	9º29'35" N, 83º29'7" W	Collected from the distal side of the till exposure in the small outlet canyon below Lake 4
Sample 4	Valle de las Morrenas	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	3430	9º29'35" N, 83º29'7" W	Collected from a lateral moraine in the lee of the waterfall rock step also below Lake 4
Sample 5	Valle de las Morrenas	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	3430	9º29'35" N, 83º29'7" W	Collected from a lateral moraine in the lee of the waterfall rock step also below Lake 4
Sample 6	San Gerardo	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	1472	9º29'35" N, 83º29'7" W	Collected from the upper terrace of the San Gerardo canyon
Sample 7	San Gerardo	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	1358	9º29'35" N, 83º29'7" W	Collected from the main-river terrace matrix
Sample 8	Valle de las Morrenas	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	3535	9º29'35" N, 83º29'7" W	Collected from the moraine damming Lake 2-A
Sample 9	San Gerardo	Cerro Chirripó, Cordillera de Talamanca, Costa Rica	1401	9º28'7" N, 83º35'26" W	Collected from the north side of Río Chirripó, upper San Gerardo

canyon. The terraces are composed of debris-flow deposits, which are hypothesized to have moved down the mountain from areas of glacial activity (Orvis, pers. comm.[1]). The deposits are conjectured to be the result of mountaintop glaciers advancing down onto slopes too steep to hold them or their moraines. The clasts of the debris flows vary in size, from boulders over 10 m in length to silt-sized materials.

1.3.2 Cordillera Central, Dominican Republic

The Dominican Republic comprises the eastern side of the island of Hispaniola, which is the second largest island of the Greater Antilles. The Cordillera Central mountain range, which extends across Hispaniola in a northwesterly direction, has three peaks over 3000 m and more than 20 higher than 2000 m (Bolay 1997; Orvis et al. 1997; Kennedy et al. 2006). Cordillera Central uplift was Plio-Pleistocene, and the basement lithology is mainly Cretaceous, including accreted sedimentary and metamorphic rocks and island-arc plutonics (Orvis et al. 1997). Long-term climatic data are unavailable for the highlands, but general trends have been derived from lower-elevation weather stations (Kennedy et al. 2006). Trailing winter mid-latitude fronts (from the northwest) and the northeast tradewinds are blocked by the Cordillera Central and, therefore, the north flank receives at least 45–50% more precipitation annually than its southern counterpart. Winter weather is typically defined by dry, stable conditions apart from the occasional mid-latitude storm front (Orvis et al. 1997; Kennedy et al. 2006). Horst (1992) estimated leeward rainfall levels of 625–825 mm annually, and 1750–2500 mm annually on windward slopes (Kennedy et al. 2006). Elevations above 2100 m across the Cordillera Central can experience sub-freezing temperatures at night year-round; diurnally highland temperatures

[1] Dr. Orvis studied ice and sediment dynamics under glaciologist John Menzies at Brock University, Ontario, in 1997, and in turn has shared insights he gained there with me. In this chapter and later chapters I cite concepts of that intellectual heritage as “Orvis, pers. comm.”

can range from less than 0 to over 30 °C (Kennedy et al. 2006). Higher elevations (>1800 m) on both sides of the Cordillera Central are dominated by *Pinus occidentalis*; most broadleaf species are not usually found at elevations above 2500–2600 m. Understory vegetation on the windward flank is both denser and richer due to higher rainfall levels.

Although some evidence supports a history of glacial activity in the Cordillera Central, no one has unequivocally proven that glaciers existed there. Aerial photography revealed suspected glacial geomorphic features in the Cordillera Central, including cirque-like depressions (Schubert and Medina 1982). Climate during the last Pleistocene glacial advance appears to have varied on Hispaniola as in other tropical areas. Late Cenozoic block fields, alluvial fans, and cirque-like features all suggest formation during climatic regimes which differed greatly from the present interglacial conditions (Orvis et al. 1997). Orvis et al. (1997) concluded that evidence exists to support an inference of valley glaciation and moderate cirque formation in the Hispaniola highlands during the last glaciation. El Valle de Bao and Macutico, the two principal study sites in the Dominican Republic (Figure 2), are on opposing flanks of the Cordillera.

El Valle de Bao

El Valle de Bao (~1800 m valley floor elevation, 19°04' N, 71°05' W) is located in Armando Bermúdez National Park on the northeastern flank of the Cordillera Central (Orvis et al. 1997; Clark et al. 2002). This savanna is treeless; *Danthonia domingensis* and other grasses and sedges dominate the valley floor. The slopes of Loma del Pico and Loma la Pelona, the peaks surrounding this valley, are home to pine stands on the lower and upper levels and to broadleaf trees at certain mid-slope positions from which cold air drains (Kennedy et al. 2006). Most typically, freezing temperatures occur above 2100 m in the Cordillera Central, but El Valle de Bao will freeze at 1800 m when cold air drains from higher slopes and pools on the valley floor (Orvis et al. 1997). Alluvial fans are visible in aerial photographs below the east wall of Valle de Bao, but other geomorphic aspects are suggestive of a glacial history in the drainage above (Orvis et al. 1997). Sample 18 was collected in the upper drainage of El Valle de Bao from a candidate till deposit exposed on the floor of a possible cirque (Table 2).

Macutico

The Macutico region (~2000 m, 19°02' N, 71°05' W) is located within José del Carmen Ramírez National Park, on the southwest flank of the Cordillera Central, nearly opposite to El Valle de Bao (Horn et al. 2000). The savanna landscapes (sabanas) found scattered throughout Macutico and nearby areas are dominated by grasses, specifically *D. domingensis*; this region has a long history of fire (Kennedy et al. 2005). The underlying geology in the Macutico sites is the granitoid Macutico batholith (Horn at al. 2000; Clark et al. 2002), a parent material for sediments that is fairly similar to the granodiorites that underlie much of Valle de Las Morrenas in Costa Rica. Río Macutico and its tributaries have headwaters on the southwestern flank of the Cordillera Central and flow through Macutico; of the several lakes found here, Laguna Grande de Macutico is the largest (Orvis et al. 1997; Kennedy et al. 2005). My SEM samples 10, 11, and 17 are from field sediment samples that were collected from suspected ground and terminal moraines near Río Macutico; samples 12–15 and 18 are from field sediment samples that were collected by coring from mineral facies that underlie Laguna Grande de Macutico (Table 2).

Table 2. Sample locations and descriptions, Dominican Republic

Sample	Site Area	Region	Elev. (m)	Coordinates	Site Description
Sample 10	Macutico	Cordillera Central, Dominican Republic	1997	19º2'1" N, 71º4'22" W	Collected from a diamict along Río Macutico
Sample 11	Macutico	Cordillera Central, Dominican Republic	2000	19º1'60" N, 71º4'26" W	Collected from a diamict along Río Macutico
Sample 12	Macutico	Cordillera Central, Dominican Republic	2055	19º2'0" N, 71º5'29" W	Collected from Laguna Grande de Macutico, 258.5–260 cm below the sediment-water interface
Sample 13	Macutico	Cordillera Central, Dominican Republic	2055	19º2'0" N, 71º5'29" W	Collected from Laguna Grande de Macutico, 271–273 cm below the sediment-water interface
Sample 14	Macutico	Cordillera Central, Dominican Republic	2055	19º2'0" N, 71º5'29" W	Collected from Laguna Grande de Macutico, 177–181 cm below the sediment-water interface
Sample 15	Macutico	Cordillera Central, Dominican Republic	2055	19º2'0" N, 71º5'29" W	Collected from Laguna Grande de Macutico, 240.5–243.5 cm below the sediment-water interface
Sample 16	Macutico	Cordillera Central, Dominican Republic	2055	19º2'0" N, 71º5'29" W	Collected from Laguna Grande de Macutico, 271–278 cm below the sediment-water interface
Sample 17	Macutico	Cordillera Central, Dominican Republic	1991	19º2'7" N, 71º4'38" W	Collected from a long diamict scarp transverse to Río Macutico
Sample 18	El Valle de Bao	Cordillera Central, Dominican Republic	2382	19º1'39" N, 71º2'30" W	Collected from a cutbank in recent incision of a cirque-like headwater hollow above Valle de Bao

1.4 Thesis Organization

I conducted this thesis research in four basic phases. The first was a reconnaissance phase wherein I researched and tested various laboratory and microscopy techniques. I created a Lithium heteropolytungstate heavy liquid separation procedure to isolate 250–125 µm quartz grains from other 250–125 µm grains within each mixed-mineral sand sample. All field sediment samples had been collected on previous research trips to Costa Rica and the Dominican Republic by Orvis and Horn and collaborators. Prior to preparation for SEM analysis, the sands had undergone particle size analysis preparation, including, in addition to already separating sand size classes suitable for SEM analysis, treatment to remove organics and to reduce adhering metal oxides and carbonates that could have cemented particles together after they were originally deposited. Carbonates were removed using a solution of acetic acid buffered with sodium acetate, metal oxides using buffered sodium hydrosulfite, and organics with 30% H_2O_2. The remaining three phases of my research included mounting and preparation for SEM viewing, SEM analysis, and the statistical analysis of data—including the original development of statistical tests in collaboration with my advisor, Dr. Orvis. With a scanning electron microscope, I analyzed sand grain surfaces for the presence or absence of microtextures suggested to be characteristic of glacigenic sediments in the literature (Table 3). This list was compiled from multiple studies (Krinsley and Donahue 1968; Margolis and Kennett 1971; Krinsley and Doornkamp 1973; Higgs 1979; Bull 1986; Mahaney 1991; Helland and Holmes 1997; Mahaney and Kalm 2000; Mahaney 2002). Finally I report the results of the statistical testing for these microtextural signature patterns among and across eighteen samples of fine (250–125 µm) quartz sand grains collected as described above in glacierized or purportedly glacierized areas of the tropical mountains of Costa Rica and the Dominican Republic.

Chapter 1 introduces the subject of the thesis and the study area. Chapter 2 covers the background of the research: the history of scanning electron microscopy and its applicability in paleoenvironmental studies, specifically applications involving the analysis of sand grain microtextures; the dynamics of englacial environments as they affect sand grains; and the design of the research conducted for this thesis. Chapter 3 describes the methodology of the thesis: sample preparation, scanning electron microscopy, and statistical analysis. Chapter 4 presents the results, and chapter 5 includes discussion of research implications and my broader conclusions.

Table 3. List of common microtextures associated with glacigenic sediments (Krinsley and Donahue 1968; Margolis and Kennett 1971; Krinsley and Doornkamp 1973; Higgs 1979; Bull 1986; Mahaney 1991; Helland and Holmes 1997; Helland et al. 1997; Mahaney and Kalm 2000; Mahaney 2002).

1) Fracture Face	14) Weathered Features
2) Sub-parallel Linear Fractures[2]	15) Adhering Particles
3) Conchoidal Fractures	16) Precipitation Features
4) Curved Grooves	**17) Linear Steps**
5) Straight Grooves	**18) Deep Troughs**
6) Sharp Angular Features	**19) Mechanically Upturned Plates**
7) Low Relief	20) Abrasion Features
8) Medium Relief	21) V-shaped Percussion Fractures
9) High Relief	22) Radial Fractures
10) Crescentic Gouges	**23) Breakage Blocks**
11) Arc-Shaped Steps	24) Edge Rounding
12) Dissolution Etching	25) New Growth
13) Preweathered Features	

[2] Microtextures considered to be diagnostically glacigenic are listed in bold. Numbers preceding microtexture names are for descriptive purposes only.

CHAPTER 2. BACKGROUND

2.1 Scanning Electron Microscopy

By definition a scanning electron microscope (SEM) uses an electron beam to scan the surface of a specimen, and then uses temporal variations in the electron reflection intensities to assemble an image of the specimen (Bozzola and Russell 1998). Unlike transmission instruments, which project electrons through thin-section specimens to create a 2-dimensional image, scanning electron microscopes allow users to image and analyze a 3-dimensional specimen. Transmission electron microscopes have been around since the 1930s, but the commercial introduction of the SEM in the 1960s allowed for routine surface analysis of solid specimens (Bozzola and Russell 1998).

An SEM uses an electron gun as its illumination source and magnetic fields as lenses. A condenser lens focuses the flux of electrons into a thin beam, which then passes through scan coils, to adjust focal length. The beam is then refocused into a minute spot by an objective lens and the spot scans across the specimen to create a raster. The electrons are both interacting with and controlled by the oscillating electromagnetic field created by the scan coils (JEOL 2006). The secondary electrons (SE), those emitted by the specimen after it has been bombarded by the electron gun beam, form the signal collected by the detector, and this signal is amplified and reassembled into an image by reconstructing the scan pattern of the excitation beam. The SE are very low energy electrons and therefore only those emitted at or very near the surface of the specimen—as opposed to deep within it—can escape the specimen to contribute to the image (JEOL 2006). The image displayed on the SEM viewing screen recreates the spatial pattern of different levels of brightness sensed by the SE detector. Thus the SEM uses sequential, time-based detections, mapped to the spatial position of the beam at the time, to create an image.

The advent of digital technology enables a pixel-by-pixel raster scan as opposed to the older analog imaging technique of lines and spacing on a fluorescing screen. SEM magnifies by changing the size of the scanned region on the specimen. Higher magnifications are created by scanning a smaller region and then require a smaller focused beam spot. A higher magnification on the viewing screen is therefore a smaller raster on the specimen. In order for the detector to accurately capture a signal, the electron beam must function in a vacuum; air in the specimen chamber will scatter the electrons and interfere with detection. The specimen must also be coated with a conductive layer to prevent charging of the specimen and subsequent imagery complications. Image quality primarily reflects the signal-to-noise ratio related to these two issues. A poor signal-to-noise ratio results in snowy or grainy images; the signal must be substantially greater than the noise for the image to appear smooth (JEOL 2006). For sharp images, the size of the beam spot must be approximately equal to the finest detail of the specimen that is of interest to the investigation.

2.2 SEM Analysis of Sediments

The SEM has many practical applications in environmental studies. Its various methods of surface analysis allow scientists to view sediments of various kinds, charcoal, pollen, and other materials at high magnification, resolving details otherwise unavailable. In studies of glacial environments, sand grains have been analyzed to determine the effects of ice thickness (overburden pressure) and relative transport distance within ice on surface microtextures. Comparisons between alpine and continental glaciers reveal differences in the frequency of fractures; fractures are more commonly created under greater pressures, found under thicker ice (Mahaney 1995). Non-glacial microtextures found on a glacially transported grain give clues to weathering processes and similar history both before and after glacial transport occurred. In early studies, the presence or absence of certain microtextures, considered to be diagnostic, was used to distinguish between glacial and non-glacial sediments; however, no researcher used a standardized sampling size, i.e. number of grains examined, and to this day no standardized method, grounded in statistics, for determining sample size has been established. This thesis is most concerned with the SEM analysis of englacial sediments (Mahaney 2002) that were collected from sites once glaciated, or purported to be so, but also addresses the question of a standardized method for selecting sample size.

Krinsley and Doornkamp (1973) published one of the first SEM image compendia of sand grain surface textures, *Atlas of Quartz Sand Surface Textures*. This atlas discusses how various environments modify grains, the microtextures attributed to those environments, and how one can utilize SEM technology to determine genesis. They described glacial grains as extremely angular; larger grains (>200 µm) display conchoidal fractures and smaller grains (<200 µm) in their study tended to exhibit flat cleavage surfaces and upturned cleavage plates, as well as some conchoidal fracturing. Krinsley and Doornkamp (1973) established a theory that grain morphology is diagnostic of the environmental history of the particular sediment under study. They also emphasized that, in their opinion, no single microtexture is sufficient to determine genesis.

Margolis and Kennett (1971) analyzed glacially derived ice-rafted sands from 18 Cenozoic South Pacific deep-sea cores. The percentage of quartz grains per sample was determined using a point-count method; percentages were then checked using X-ray diffraction for bulk sample mineralogy on selected samples. Margolis and Kennett compiled a list of 22 diagnostic microtextures and recorded the occurrence of any microtexture found on >10% of a grain's surface. They concluded that certain microtextures, including large breakage blocks, large conchoidal fractures, step-like features, angularity, and high relief, were common features on sand grains of glacial origin, but that no single feature can be used to determine genesis. Rather, a combination of highly diagnostic microtextures must be found on a statistically significant proportion of grains in a sample to make an inference regarding origin (Margolis and Kennett 1971).

Using an SEM to analyze grains collected from the Glacier de Tsidjiore Nouve in Norway, Gomez and Small (1983) concluded that englacial grains were derived from both subglacial (shear plane) material and supraglacial debris from subaerial weathering of extraglacial rocks exposed in the firn basin. Gomez and Small (1983) classified englacial grains into two categories: those with shear plane characteristics and those with supraglacial (passive transport) characteristics. The former were described as more angular and possessing typically glacial microtextures; the latter, more rounded with dull, weathered surfaces that appeared fresh upon initial examination. Gomez and Small (1983) attributed this mixing of grain types within the englacial layer to the incorporation of supraglacial debris via crevasses in the firn zone. This thesis specifically focuses on sediments that likely were transported within the englacial layer and on their microtextures, including many that formed as a result of non-passive transport.

Helland and Holmes (1997) performed SEM microtextural analyses on sediments collected from an Ocean Drilling Project (ODP) site off the coast of Greenland. They analyzed sediments for a list of microtextures, compiled from Krinsley and Donahue (1968), Margolis and Kennett (1971), Higgs (1979), and Bull (1986). Helland and Holmes divided the microtextures into three categories: morphological (relief), mechanical (fractures), and chemical (solution). They concluded, based on microtextural percentages, that 5 of their 11 samples had a glacial history. Also working with ODP sediments, Strand et al. (2003) analyzed quartz grains from a site at Prydz Bay, Antarctica and recorded the frequency of occurrence of 27 different microtextures. Using a range of microtextures derived from the works of Mahaney et al. (1996) and Helland and Holmes (1997), sediments were characterized as either glacial or non-glacial by the diagnostic textures found on sand grain surfaces. Strand et al. (2003) found that angular edges, step-like features and edge abrasions were the most common features in the glacial deposits.

SEM analysis of sand grains has been used to infer glacier thickness, transport histories, and ice dynamics at several Pleistocene- and Holocene-era glacial sites (Mahaney 1995). Mahaney studied approximately 500 till grains from glaciated areas in Antarctica, Europe, Asia, Africa, and North America. His objective was to analyze a large sample of grains to determine whether SEM microtextures could be used to identify glacial sediments. Mahaney (1995) concluded that glacial fracture microfeatures could be used to infer transport history and ice thickness. Mahaney and Kalm (2000) found that glacial microtextures are distinctly different from fluvial microtextures; they distinguished between different depositional environments through SEM analysis of microtextures of three sample suites collected in Estonia and Latvia. Building on the work of Krinsley and Doornkamp, as well as his own, Mahaney's *Atlas of Sand Grain Surface Textures and Applications* (2002) describes in detail how one can use SEM to study microtextures and, in turn, what environmental histories those microtextures reveal.

The body of work detailed above suggests that the processes that create the unique array of microtextures seen on glacial grains are a part of the complexities of a glacial system. To understand how certain microtextures are formed on glacial sand grain surfaces, one must first look at the processes that occur within a glacier. The pressure from ice, transport paths of sediments, and rates of glacial flow affect the environment down to a microscopic scale. In essence, the glacial history of an area is recorded on the surfaces of sand grains.

2.3 Glacial Environments

Research in glaciology has been exceptionally successful at analyzing aspects of environments in known glaciated sites; the same cannot be said of analyzing environments to determine if sites were once glaciated. The SEM analysis of sand grain surface microtextures, however, may provide a means to do just that. An accurate test of microtextural signature patterns to determine environmental provenance of sediments will help reveal the environmental history of an area, especially when used in concert with other reliable research methods.

2.3.1 Glaciers

Glaciers are large, slow-moving rivers or sheets of ice that form through the annual accumulation and compaction of snow and ice. Most glaciers can be divided into two zones: an ablation zone near the terminus and an accumulation zone at high elevation or high latitude. These two zones are divided by an equilibrium line where annual losses and gains are balanced. The altitude of the equilibrium line (ELA) is dictated by both climate and topography (Benn and Evans 1998). Growth of the glacier as a whole occurs when accumulation of snow and ice exceeds ablation losses. Benn and Evans (1998) described glaciers as complex systems, with inputs of snow and ice and outputs most often in the form of meltwater. Glaciers are also considered sensitive barometers of climate change, susceptible to any changes in weather patterns. Observed increases in glacial melting over the past century provide proof of the delicate balance between the climate and the survival of glaciers (Benn and Evans 1998).

The two main types of glaciers are continental and alpine. The former refers to massive ice sheets that cover large land areas, such as Greenland. Alpine glaciers, those found in mountainous terrains, are much smaller than their continental counterparts; a typical post-ice landscape is a network of cirques and troughs created through erosion rather than the scouring on scales of hundreds to thousands of kilometers typical of continental ice sheets (Benn and Evans 1998). The size difference, along with differences in transport distance and basal pressure, is reflected by a difference in surficial fracture frequency (Mahaney 2002). Thicker continental ice sheets increase basal pressures; higher pressures, combined with extended grinding over long distances and longer time periods, result in higher frequencies of diagnostic textures such as sub-parallel linear and conchoidal fractures on sand grains entrained by the glacial system.

Alpine glaciers are more limited in extent, thus the potential distance of grain transport is less. The low frequency of certain fracture types in alpine samples appears to be the result of lower shear stress levels, especially as many alpine subglacial tills are well lubricated by meltwater (Mahaney 1995). Smaller alpine glaciers may collect less debris overall and therefore may have lower potential to develop debris-rich shearing and grinding ice. The majority of microtextures considered diagnostic of glacial transport are primarily formed within debris-rich zones; the specific processes that generate so-called glacial microtextures are discussed in detail later in the thesis. The quartz sand grains analyzed for this thesis were collected from tropical highland areas that are either known to have supported, or are purported to have supported, small ice caps and alpine glaciers at least briefly during the Pleistocene.

2.3.2 Glacial Flow and Debris Generation

The processes that create the unique array of microtextures seen on glacial grains are one small part of the many complex interactions that occur within a glacial system. The slow movement of glacial ice, characterized by a stick-slip style of motion, creates some microtextures typically diagnostic of glacial environments on the surfaces of sand grains. Others are produced within the ice as sand grains in the debris-rich basal zone impinge upon each other as the ice undergoes shearing deformation; this slow, static-pressure, tangential interaction between grains is analogous to “flaking” techniques used by Neolithic humans working flint (Orvis, pers. comm.) and can result in similar textures.

Multiple factors control the rate of glacial flow. The temperature of the ice, presence or absence of water, concentration of basal load, and roughness and slope of the bed can all affect glacial movement. High concentrations of basal debris and an irregular bed increase drag and impede sliding as ice is forced to internally shear. Benn and Evans (1998) describe the rate of motion of glaciers as being acutely dependent upon both the pressure and amount of water at the glacial bed. As pressure increases downward through a glacier, the melting temperature of ice decreases. The flow of a glacier is strongly arrested by a frozen bed and lack of meltwater; basal sliding is nearly impossible without liquid water (Benn and Evans 1998). Even a glacier with basal ice near the pressure melting point (the melting point of ice under pressure), which means some patches of its sole are lubricated, will move more readily across a landscape than a glacier with a fully frozen bed, which must move entirely by internal shearing and deformation. Large amounts of meltwater at the bed, produced by surface melting and basal melting, can markedly increase the rate of glacial flow. Other sources of meltwater include rainfall onto the glacier itself, and snowmelt and run-off from surrounding ice-free slopes. In addition to facilitating flow, meltwater also significantly contributes to erosion, debris transport, and deposition (Benn and Evans 1998).

Effective rates of sliding and erosion are therefore closely related to temperature. Glacial ice can be classified roughly into two types: warm-based ice and cold-based ice. The term warm-based signifies ice at the pressure melting point, and cold-based ice refers to ice colder than that at base (Hambrey 1994; Benn and Evans 1998). In warm-based states, glacial meltwater may flow relatively freely and may reach the bed quickly, which can facilitate glacial movement. In cold-based states, despite surface melting, meltwater tends to flow towards the ice margins rather than the bed (Hambrey 1994; Benn and Evans 1998). However, as Benn and Evans (1998) point out, the thermal conditions of an individual glacier may vary temporally and spatially, and thermal classifications should be applied only to local, current conditions.

For the purpose of this thesis, the most important aspect of glacial flow is the interaction of glacial ice with mineral debris that is collected as a glacier moves across a landscape. As stated earlier, the dynamics of glaciers, especially grain-to-grain contact that occurs in debris-rich shear zones, create unique microtextures on the surface of sand grains. The collection, entrainment, and ultimate release of debris can substantially modify the shape and surface features of sediment grains. Once debris enters a glacial system it can be subjected to physical and chemical weathering, grinding and shearing against bedrock or other debris clasts, and turbulent transportation via meltwater. Quartz sand grains may enter and exit the system along a variety of pathways, with weathering and abrasive grinding overprinting past microtextural evidence and the vibrations and static shearing that accompany glacial movement creating new textures. After sediment is washed out of a glacial system, the relative hardness of quartz allows microtextures to remain intact on grain surfaces and thus provide an enduring record of environmental provenance.

Debris may enter a glacial system in a variety of ways, chief of which is erosion of underlying regolith and bedrock. Subglacial erosion can either occur as abrasion, by grinding englacial material against the bed, or by means of plucking, dislodgement of larger rock fragments (>1 cm) or clasts or sheets of frozen sediment. Concentrations of temporary glacial stresses can exploit weaknesses in rock surfaces and pluck out fragments as the main body of ice flows past. With abrasion, basal layers and already-entrained debris score the underlying bedrock. Glacial scouring often creates striae as rock particles are dragged over other clasts or bedrock, gouging out thin grooves as well as a variety of other features. Scouring and internal shearing of debris-rich ice also generates glacial flour, fine silt-to-clay-sized particles of unweathered sediment that give meltwater a cloudy appearance. Between striae, rock surfaces are polished and smoothed out as sliding basal ice removes small protuberances (Benn and Evans 1998; Pidwirny 2006). Moving meltwater can also be an effective agent of both proglacial and subglacial erosion. Abrasive wear of the bedrock by rapidly flowing water and its suspended load can produce pits and grooves in the bed. These particles can be captured by ice and transported further, or deposited as erosional landforms. Debris may also enter a glacier from a supraglacial position as material from valley walls falls on top of glacial ice and then becomes entrained (Benn and Evans 1998).

Sediments are obviously modified by all dynamic erosional processes, but it is not until particles become entrained in ice that the tell-tale signs of glacial transport and deposition appear. In debris-rich zones, high pressure glacial shearing forces grains into contact with one another. Massed grains collected in churning basal ice will contact each other in slow-motion, glancing, nearly static contacts. It is the sum of internal shearing and basal grinding of ice and debris within the glacier that creates a recognizably glacial suite of diagnostic microtextures.

2.3.3 Englacial Sediments and Microtexture Generation

The term englacial refers to areas physically within the flowing, shearing glacier ice (as opposed to riding passively on the top), whose sediments make up a large fraction of what gets deposited in moraines and other till deposits, or gets carried in and ultimately deposited as kame, esker, outwash, and other alluvial deposits by meltwater streams. The sand grains analyzed in the thesis were all collected from sites that would logically include englacial grains, whether they are sites that are known to have been glaciated, or others that may potentially have been glaciated.

Mahaney (2002) described the englacial environment as being relatively free originally of clastic load, but with subsurface channels that may move meltwater, and, as a result, sand grains, through sluiceways into the ice via re-freezing. This is particularly apt to occur where the pressure freezing point of basal ice is low upstream of an obstruction because pressure is higher there due to impaction against the obstruction, and the freezing point is higher immediately downstream of the obstruction—the ice tends to melt, sluice its way past, and immediately refreeze along with whatever debris it entrained, without ever changing temperature.

Other modes of debris enrichment include wholesale entrainment of underlying soft sediment, common where cold-based ice crosses till or other loose regolith that is itself water-saturated and frozen so that the zone of basal shearing may extend down into the underlying bed; and the breaking up of larger clasts simply due to shearing and slow turbulence of the ice under pressure. These forces are insufficient to crush sand-size grains of most minerals even beneath kilometers of ice, but once the basal ice becomes enriched with enough debris, the probability of grain-to-grain contact increases and entrained grains grind each other to flour, chiefly through tangential rotational contact and resultant "chipping." Basal ice exposed at the melting snouts of glaciers can be so dark and sediment-filled it is difficult to think of it as ice in any normal sense (Orvis, pers. comm.).

Once within a glacial system, englacial grains can either be subjected to high levels of pressure and concentrated energies inside shearing zones, or transported passively. Glacial debris passively transported on top of a glacier, or passively within clean ice or a non-shearing horizon of a glacier, may acquire no new microtextural signatures. However, mineral debris transported within shearing horizons of glaciers that contain high concentrations of debris will acquire diagnostic microtextures that result from static-load shearing of grain margins against each other, and from grinding against the materials of the glacier bed. Englacial debris may be frozen in ice, but that ice is churning nonetheless and applying energy to its sediments. Paired with the simple weight of glacial ice, that energy can be concentrated on small clasts as particles are forced into a slow-motion, shearing contact as glacial ice shifts internally. As stated earlier, areas with high concentrations of debris have a higher probability of grain-to-grain contact, and this type of shearing creates sub-parallel conchoidal fracturing as well as other diagnostic microtextures such as step-like features, mechanically upturned plates, and grooves (Mahaney 2002; Menzies 2002).

The vibration caused by the stick-slip movement of glacial ice can produce its own class of deeply entrenched microtextures on sand grain surfaces in the form of deep troughs and grooves, which are thought to be exclusive to grains transported by glacial ice. Englacial grains can be further modified by abrasive grinding that can erase signs of preweathering and other microtextures that existed at the onset of ice transport (Mahaney 2002).

A wide array of microtextures can be seen on the surfaces of quartz sand grains of glacial origin (Mahaney 2002). The list of 25 microtextures included in this thesis was compiled from multiple SEM studies on microtextural signatures of glacial grains, and while not exhaustive, comprises most microtextures considered to be typically diagnostic of glacial transport. The specific processes that generate such microtextures are discussed below. Other microtextures, for example lattice fracturing and craters, can be generated within a glacial environment, but are not limited to transport by ice and were therefore not included in this thesis.

Grains that are not transported passively can become heavily fractured under the high pressures that forces grains into contact with one another. Fractures considered diagnostic of glacial transport (i.e., sub-parallel linear and conchoidal fractures, step-like features, grooves) are most often generated during grain-to-grain contact. Glacial grains tend to have medium-to-high relief. Mahaney (2002) defines relief as the difference between the high and low spots on grain surfaces, and proposes that the degree of relief on glacial grains is directly related to ice thickness and ice transport distance. Extensive glacial crushing and grinding can fracture grains, thus creating higher relief and sharper edges. Grooves and deep troughs are commonly associated with glacial dynamics in which fixed grains score other grains, that is, when grains are held static in ice and impact bedrock and debris as glacier ice flows across a landscape (Mahaney 2002; Orvis, pers. comm.).

Deeply inscribed conchoidal fractures and other less concentric curved features, considered to be highly indicative of glacial transport, also form as a result of grain-to-grain contact during glacial transport. Concentric fractures typically result from the shattering of a vitreous or other material lacking cleavage, in response to a blow or to non-progressing pressure exerted at a point. Glacigenic sediments are likely to exhibit an unusually high proportion of sub-parallel curvilinear fractures, because of the many opportunities for static loading at grain-to-grain contacts within the shear zone and progressing pressure when failure occurs, owing to the elasticity of the system. Landslides and debris flows, in contrast, provide more opportunities for concentric fractures to occur. For both, the resulting microtextures include many partial-surface categories such as fracture faces, sub-parallel linear fractures, and various grooves, gouges, and arc-shaped steps. For example, imagine a fracture that created one side of a 2000-µm grain, which was subsequently re-fractured into numerous 125-µm grains: many will retain on one side a small section of that original 2000-µm fracture. Some of these microtextures may result from surface-to-surface abrasion processes as well (Mahaney 2002; Orvis, pers. comm.).

Abrasion can further modify grains entrained in ice by rounding previously sharp edges and by polishing surfaces. Linear steps, which share similar characteristics with sub-parallel linear fractures, but are more deeply imbedded within grain surfaces, are hypothesized to be associated with glacial crushing. V-shaped percussion fractures are generally considered a diagnostic signature of a history in a fluvial, and particularly a relatively high-energy fluvial, environment. Glacial ablation and other processes result in sediment transport through subglacial and englacial meltwater channels and along kames and kame terraces, and because of this, a proportion of glacierized sand grains will exhibit V-shaped scarring (Orvis, pers. comm.). Glacial grains may also exhibit edge-rounding caused by fluvial transport.

Mechanically upturned plates and breakage blocks suggest plucking-style breakage by torsion or pulling, dynamics associated with basal ice but which are uncommon in other environments. Weathering and dissolution etching, resulting from solution of the mineral surface of grains, can occur before or after glaciation. Preweathered surfaces are those that underwent weathering prior to glaciation and were subsequently overprinted with fresh fractures and abrasion features during glacial transport (Mahaney 2002).

Therein is the challenge of determining glacial history of an area based on sediment microtexture signatures: individual grains may carry multiple microtextures diagnostic of glacial transport, or none at all; and grains may also carry both pre- and post-glacial weathering microtextures, independent of any glacial history. Accurate microtexture signature identification—that is, an ability to characterize and describe the proportions with which various microtextures occur within a sample of sand grains—and subsequent environmental provenance inferences must be based on analysis of a representative number of grains. Without an adequate sample size, the microtextural signature cannot be presumed to represent the field sample nor its parent population. The cataloging and analyses of microtextures on individual grains and across sand grain samples should theoretically allow an investigator to discern a microtextural signature that can be useful in determining the genesis of samples.

2.4 Quantitative Analyses

While the usefulness of SEM microtextural analysis for determining sediment signatures is well documented, no single researcher has established a universally accepted, precise sample size specific to the task of reliably distinguish environmental provenances of samples. Margolis and Kennett (1971) analyzed 25 uni-crystalline quartz sand grains selected at random from multiple deep-sea core sediment samples; sets of 25 were selected so that the researchers could "quantitatively" determine the origin of Subantarctic deep-sea core sands, but no other justification for this sample size was given. Krinsley and Doornkamp (1973) recommended 15–20 grains for detailed analysis, asserting that 16 grains were adequate to study the microtextural variability in a single sample. Baker (1976) conducted a statistical evaluation on selected microtextures found on quartz sand grains from eolian and subaqueous environments. He compared the frequency of occurrence of certain microtextures for various sample sizes (20, 30, 40, and 50 grains) and found little difference between the means and standard deviations of the sample sets. Based on these analyses, and what he described as a prohibitive amount of time required to study larger sample sizes, Baker (1976) concluded that 20 grains was the most practical sample size.

At the time when these early SEM provenance efforts were establishing de facto precedents, SEM was a new technology. The machines were large and unwieldy, auxiliary equipment was finicky, obtaining and recording high-quality images was a challenge, and the entire enterprise was expensive. Analysis of sand grains was time-consuming, and most researchers probably had to compete for machine time with other users. Published assessments of adequate sample sizes from this period probably represent compromises between what the researchers might have considered ideal, and what was practical.

Tovey and Wong (1978) discussed problems with the (then) current techniques for preparation, selection, and interpretation of sediments studied with scanning electron microscopes. Focusing on the quantitative aspect of SEM analysis, Tovey and Wong (1978) attempted to determine, based on mean grain size, what sample size is adequate to accurately represent the parent population. They outlined four different methods of sample selection and advocated the random selection of grains as the best method for achieving statistically accurate results. To test this method, they randomly selected and analyzed a sample of 51 sand grains of mixed sizes from grains mounted on an SEM stub. They determined the mean size of each of the randomly selected grains and plotted the results in a histogram. Then six subsamples, four with 10 grains, two with 20, and two with 30, were randomly selected from the 51 and compared. These subsample results were also plotted in histograms and each histogram was compared to the plot of the original 51-grain sample. Tovey and Wong (1978) noted that the histograms of the subsamples did not bear much resemblance to the histogram of the original sample until the subsample size reached 30 grains. To determine whether the 51 grains adequately represented the parent population, they sieved a quantity of the original field sample using a standard dry sieving technique and estimated the number of grains in each size class based on the weight collected. They compared the size distributions of this larger sample with the sample of 51grains as measured in the sieve and SEM, and found the distributions to be very similar. Using this logic, Tovey and Wong (1978) concluded that 50 randomly-selected sand grains could adequately represent the size distribution of a parent population and were sufficient for analysis, and that 30 grains minimum must be analyzed to discern any significant information from surface textures.

Bull (1981) also discussed various analytical problems of environmental reconstruction by electron microscopy. He highlighted the wide variety of sample sizes used in (then) current studies, ranging from 10 grains to as many as 200 or 300. He described sample size as being far from standardized despite its obvious importance, and pointed out that even studies specific to the number of grains necessary for analysis disagree. Bull specifically compared his own findings that 20 grains were sufficient for analysis to the previously mentioned conclusions of Tovey and Wong (1978). However, in a later study, Bull (1986) agreed with Tovey and Wong (1978) that 30–50 quartz grains must be analyzed for meaningful interpretation. Dowdeswell (1982) also referred to Tovey and Wong (1978) as the basis of the sample size used in his Fourier shape analysis study. He analyzed 158 grains, but only 25–30 grains per sample in detail (Dowdeswell 1982).

Despite the efforts of Tovey and Wong (1978), sample size has continued to vary among more recent studies. Often the rationale behind sample size choice is not explained; researchers select a size that fits within the framework of their studies. Citing Krinsley and Doornkamp (1973) and Baker (1976), Higgs (1979) reported that 20 monocrystalline grains were sufficient to represent the variability of characteristics found in a single sample. Gomez and Small (1983) analyzed 160 grains total, 120 grains from four englacial debris layers and 20 grains each from shear plane and supraglacial zones, in an attempt to determine the genesis of the englacial sediments. Gomez and Small (1983) prepared grains for microscopy according to the standard methods of Whaley and Krinsley (1974), but provide no specific reasoning on choice of sample sizes. Helland and Holmes (1997) randomly selected 30–40 grains from each of their 11 Ocean Drilling Project samples for analysis of the presence or absence of 27 different microtextures. Strand et al. (2003) followed similar procedures in the random selection of 20–30 grains each from 19 different ODP samples. Both studies make references to Krinsley and Doornkamp (1973), but do not discuss sample size rationale.

Bernet and Bassett (2005) combined scanning electron microscopy-cathodoluminescence (SEM-CL) analysis of thin sections and optical microscopy techniques to distinguish environmental provenance of quartz sands in their "coarse- to medium-grained" size category. Citing other SEM-CL studies (Seyedolali et al. 1997; Kwon and Boggs 2002), Bernet and Basset (2005) concluded, without providing details, that at least 100 randomly selected quartz grains should be analyzed to deduce provenance. However, neither Kwon and Boggs (2002) nor Seyedolali et al. (1997) included evidence supporting their sample sizes.

In a study on quartz sand grain surface micromorphology as an indicator of glacial sediment conditions, Alekseeva (2005) randomly selected 50–60 grains in the medium (500–250 µm) sand fraction from each of 27 different samples. Alekseeva (2005) arrived at a grain count of 20 as sufficient to provide a representative sample, citing methods for determining sample sizes published in Simonov (1999), but the latter is unfortunately published in Russian so I was unable to further elucidate Alekseeva's logic. Referring to studies by Higgs (1979), Krinsley and Doornkamp (1973) and others, Alekseeva (2005) preceding stated that the majority of researchers recognize a sample size of 20 as able to represent the diversity of surface features found in a sample of sand grains. Sample size has historically depended more upon the researcher than any particular protocol, much less a protocol arrived at through any analysis of sample variance. Table 4 lists examples of sample sizes found in the literature. To be fair, some of these researchers were focusing on establishing the mere presence of particular microtextures within a sample, while others were attempting to quantify their prevalence—but that distinction begs the question of whether merely establishing the presence of a microtexture in a sample suffices as a method of establishing the sample's provenance.

Dr. William Mahaney, a leading researcher in SEM analysis of sediments, has conducted several studies in which he analyzed grains from a range of sand-size fractions (2 mm–63 µm) using various sample sizes. While in the majority of studies Mahaney and collaborators do not provide specific evidence supporting sample size choices, it is apparent that the number of samples selected for analysis is based on the researchers' opinion of what fits best within the framework of the study.

After light microscope analysis of ca. 300 grains per sample, Mahaney (1995) selected 30 grains from each for detailed SEM analysis. In an effort to prove that relative ice thickness and transport distance influence the range of microtextures observed on individual quartz grains, Mahaney (1995) analyzed 25 coarse quartz sand grains and 300–400 fine sand quartz grains from each of 12 samples collected from tills in Antarctica. In a Siberian study on Pleistocene sands from three different major lithostratigraphic units, Mahaney (1998) analyzed between 200 and 400 quartz sand grains, and, of these quartz grains, examined approximately 40 in detail. Analyzing sediments from Estonia and Latvia, Mahaney and Kalm (2000) attempted to determine what constituted a valid sample size to allow inferences of provenance (fluvial versus glacial origin) for quartz sand grains. Towards this end, they analyzed 300–500 fine sand grains

Table 4. Sample size variation across the literature (list is not exhaustive).

Researcher(s)	Sample Size
Margolis and Kennett (1971)	25
Krinsley and Doornkamp (1973)	15–20
Baker (1976)	20
Tovey and Wong (1978)	30–50
Higgs (1979)	20
Bull (1981)	30–50
Dowdeswell (1982)	25–30
Gomez and Small (1983)	160
Mahaney (1995)	30
Mahaney (1996)	25[3]; 300–400[4]
Helland and Holmes (1997)	30–40
Seyedolia (1997)	900+
Mahaney (1998)	40[3]; 200–400[4]
Mahaney and Kalm (2000)	20–25
Mahaney (2002)	≥20
Strand et al. (2003)	20–30
Alekseeva (2005)	20
Bernet and Basset (2005)	100

[3] Wentworth coarse-to-medium sand grain size fraction.
[4] Wentworth fine sand grain size fraction.

and 100 grains each from the medium and coarse fractions; from each of these sand fractions only 20–25 were studied in detail. The sample sizes in this case were explicitly based on the decision to study a large population of sand grains in order to determine provenance (Mahaney and Kalm 2000).

In his *Atlas*, Mahaney (2002) discussed recording microtextures by frequency of occurrence and analyzing randomly selected grains from several samples as well as different size-fractions from single sample: a quick overview of fine (250–125 µm) and very fine (125–63 µm) paired with the analysis of at least 20 randomly collected grains from both the coarse (1 mm–500 µm) and medium (500–2.50 µm) fractions on the Wentworth scale. He stated that the research question should ultimately dictate both the sample size and the necessary degree of precision in analysis; exploratory investigations might not require analysis of multiple size fractions (Mahaney 2002). After studying a large metapopulation of samples with glacial provenances, Mahaney (2002) concluded that grains with englacial histories are typified by medium-to-high relief, sharp angular features, sub-parallel linear and conchoidal fractures, microfeatures associated with glacial crushing (step-like features, straight and curved grooves, and mechanically upturned plates), and by abrasion microtextures covering as much as 40% of a grain's visible surfaces. In this sense, abrasion microtextures (Mahaney 2002) include worn-down, rubbed-down, and otherwise abraded surfaces presumably created by scraping and grinding of particles in traction, whether by ice or by entrainment by wind, water, gravity-driven flows, or other processes. This description of what typifies englacial grains is fairly specific, but Mahaney did not address the question of what sample size might be required to reliably yield these typical characteristics.

Any inferences as to environmental provenance of sediments must be based on the analysis of a representative number of grains. A microtextural signature revealed through scanning electron microscopy is only valid if derived from a sample size that can be said to accurately represent its parent population. Certain sediments (e.g., beach sands) exhibit a small, consistent set of microtexture features (Mahaney 2002). Consistency of features across samples allows for identification after analysis of only a small number of sand grains. Others such as glacigenic and debris-flow sediments, however, display a much larger range of microtextural features, and these can include pre-entrainment, entrainment-related, and post-depositional signatures. According to Mahaney (2002), of all environments, glacial grains carry the largest range of diagnostic microtextures: various grooves, fractures, and abrasions created by a combination of glacial and periglacial processes. This larger range of possible microtextures requires a relatively larger number of grains to establish statistical patterns for distinguishing samples. For the purpose of this thesis, we wanted to be robust in addressing our research questions; my final sample size was, therefore, based on the need to be amply robust for the sample type with the most internal variance.

CHAPTER 3. METHODOLOGY

3.1 Reconnaissance Phase

My research was conducted in four basic phases: reconnaissance; sample selection and preparation; scanning electron microscopic analysis; and statistical analysis of data. The reconnaissance phase included background research on the various types of sediment analyzed in SEM studies, techniques of heavy liquid separation to isolate sediment mineral types, study of SEM operation including the different vacuum modes for optimal SEM viewing, and sputter-coating and the effects of specimen charging. As one mineral type reacts differently to environmental forces than another mineral type, I focused on one distinct type of mineral: quartz. The inherent hardness of quartz and its chemical resistance combine to make its microtextures resistant to erosion (Mahaney 2002). I also conducted trial experiments using control samples of quartz, feldspar, granite, and mixed minerals from crushed gneiss to develop a standardized and replicable technique for heavy liquid separation, which is explained in detail later in this chapter.

I chose to study the microtextures of 250–125 µm grains ("fine sand" on the Wentworth scale). Grains of this size are too small to be created from most plutonic rocks by the static crushing pressures that can exist in Earth's near-surface gravity field, which in both surface and englacial environments can only easily produce grains the approximate size of native crystals (typically millimeter scale), and this means that a larger proportion of these smaller grains will have been generated by tangential shearing and grinding—signature englacial dynamics. Having a consistent material type (quartz) and grain size (250–125 µm) ensured that the same physics would be involved for all samples under analysis.

The scanning electron microscope jointly owned by the Department of Geography and the Department of Earth and Planetary Sciences is a JEOL model 6060LV. This SEM allows viewing in both high vacuum and low vacuum mode. Through numerous trials in the reconnaissance phase, I determined that the high vacuum mode is most appropriate for the analysis of quartz sand grain microtextures; the low vacuum mode does not allow enough detail at high magnification, the signal-to-noise ratio being too low. Conversely, high vacuum mode requires that samples be sputter-coated with a thin conductive layer in order to avoid charging. Specimen charging can lead to artifacts, astigmatism, and a loss of contrast, all of which substantially decrease image quality and the ability of the analyst to discern the meaningful information in an image.

3.2 Sample Selection and Preparation

The second phase in my research was sample preparation, using techniques established in the reconnaissance phase. The samples that I analyzed were drawn from the fine sand fraction of laboratory sediment samples, the ready-made product of particle size analysis of laboratory sediment samples. The original field sediment samples had been collected both from known glacial sites in Costa Rica, and from sites in the Dominican Republic that would yield englacial sediments if those sites had been glaciated. Dr. Ken Orvis and I chose control samples from Costa Rican glacial deposits and samples from Dominican Republic diamictons analogous to the control samples, that is, most-likely to yield glacially-produced microtextures.

All samples had been previously treated with 30% H_2O_2 to remove organics; treated with buffered sodium acetate to remove cementing carbonates; and treated with buffered sodium hydrosulfite to remove cementing post-depositional metal oxides. Nine of the 18 samples were collected in Costa Rica: six in the Valle de las Morrenas of Cerro Chirripó and three in the San Gerardo area in the Río Chirripó Pacifico valley at the base of the Chirripó massif. The remaining nine samples had been collected in the Cordillera Central highlands of the Dominican

Republic: eight in the Macutico region of José del Carmen Ramírez National Park on the southwestern flank of the range, and one in the Valle de Bao drainage of the Armando Bermúdez National Park on the northeastern flank (Tables 1 & 2).

In Costa Rica, we selected a single glacio-lacustrine sample (sample 1), two samples of ground moraine (samples 2 and 3), three samples of lateral-to-terminal moraine (samples 4, 5, and 8), and three samples of debris flow deposits of probable glacial-periglacial origin (samples 6, 7, and 9). Samples 1–5 and 8 were collected in Valle de las Morrenas on the north flank of Cerro Chirripó. The remaining three samples are from perched terraces along the Río Chirripó Pacifico near San Gerardo de Rivas. In this tropical highland environment, glaciers, and hence englacial travel distances, are short; therefore, we selected samples with some attention to including a variety of distances from the headwall.

Sample 1, the glacio-lacustrine sample, consists of sediments which likely were deposited directly from melting ice of the retreating glacier about 1 km from the headwall. Because the lake in which the sample was collected is fairly high within the valley, the sediments were likely subjected to limited grinding. Samples 2 and 3, the ground moraine sediments, were specifically chosen to represent highly dewatered basal material, which had been deposited into a pre-glacial-advance bedrock canyon just downslope from a rock step about 1.7 km from the headwall. These two sample locations were contiguous in the field. Their contiguous nature was intended to be a test of the degree to which samples of nearly identical material from the same deposit may differ; sample 3 was about 4 cm deeper into the vertical exposure behind sample 2 and may have had less opportunity to weather.

Sample 4 is from a lateral moraine sampled about 2.2 km from the headwall, and from a depth well below any visible horizons of pedogenesis. This sample was located approximately 1 km above the terminus of this glacial advance; the age of the advance is unknown but likely occurred before 14 Ka based on the basal-sediment date of Laguna de Las Morrenas 3-A which dates the retreat of the advance in question (Orvis, pers. comm.). Sample 5 is also material collected from the same lateral moraine, but this sample was not adjacent to sample 4. Specifically, sample 5 consists of fine sediments that settled around and underneath a large boulder and was collected to test whether the depositional sorting involved affected its glacial signature. Sample 8 was collected from a recessional moraine only about 0.3 km from the headwall, in fact the highest identifiable moraine feature in its part of Valle de las Morrenas. Samples 6, 7, and 9 are debris-flow matrix samples thought to be deposited from flows of over-steepened till and ice dislodged from high in the drainage of the glacial zone above the San Gerardo site (Orvis, pers. comm.). Sample 6 appears to represent a late-glacial deposit.

From samples from the Dominican Republic, we selected two suspected ground moraine samples (samples 10 and 11), five possible proglacial lacustrine samples (samples 12–16), and two possible lateral-to-terminal moraine samples (sample 17 and 18). Samples 10 and 11, the possible ground moraine samples, are from the Macutico locale. Sample 10 had been collected from near the base of the deposit and might represent an overridden terminus; sample 11, if glacial, represents under-ice melt-out in the ablation zone. Samples 12–16 represent suspected proglacial melt-out flood clastics lain down in an overbank lacustrine environment (Laguna Grande de Macutico). Sample 17 is material from a suspected terminal or recessional moraine transverse to the Río Macutico. Sample 18 is also from a possible ground moraine or recessional moraine, located on the floor of a suspected cirque high in the drainage of El Valle de Bao (Orvis, pers. comm.).

Beginning with the 250–125 µm fine sand fraction of the laboratory sediment sample, the quartz grains from each site were separated from the various other minerals. I used a standard heavy liquid (sodium metatungstate) separation procedure to isolate the fine quartz sand grains from other sand-sized minerals. I first measured the density of the Lithium heteropolytungstate heavy liquid to check the accuracy of the labeled density by measuring exactly 25 mL of heavy liquid into a graduated cylinder and weighing that amount on an analytical balance, having first compensated for the weight of the graduated cylinder. I poured 25 mL of heavy liquid into a separatory funnel and added the sand grains representing the sample, along with an indicator quartz piece (a larger, visible fragment of known quartz crystal). I then added, one drop at a time, deionized H_2O to the suspension. Quartz has a specific gravity of 2.65; the heavy liquid used in this research, 2.85. I employed a vigorous up-and-down stirring motion to vertically mix the deionized H_2O (which floats) and heavy liquid. In between deionized H_2O applications, I allowed 60–180 seconds for settling. Once the indicator quartz no longer floated on top of the surface, but remained suspended, the sample was left to settle for 24 hours. At the end of the 24 hours, the heavier minerals that settled to the bottom of the funnel were rinsed out into a 50 mL beaker and set aside for later cleaning and inspection. The remaining sands inside the separatory funnel then consisted of a mix of quartz and lighter materials. To isolate the quartz I continued to add deionized H_2O to the top of the separatory funnel to further reduce the density of the heavy liquid until it dropped below that of quartz. Once the indicator quartz sank to the bottom of the separatory funnel, the settled fraction, now primarily quartz, was rinsed out into a 50mL beaker. I also saved the lightest mineral fraction in a 50mL beaker for later examination.

A small amount of deionized H_2O was added to the beakers of the separated fractions (heavy, quartz, and light), and the liquid from each was then poured into another beaker to capture any remaining heavy liquid for later recycling. The separated fractions were rinsed an additional ten times by adding deionized water and then draining. Afterwards, the washed fractions were dried for one hour at 108 degrees Celsius. I examined the dried samples under a dissecting microscope to check the success of separation and to ensure that sand grains were completely free of heavy liquid residue. The heavy and light sediments were not used in this research unless the quartz did not properly separate and the heavy liquid procedure had to be repeated for that particular sample. This separation procedure was applied to all samples.

Once the quartz sand grains of the fine sand fraction of each laboratory sediment sample were isolated and dried, I mounted as many grains as would easily fit on SEM stubs with carbon tape. The mounted grains were then sputter-coated with gold to avoid charging (build up of static electrical charge in the grains) while in the SEM chamber. The stubs were placed inside the sputter coater for 30 seconds and a thin, uniform layer of gold was deposited over them. A gold coat that is deposited too thickly or distributed unevenly can cause image distortion. The specimens were sputter-coated in the University of Tennessee Electron Beam Laboratory, courtesy of Dr. David Joy.

3.3 Cataloging Microtextures

The next phase in analysis was cataloguing of microtextures using the scanning electron microscope. I created a spreadsheet and documented the microtextures seen on each grain by recording their presence or absence on each grain as a whole, at least the viewable side (Table 5). I did not record the number of times a given microtexture was seen on the grain. Separate spreadsheets were created for each sample to record presence and absence data on the same per-grain basis. The goal of this approach was to allow later recombination of grains into multiple "virtual samples" to test the representativeness of different sample sizes. The 25 microtextures I checked for represent an inclusive list of those reported in the literature as commonly seen on glacially crushed quartz grains (Table 3). Mahaney's *Atlas* (2002) served as my standard reference for microtexture specifics.

I established guidelines to ensure that all samples were viewed at the same SEM magnification and that I was both consistent and confident in my presence/absence determinations. Each individual grain was imaged at a magnification level of approximately 300–500x. Quartz microtextures visible at that scale were analyzed in detail at magnification levels between 500x and 5000x. Certain microtextures on various grains were also photographed, again typically at higher magnification. Based on my experience in the reconnaissance phase, I used the following SEM settings for all samples: accelerating voltage = 15kv; working distance = 10 mm; spot size = 60 (arbitrary units, achieved by setting the JEOL JSM-6060LV spot size selector to 60).

Initially, I selected one sample from a known glaciated site in Costa Rica and analyzed approximately 300 sand grains. Individual grains were examined along traverses across the entire SEM stub, which essentially divided the sand grains into coarse rows. Each grain was analyzed for the presence or absence of all 25 microtextures (Table 3). I next analyzed a minimum of 100 grains per sample from the remaining eight Costa Rican samples. After I completed SEM analysis of the Costa Rican samples, I began SEM analysis of the Dominican Republic samples. Again, I recorded the presence or absence of the 25 microtextures on a minimum of 100 sand grains per sample. Care was taken to prevent errors, but the inclusion of a few non-quartz grains in SEM analysis was possible; however, on grains of this size, much of the

Table 5. Example of microtexture identification table

The example shows a subset of the full 25-microtexture identification table for Sample 1, with results for the presence and absence of microtextures (Mctx) 1–8 only on grains 1–20. For this table, “1” indicates presence and “0”, absence.

	Mctx 1	Mctx 2	Mctx 3	Mctx 4	Mctx 5	Mctx 6	Mctx 7	Mctx 8
Grain 1	0	1	0	0	0	1	0	1
2	0	1	0	0	1	0	0	0
3	0	1	0	0	0	1	0	1
4	0	1	1	0	0	0	1	1
5	0	1	1	0	0	1	0	1
6	0	1	0	0	1	1	0	1
7	1	1	0	0	0	0	1	0
8	0	1	1	0	0	0	0	1
9	0	1	1	0	0	0	0	0
10	0	1	1	0	0	0	0	0
11	0	0	0	1	0	1	0	1
12	0	1	1	1	0	0	0	1
13	0	1	1	0	1	1	0	1
14	0	1	1	0	0	0	0	1
15	0	1	1	0	0	0	1	0
16	0	0	0	0	0	0	0	1
17	0	1	1	0	0	1	1	0
18	0	1	0	0	0	0	0	1
19	0	1	0	0	1	1	0	0
20	0	1	1	0	1	0	0	1

microtextural patterning will be similar, so the statistical impact of misidentifications should be negligible. The most likely contaminants would be orthoclase (specific gravity of dense specimens can reach 2.56) and albite-rich phases of plagioclase (the specific gravity of pure albite is 2.62), although the cleavage usually reveals feldspar's identity.

3.4 Statistical Analysis

To discern a microtextural signature pattern within a single sample, I first graphed the raw microtexture results and analyzed frequencies of microtexture occurrence for each sample. I then measured associations between microtextures within single samples. I conducted chi-square goodness of fit tests to measure the probability of covariance or mutual exclusivity between microtextures within single samples. For every analyzed grain in each of the 18 samples, individual microtextures were compared to see which, if any, tended to occur together on the same sand grain, which tended to occur apart, and which were mutually exclusive (Table 6). Microtexture pair associations with a 0.05 or lower *p* value were documented for later evaluation; I also noted any associated microtexture pairs that occurred across multiple samples.

I next calculated confidence intervals based on the number of grains analyzed within each sample. Confidence intervals were determined using a bootstrapping method to calculate theoretical and empirical confidence at the 99%, 95%, 90%, and 68% levels. However, as we want to robustly say whether samples are truly different, this thesis focuses only on the 99% confidence level. In a parallel study, Dr. Ken Orvis performed the bootstrapping investigation by generating 10,000 virtual "sand grains," in which the 25 microtextures were randomly assigned either a 1 or 0, based on proportions for each microtexture as found in sample 2 (my largest sample). The original random number sets were then rerandomized and again used to assign 250,000 microtextures in each of four other spreadsheets; these five separate virtual samples, consisting of 10,000 random "grains" each, formed the basis for the bootstrapping, in which subsamples of a given size were randomly drawn 1000 times from each of the five larger virtual samples, and the probability of particular departures from the actual proportional values were empirically determined for that subsample size (Table 7). Thus the width of the 99% confidence interval for a single sample is dependent upon sample size. For sample 1, which has 150 grains, the empirical 99% confidence interval is ±9.00. The empirical 99% confidence interval for sample 2, with a sample size of 300, is ±6.67. The remaining samples, 3–18, each have 100 grains and the interval is ±11.33 (Table 7). Once the 99% confidence levels had been determined for every sample, the results were graphed. The actual sample results were then visually compared to determine which microtextures, if any, could be said to differ based on lack of overlap of the confidence intervals. All statistical analyses were completed in Microsoft Excel using statistical macros written by Dr. Orvis and myself.

Table 6. Example of chi-square goodness-of-fit results

This step was designed to test for patterns of co-occurrence and mutually-exclusive occurrence of microtextures within a sample. The example shows a subset of the full 25-microtexture matrix for Sample 7, with chi-square results for microtextures (Mctx) 1–8 only. In this particular case the microtexture pairs 1 and 7 (fracture faces and low relief), 3 and 6 (conchoidal fractures and angular features), and 7 and 8 (low relief and medium relief) all display *p* values less than 0.05. Further examination revealed no importance in the relationship between microtextures 1 and 7; these features were found on only a small minority of grains in sample 7 and occurred together nearly as often as apart. However in this sample conchoidal fractures (3) did tend to occur on grains without sharp, angular features (6). The strong mutual exclusivity of microtextures 7 and 8 is expected, considering that grains may only be classified as one relief type. Degrees of freedom = 2 unless otherwise indicated.

Mctx 1								
Chi-Sq	**Mctx 1**							
P-Val								
Mctx 2								
Chi-Sq	0.834	**Mctx 2**						
P-Val	0.659							
Mctx 3								
Chi-Sq	0.363	0.740	**Mctx 3**					
P-Val	0.834	0.691						
Mctx 4								
Chi-Sq	0.665	0.138	0.021	**Mctx 4**				
P-Val	0.717	0.933	0.989					
Mctx 5		D.F. = 1						
Chi-Sq	1.808	0.118	0.814	0.152	**Mctx 5**			
P-Val	0.405	0.731	0.666	0.927				
Mctx 6								
Chi-Sq	0.101	0.140	7.832	5.373	0.188	**Mctx 6**		
P-Val	0.951	0.933	0.020	0.068	0.910			
Mctx 7		D.F. = 1		D.F. = 1				
Chi-Sq	9.545	0.063	1.145	0.639	0.148	0.005	**Mctx 7**	
P-Val	0.008	0.802	0.564	0.424	0.929	0.998		
Mctx 8		D.F. = 1					D.F. = 1	
Chi-Sq	3.519	0.325	0.567	0.497	0.698	0.043	29.498	**Mctx 8**
P-Val	0.172	0.569	0.753	0.780	0.705	0.979	0.000	

(light green)	Probability of non-random covariance or mutual exclusivity >50%
(yellow)	Probability of non-random covariance or mutual exclusivity >95%
(orange)	Probability of non-random covariance or mutual exclusivity >99%
(red)	Probability of non-random covariance or mutual exclusivity >99.9%

Table 7. Bootstrapping results

For this N (sample size):	99% confidence interval (±, %)	95% confidence interval (±, %)	90% confidence interval (±, %)	ca. 68% confidence interval (±, %)
5	46.33	36.00	30.00	16.00
10	35.00	25.33	21.33	12.33
15	28.33	21.33	17.33	10.00
20	25.00	19.00	15.00	9.00
25	22.33	16.33	13.67	7.67
30	20.67	15.00	12.00	7.00
50	15.40	10.86	8.75	4.93
100	11.33			
150	9.00			
300	6.67			

CHAPTER 4. RESULTS

4.1 Raw Results

Across all samples, I found that sub-parallel linear fractures are the most common microtexture (Tables 8 and 9, and Figure 3). Other microtextures considered typically diagnostic of glacial environments by Mahaney and Kalm (2000)—conchoidal fractures, curved grooves, medium-to-high relief, and step-like features—are also seen in every one of the 18 samples. As a group, the Costa Rican samples have similar microtextural signatures to each other, as do the Dominican Republic samples as a group, and in fact the two groups are nearly indistinguishable. Independence testing revealed a variety of relationships between microtexture types in single samples but none that formed strong patterns across multiple samples; these and other relationships are discussed in detail below (Table 10). In the following sections I discuss the microtextural characteristics of each sample, with a focus on certain microtextures shown in the literature to be common to glacierized grains.

4.1.1 Costa Rican Samples

Samples 1–9 are sediments collected from within or near known glaciated sites in Costa Rica. Samples 6, 7, and 9 are from sediments suspected to be glacial debris transported as debris flows down the Río Chirripó Pacifico drainage to the San Gerardo vicinity at the base of Cerro Chirripó; the remaining are from till deposits in Valle de las Morrenas, Cerro Chirripó.

As a group, the quartz sand grains from the Costa Rican samples have quite similar microtextural characteristics (Table 8; Figure 3). A typical grain has medium-to-high relief, somewhat angular features, sub-parallel linear and conchoidal fracturing, adhering particles, and evidence of dissolution etching and precipitation (Figure 4). Microtextures considered by Mahaney (2002) to be typically diagnostic of glacial environments, such as step-like features and

Table 8. Percentage of microtexture occurrence, Costa Rica samples

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Average
1. Fracture Faces	3.3	8.0	0.0	8.0	2.0	1.0	11.0	8.0	15.0	6.3
2. Sub-parallel Linear Factures	90.0	85.7	94.0	95.0	96.0	84.0	96.0	87.0	95.0	91.4
3. Conchoidal Fractures	48.0	54.7	61.0	59.0	72.0	45.0	46.0	58.0	53.0	55.2
4. Curved Grooves	8.7	22.3	18.0	40.0	15.0	7.0	18.0	17.0	40.0	20.7
5. Straight Grooves	18.7	35.0	19.0	30.0	23.0	18.0	14.0	28.0	38.0	24.9
6. Sharp, Angular Features	28.7	44.0	18.0	58.0	23.0	30.0	41.0	34.0	68.0	38.3
7. Low Relief	8.7	6.3	8.0	5.0	3.0	14.0	10.0	7.0	18.0	8.9
8. Medium Relief	70.7	59.7	72.0	64.0	70.0	65.0	77.0	73.0	66.0	68.6
9. High Relief	20.7	34.0	20.0	31.0	27.0	21.0	13.0	20.0	16.0	22.5
10. Crescentic Gouges	4.7	10.3	7.0	7.0	6.0	5.0	6.0	5.0	10.0	6.8
11. Arc-Shaped Steps	4.7	11.3	4.0	16.0	12.0	5.0	1.0	2.0	10.0	7.3
12. Dissolution Etching	78.0	74.7	64.0	67.0	74.0	65.0	71.0	71.0	69.0	70.4
13. Preweathering	13.3	30.0	13.0	16.0	21.0	7.0	12.0	15.0	27.0	17.1
14. Weathering	56.7	54.3	53.0	53.0	57.0	48.0	38.0	47.0	47.0	50.4
15. Adhering Particles	60.7	58.3	47.0	48.0	36.0	70.0	35.0	33.0	64.0	50.2
16. Precipitation	54.0	45.0	46.0	59.0	49.0	54.0	55.0	41.0	51.0	50.4
17. Linear Steps	10.7	13.7	9.0	17.0	16.0	5.0	6.0	7.0	18.0	11.4
18. Deep Troughs	8.0	12.3	14.0	14.0	13.0	8.0	21.0	14.0	20.0	13.8
19. Mechanically Upturned Plates	40.0	25.7	28.0	29.0	33.0	40.0	41.0	24.0	53.0	34.9
20. Abrasion	16.0	36.0	23.0	43.0	31.0	20.0	45.0	44.0	57.0	35.0
21. V-shaped Percussion Fractures	12.7	19.7	6.0	29.0	14.0	12.0	16.0	10.0	11.0	14.5
22. Radial Fractures	3.3	10.3	4.0	10.0	10.0	5.0	7.0	3.0	6.0	6.5
23. Breakage Blocks	14.7	16.3	5.0	10.0	3.0	14.0	8.0	6.0	12.0	9.9
24. Edge Rounding	5.3	2.3	5.0	4.0	10.0	6.0	2.0	3.0	3.0	4.5
25. New Growth	4.7	7.7	2.0	7.0	6.0	4.0	5.0	6.0	5.0	5.3

Table 9. Percentage of microtexture occurrence, Dominican Republic samples

	Sample 10	Sample 11	Sample 12	Sample 13	Sample 14	Sample 15	Sample 16	Sample 17	Sample 18	Average
1. Fracture Faces	3.0	4.0	6.0	2.0	1.0	2.0	2.0	1.0	11.0	3.6
2. Sub-parallel Linear Factures	94.0	98.0	94.0	98.0	99.0	100	99.0	99.0	94.0	97.2
3. Conchoidal Fractures	61.0	75.0	68.0	76.0	76.0	80.0	66.0	71.0	62.0	70.6
4. Curved Grooves	25.0	15.0	29.0	11.0	16.0	21.0	13.0	17.0	41.0	20.9
5. Straight Grooves	22.0	17.0	18.0	16.0	25.0	23.0	19.0	18.0	36.0	21.6
6. Sharp, Angular Features	28.0	9.0	47.0	21.0	22.0	35.0	25.0	23.0	39.0	27.7
7. Low Relief	11.0	2.0	8.0	4.0	10.0	8.0	1.0	5.0	11.0	6.7
8. Medium Relief	68.0	73.0	68.0	76.0	73.0	66.0	76.0	76.0	66.0	71.3
9. High Relief	21.0	25.0	24.0	20.0	17.0	26.0	23.0	19.0	23.0	22.0
10. Crescentic Gouges	4.0	3.0	6.0	4.0	4.0	5.0	1.0	3.0	11.0	4.6
11. Arc-Shaped Steps	5.0	3.0	17.0	6.0	12.0	9.0	8.0	5.0	13.0	8.7
12. Dissolution Etching	61.0	73.0	57.0	59.0	50.0	74.0	63.0	61.0	62.0	62.2
13. Preweathering	10.0	10.0	18.0	3.0	19.0	15.0	12.0	13.0	17.0	13.0
14. Weathering	51.0	76.0	38.0	55.0	43.0	51.0	53.0	41.0	53.0	51.2
15. Adhering Particles	41.0	35.0	49.0	50.0	53.0	68.0	51.0	37.0	55.0	48.8
16. Precipitation	31.0	35.0	33.0	30.0	34.0	27.0	15.0	28.0	47.0	31.1
17. Linear Steps	10.0	11.0	10.0	13.0	15.0	25.0	16.0	15.0	11.0	14.0
18. Deep Troughs	7.0	4.0	14.0	4.0	8.0	9.0	5.0	8.0	17.0	8.4
19. Mechanically Upturned Plates	28.0	54.0	29.0	27.0	32.0	30.0	41.0	34.0	34.0	34.3
20. Abrasion	24.0	22.0	34.0	27.0	29.0	52.0	34.0	18.0	46.0	31.8
21. V-shaped Percussion Fractures	1.0	6.0	3.0	5.0	8.0	5.0	6.0	12.0	11.0	6.3
22. Radial Fractures	2.0	1.0	5.0	1.0	3.0	1.0	3.0	1.0	8.0	2.8
23. Breakage Blocks	10.0	10.0	6.0	22.0	16.0	27.0	6.0	17.0	24.0	15.3
24. Edge Rounding	0.0	1.0	0.0	1.0	1.0	1.0	1.0	0.0	3.0	0.9
25. New Growth	1.0	1.0	3.0	2.0	1.0	1.0	8.0	2.0	3.0	2.4

Table 10. Microtexture pair relationships

Microtexture pairs were tested to determine which, if any, appeared either to occur together or to occur separately, i.e. not on the same grains, more than expected. Chi-square testing (Table 6) yielded 140 instances, out of 5400 possible pairings in all 18 samples, where the patterns of occurrence of microtexture pairs suggested significance ($p \leq 0.05$). The preponderance of these turned out to be cases where the microtextures only occurred on a few grains to begin with, so the statistical significance result was spurious. Others (e.g., "medium relief" versus "high relief") were the expected result of the analytical method.

The numbers in parentheses indicate the number of samples in which a pairing occurred within a major sample group; groups are ordered as (Costa Rican upland, Costa Rican downslope, Dominican Republic). For example, microtexture 2 (sub-parallel linear fractures) was paired with microtexture 3 (conchoidal fractures) in 3 different samples: 1 Costa Rican upland sample and 2 Dominican Republic samples.

Microtexture **2**:	
	3 (1, 0, 2)
Microtexture **3**:	
	4 (0, 0, 1); **6** (0, 1, 0); **15** (1, 0, 0); **19** (0, 0, 1); **21** (0, 0, 1)
Microtexture **4**:	
	12 (0, 0, 1); **18** (0, 1, 0)
Microtexture **5**:	
	12 (0, 0, 1)
Microtexture **7**:	
	8 (5, 3, 6)
Microtexture 8:	
	9 (6, 3, 9)
Microtexture **9**:	
	23 (1, 1, 1)
Microtexture **11**:	
	12 (0, 0, 1); **21** (0, 0, 1)
Microtexture **12**:	
	17 (0, 0, 1)
Microtexture **14**:	
	17 (0, 0, 1)
Microtexture **15**:	
	20 (2, 0, 0)
Microtexture **16**:	
	22 (0, 0, 2)
Microtexture **18**:	
	22 (1, 0, 0)

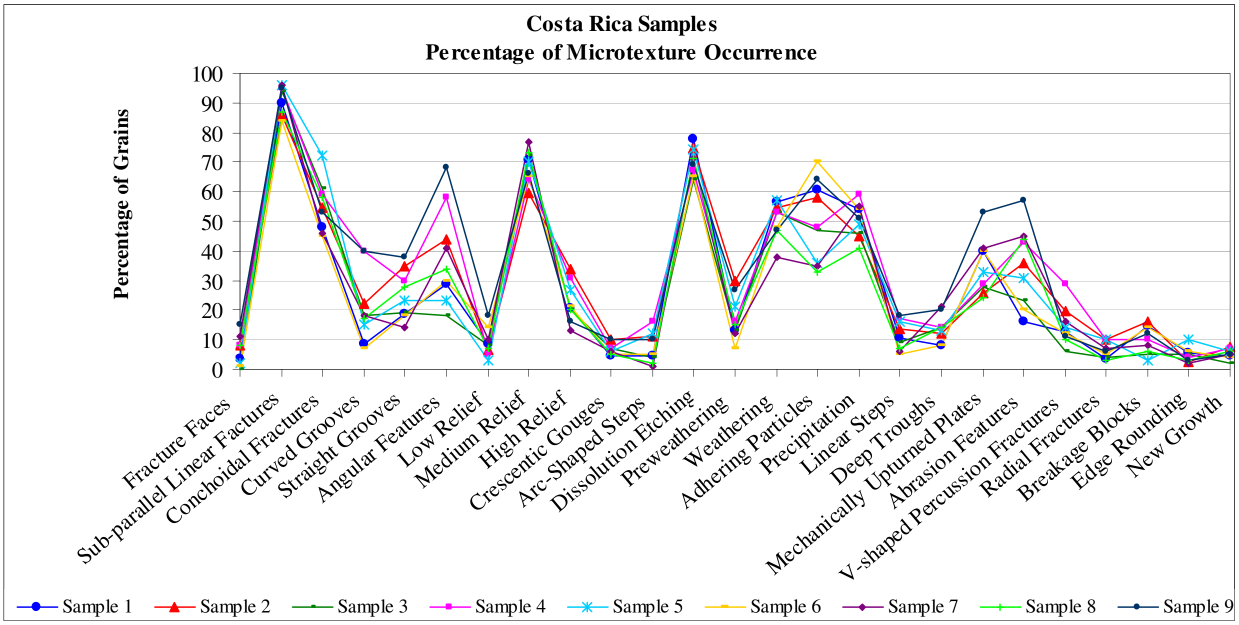

Figure 3. Results for Costa Rican samples 1–9

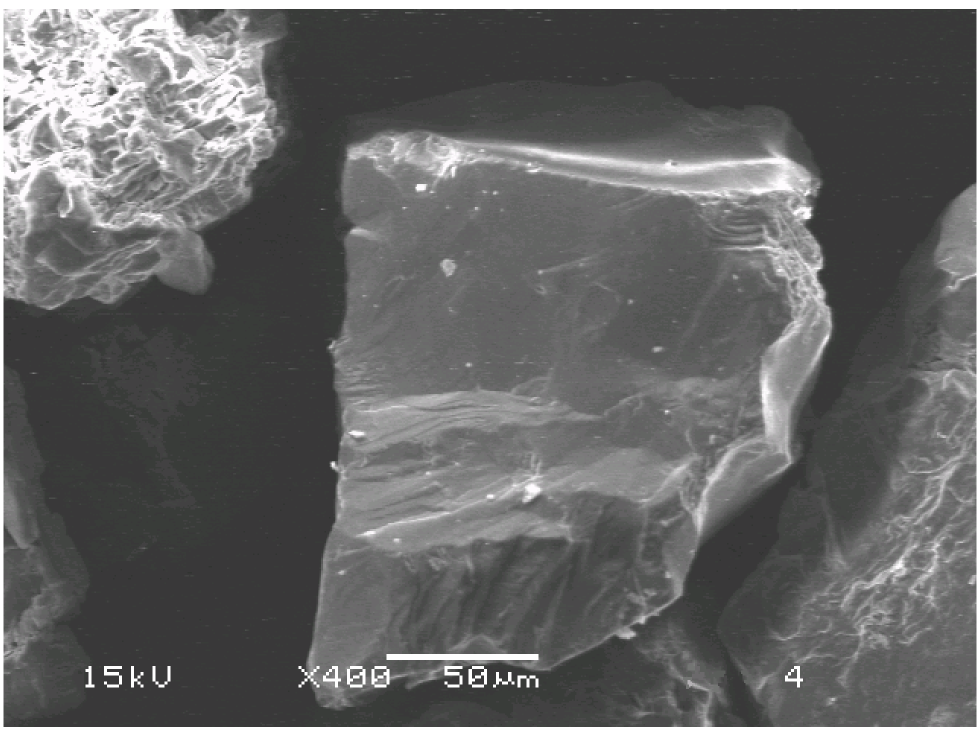

Figure 4. Example grain, sample 4, Costa Rica

curved grooves, are found in every Costa Rican sample, but not necessarily on a high proportion of grains. No substantial differences between Valle de Las Morrenas and San Gerardo samples were found. However, weathering is a less dominant feature among San Gerardo samples than at Valle de las Morrenas.

Glacio-Lacustrine

Sample 1 is from a basal glacial-flour facies of a core of bottom sediments from Lago Morrenas 1. Over 60% of all grains in sample 1 display medium relief with sub-parallel linear fracturing, dissolution etching, and adhering particles (Figure 5). Nearly half of the grains have conchoidal fractures, mechanically upturned plates, precipitation and weathering. Straight grooves, often indicative of glacigenesis, are found on almost 20% of grains. Independence testing revealed that in sample 1 deep troughs, while rare, tend to appear without radial fractures, but neither occur on a majority of grains. No other significant microtextural relationships were found in this sample.

Ground Moraine

Samples 2 and 3 (Figures 6 and 7) are contiguous samples of highly compacted ground moraine about twice the distance from the headwall as sample 1. The majority of grains from sample 2 have medium-to-high relief, sub-parallel linear fracturing, adhering particles, dissolution etching, and weathering (Figure 8). Groove-like features are seen on a considerably higher portion of grains in sample 2 than in sample 1: curved and straight grooves occur on 22.3% and 35.0%, respectively, of grains in sample 2 as compared to 8.7% and 18.7% in sample 1. Linear and arc-shaped steps, considered diagnostic of glacial transport, are found on over 10% of the grains. Figures are labeled to indicate the class and source of sediment; see table 11. Independence testing showed that breakage blocks occur more often on grains with high relief,

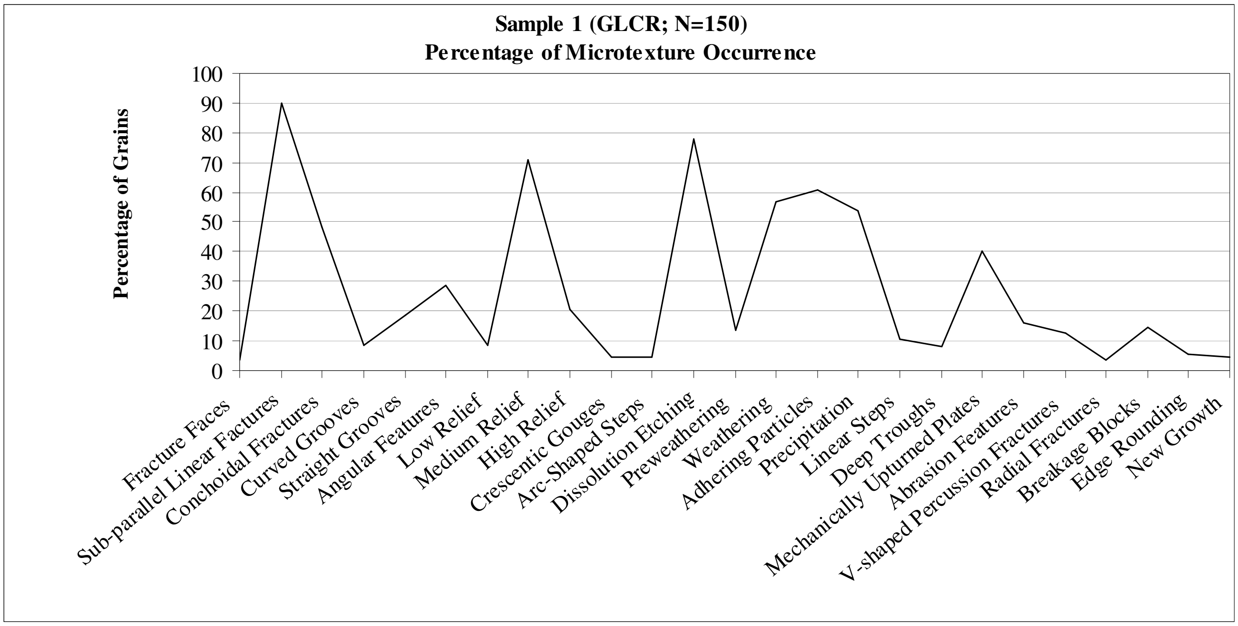

Figure 5. Results for sample 1 (glacio-lacustrine, Costa Rica)

Table 11. Class and sediment-source identification codes

GLCR	Glacio-lacustrine sediments, Costa Rica; sample 1
GMCR	Ground moraine sediments, Costa Rica; samples 2 and 3
LTMCR	Lateral-to-terminal moraine sediments, Costa Rica; samples 4, 5, and 8
DFCR	Glacial-periglacial debris flow deposits, Costa Rica; samples 6, 7, and 9
GMDR	Suspected ground moraine sediments, Dominican Republic; samples 10 and 11
PGDR	Suspected proglacial lacustrine sediments, Dominican Republic; samples 12–16
LTMDR	Suspected lateral-to-terminal moraine sediments, Dominican Republic; samples 17 and18

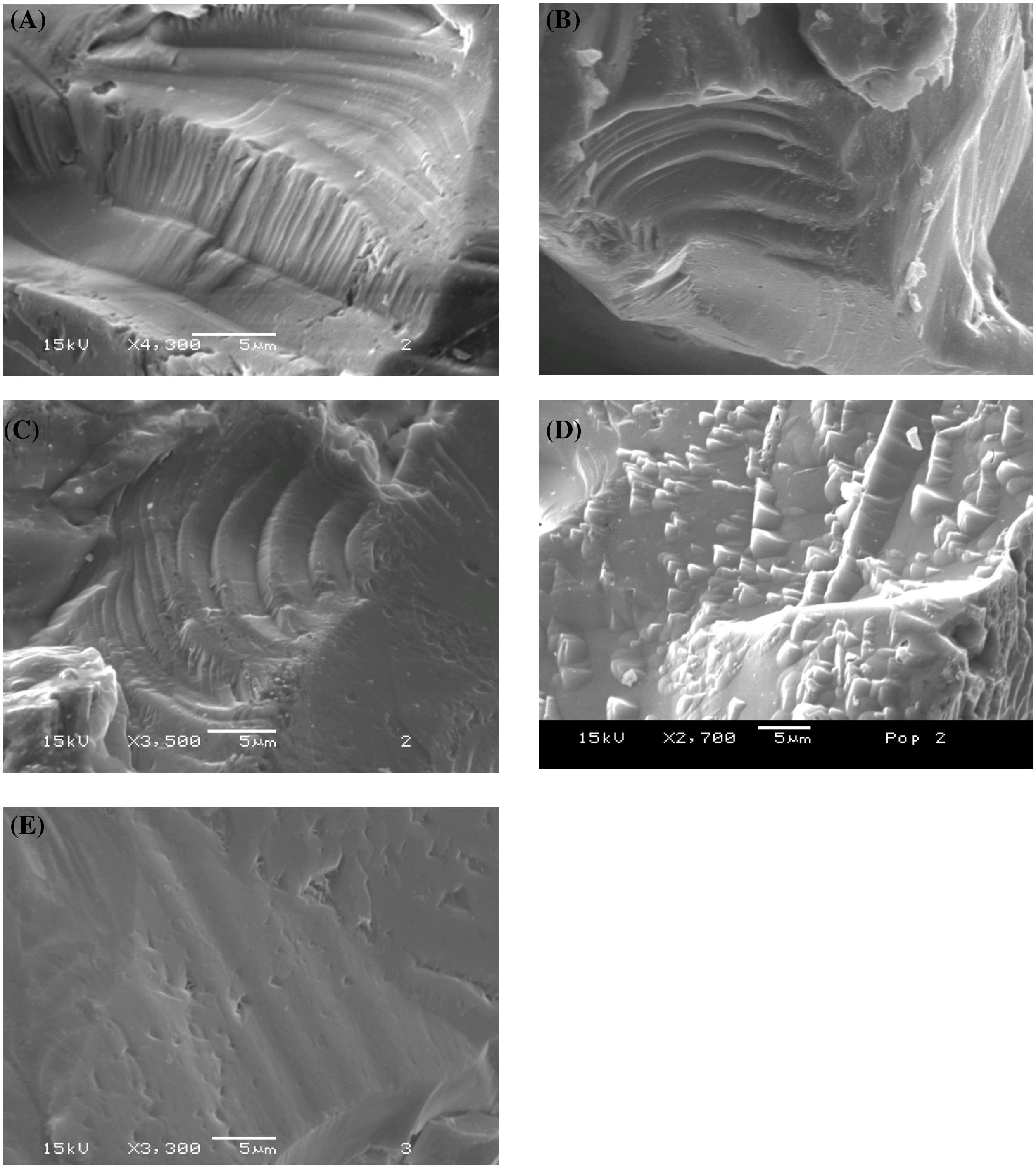

Figure 6. Microtexture examples, from samples 2 and 3 (GMCR[5])

(A) Sample 2: sub-parallel linear fractures, curved grooves; (B) Sample 2: conchoidal fractures; (C) Sample 2: arc-shaped steps, sub-parallel linear fractures, weathering; (D) Sample 2: new growth; (E) Sample 3: v-shaped percussion fractures, straight grooves.

[5] See table 11 for an explanation of identification codes.

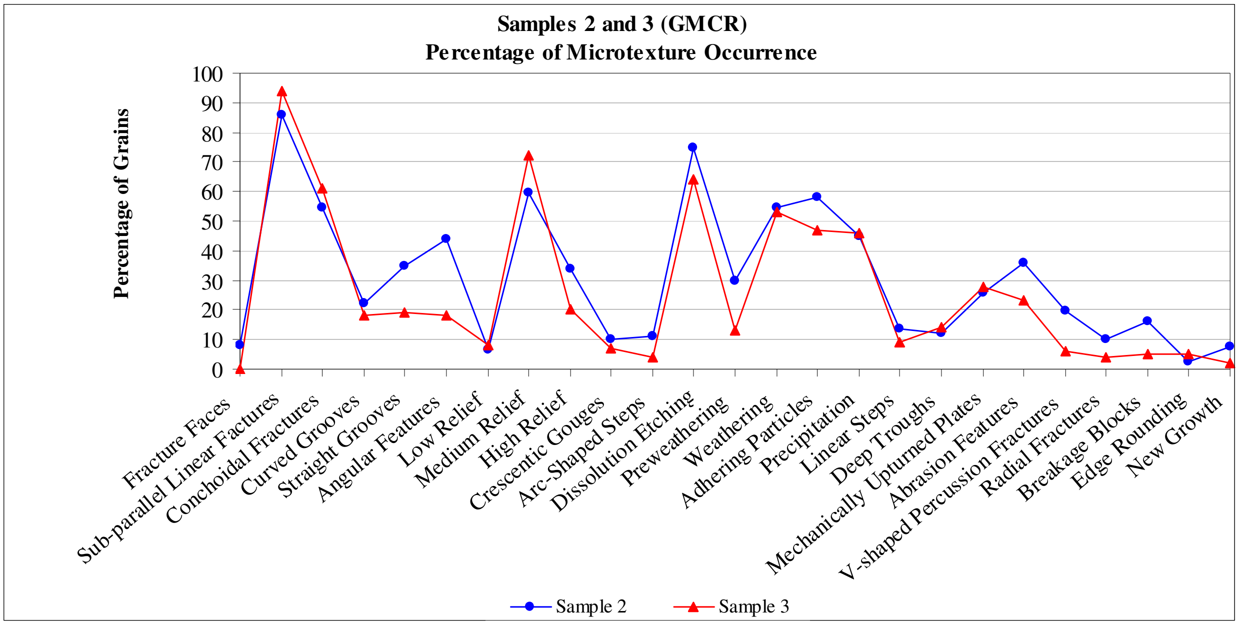

Figure 7. Results for samples 2 & 3 (ground moraine, Costa Rica)

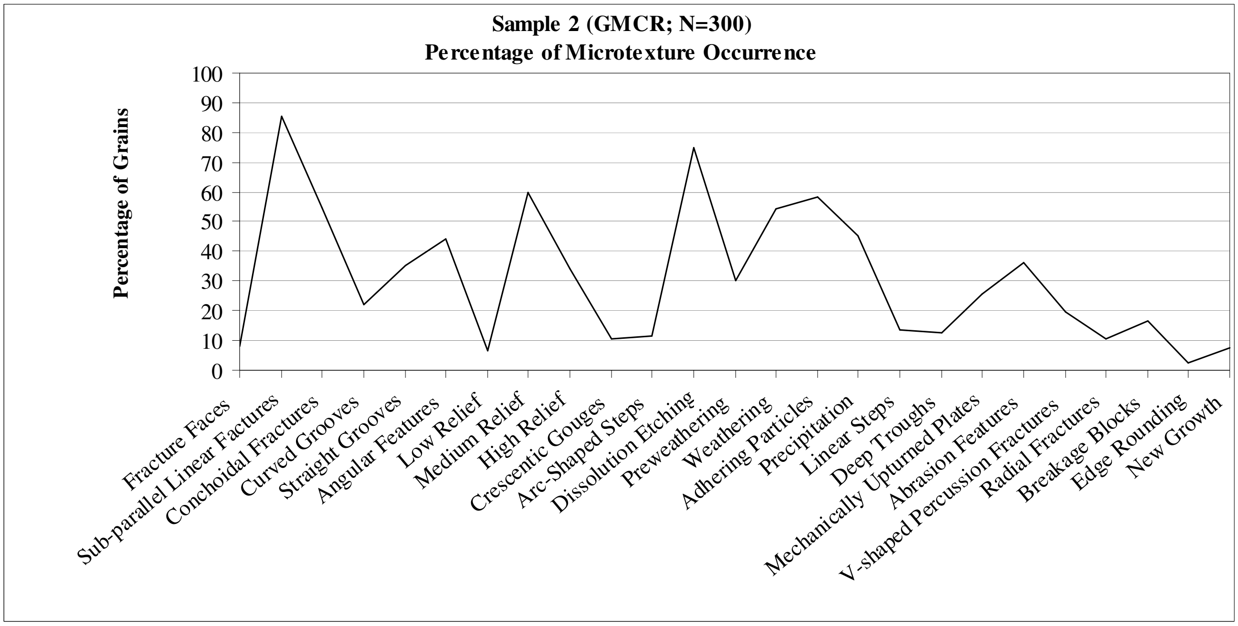

Figure 8. Results for sample 2 (ground moraine, Costa Rica)

and that abrasion tends to occur with adhering particles. No other significant measures of dependence were seen in the remaining microtextures.

The grains in sample 3 are fairly similar to sample 2, but with a complete lack of fracture faces and somewhat less preweathering (Figure 9). Dissolution etching, another weathering indicator, was also found on fewer grains. Independence testing revealed that conchoidal and sub-parallel linear fractures are almost always found on the same grain.

Lateral-to-Terminal Moraine

Samples 4, 5, and 8, all lateral-to-terminal moraine samples, share many microtextural characteristics (Figure 10). The majority of quartz grains from sample 4, from a lateral moraine still farther down the valley, display dissolution etching, medium relief and sub-parallel linear fractures (Figure 11). Curved grooves and straight grooves are found on 40.0% and 30.0% of grains, respectively. Nearly half of the grains exhibit abrasion features. This sample contains the highest incidences of v-shaped percussion fracturing, a microtexture most often found in fluvial environments. Linear steps, shown in the literature to be glacigenic, are seen on slightly less than 20% of grains. No significance in the measures of independence or correlation between microtextures was found in this sample.

As with the other samples, a majority of grains in sample 5, a sample from a markedly finer-textured (and possibly sorted) section of till within a few meters of where sample 4 was collected, show evidence of dissolution etching, sub-parallel linear and conchoidal fracturing with medium relief (Figure 12). Over half of the sample displays signs of weathering and precipitation, both of which occur in pre- and post-glacial environments. Typically glacigenic groove-like features, including curved and straight grooves as well as deeply embedded troughs,

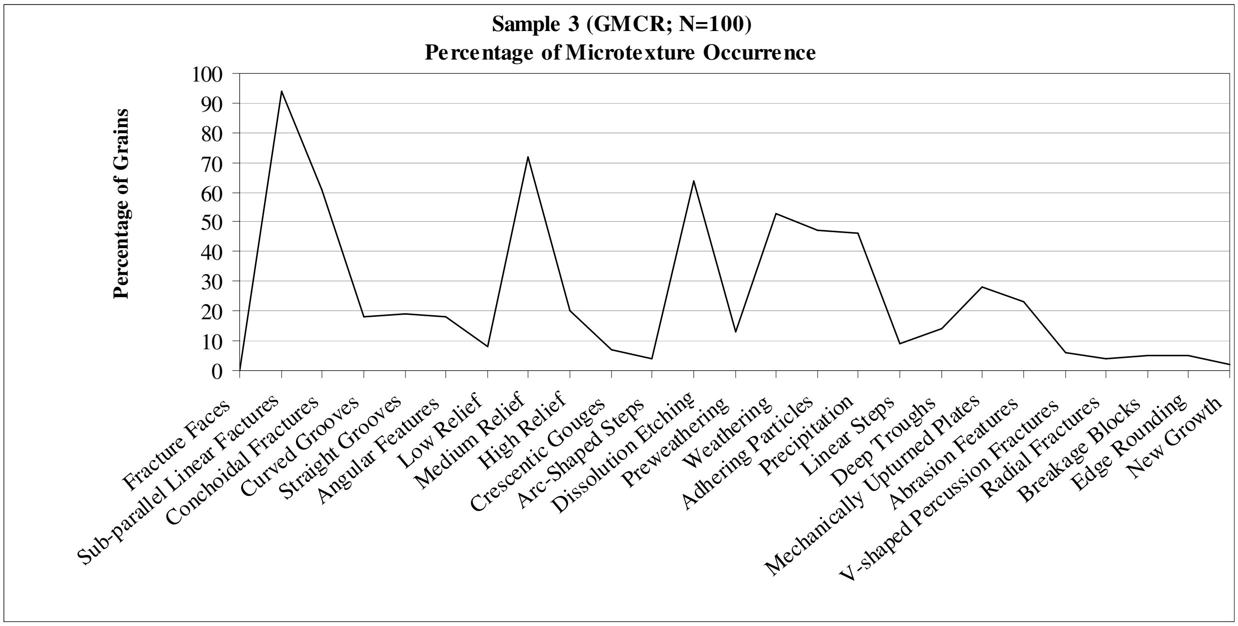

Figure 9. Results for sample 3 (ground moraine, Costa Rica)

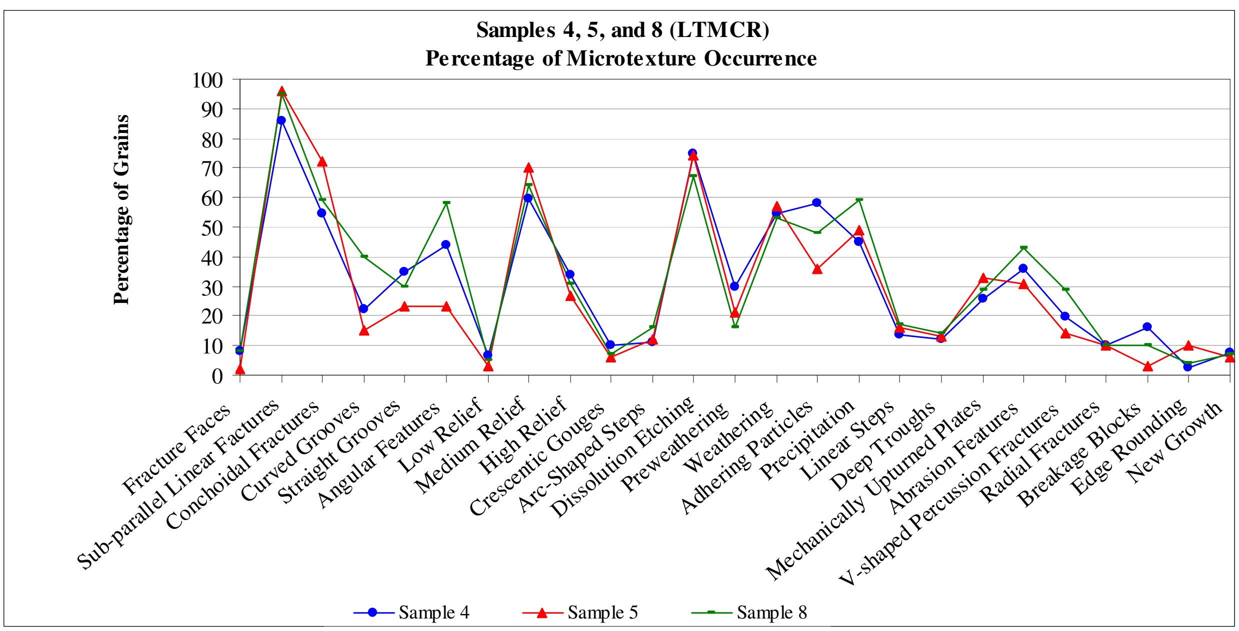

Figure 10. Results for samples 4, 5, & 8 (lateral-to-terminal moraine, Costa Rica)

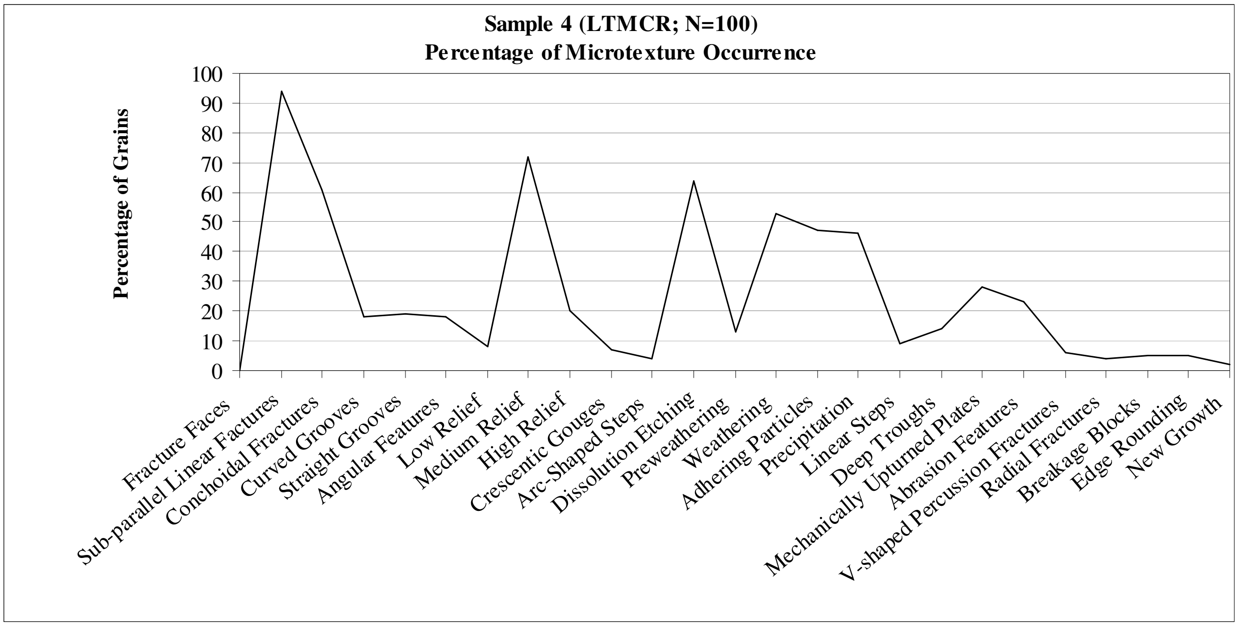

Figure 11. Results for sample 4 (lateral-to-terminal moraine, Costa Rica)

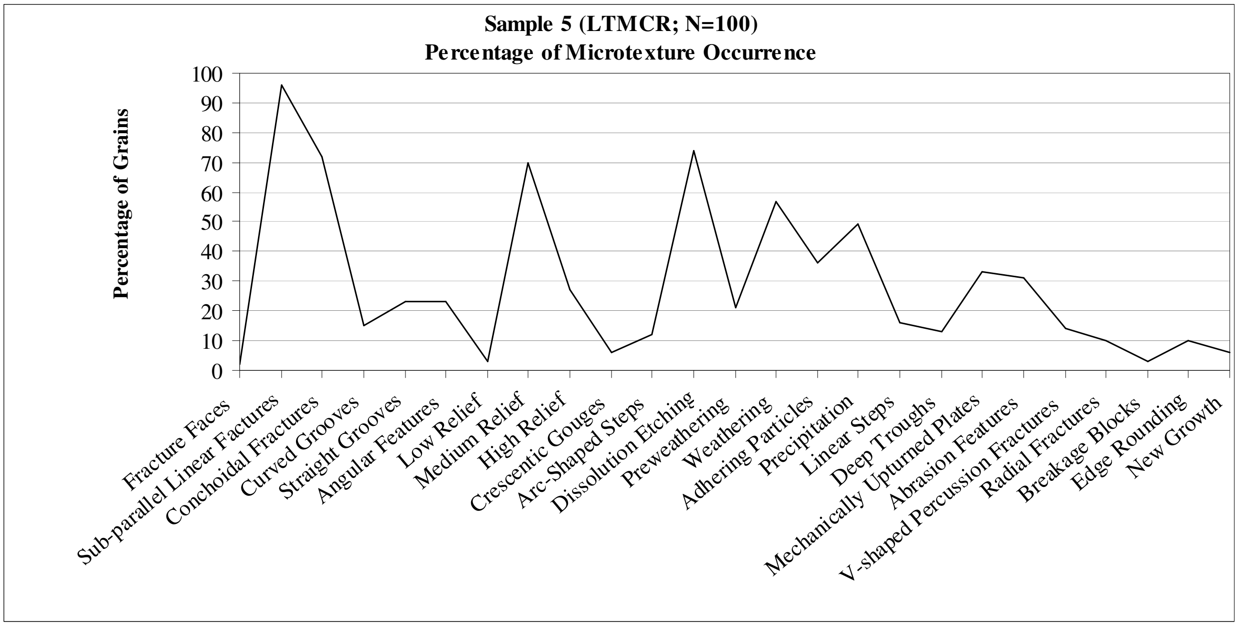

Figure 12. Results for sample 5 (lateral-to-terminal moraine, Costa Rica)

exist on a small number of grains. One-third of grains also have abrasion characteristics and adhering particles, which tend to occur together on the same grain, a trend also seen in sample 2.

A majority of grains in sample 8, from a small recessional moraine very near the headwall, display similar microtextures to previously discussed samples: sub-parallel linear and conchoidal fractures, medium relief, and evidence of dissolution etching and precipitation (Figure 13). Approximately 20% of grains have high relief, which appears fairly typical for the Costa Rican samples. Sample 8 has the lowest percentage of mechanically upturned plates, and a very small number of grains exhibit step-like features (Figure 14), both of which are considered diagnostically glacial in origin. Independence tests showed that conchoidal fractures were most often found on grains without any evidence of abrasion.

Glacial-Periglacial Debris Flow

The grains in samples 6, 7, and 9 (Figure 15) display somewhat less weathering than others despite the base-of-mountain sites where they were collected, diamict terraces perched above the modern Río Chirripó Pacifico, surrounded by hillslopes covered in deeply weathered regolith. The Macutico deposits, however, are similar to the Valle de Las Morrenas samples in other respects: medium relief dominates with high incidences of sub-parallel and conchoidal fracturing. Mechanically upturned plates are seen on over 40% of grains in each of the three samples; with the exception of sample 1, these debris flow samples have the highest percentage of grains with this microtexture among the Costa Rican samples. Deep troughs are found on more than 20% of grains in both samples 7 and 9, but only on a small minority of grains in sample 6. Sample 6 (Figure 16) also has a much lower occurrence of grains with abrasion

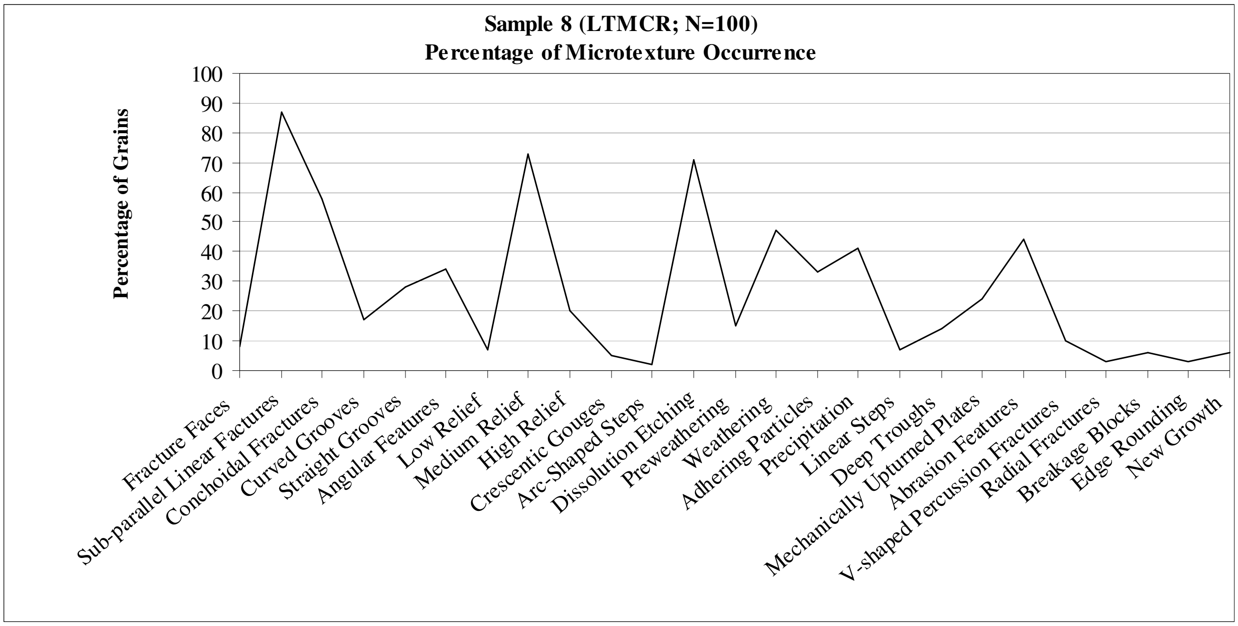

Figure 13. Results for sample 8 (lateral-to-terminal moraine, Costa Rica)

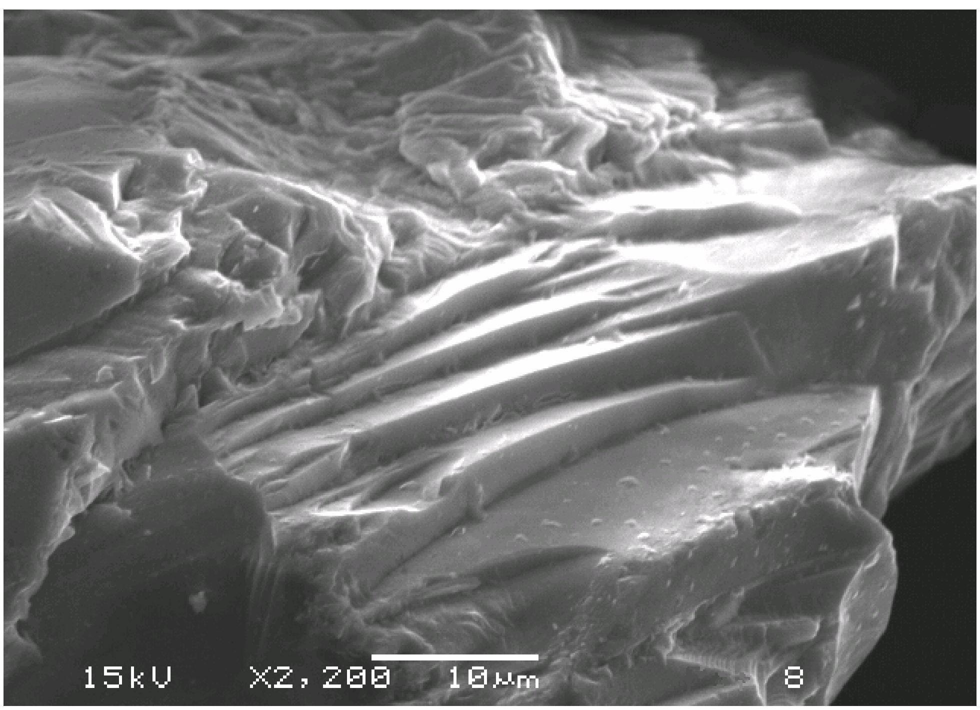

Figure 14. Microtexture examples, sample 8 (LTMCR[5]): linear steps, mechanically upturned plates

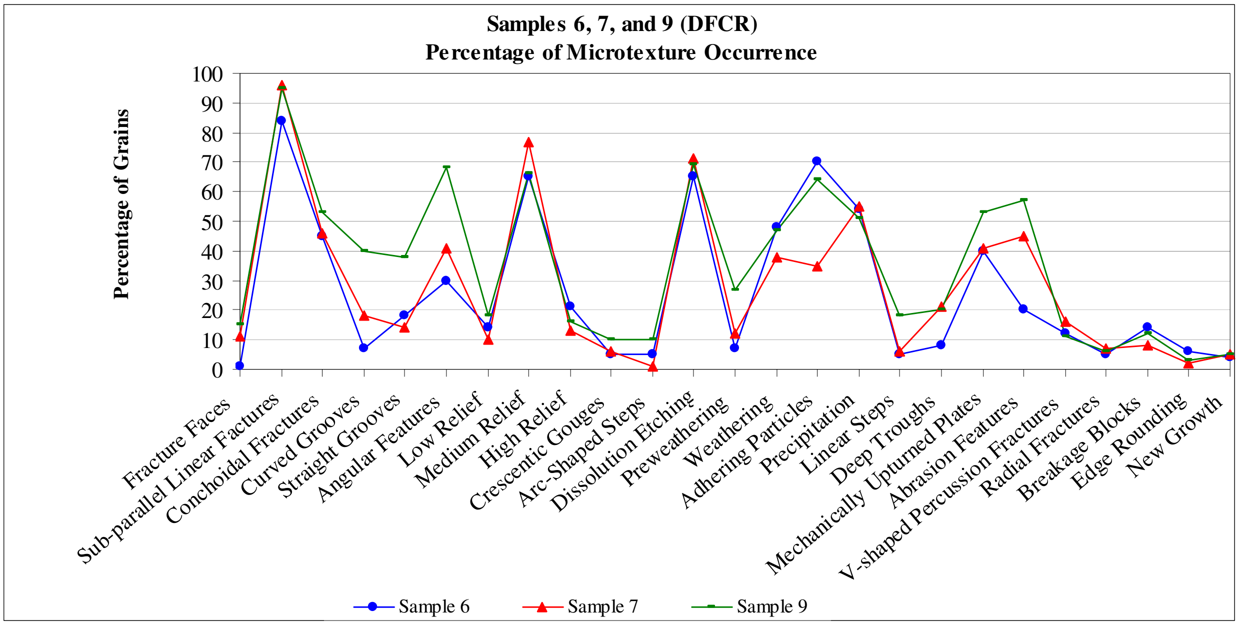

Figure 15. Results for samples 6, 7, & 9 (debris flow, Costa Rica)

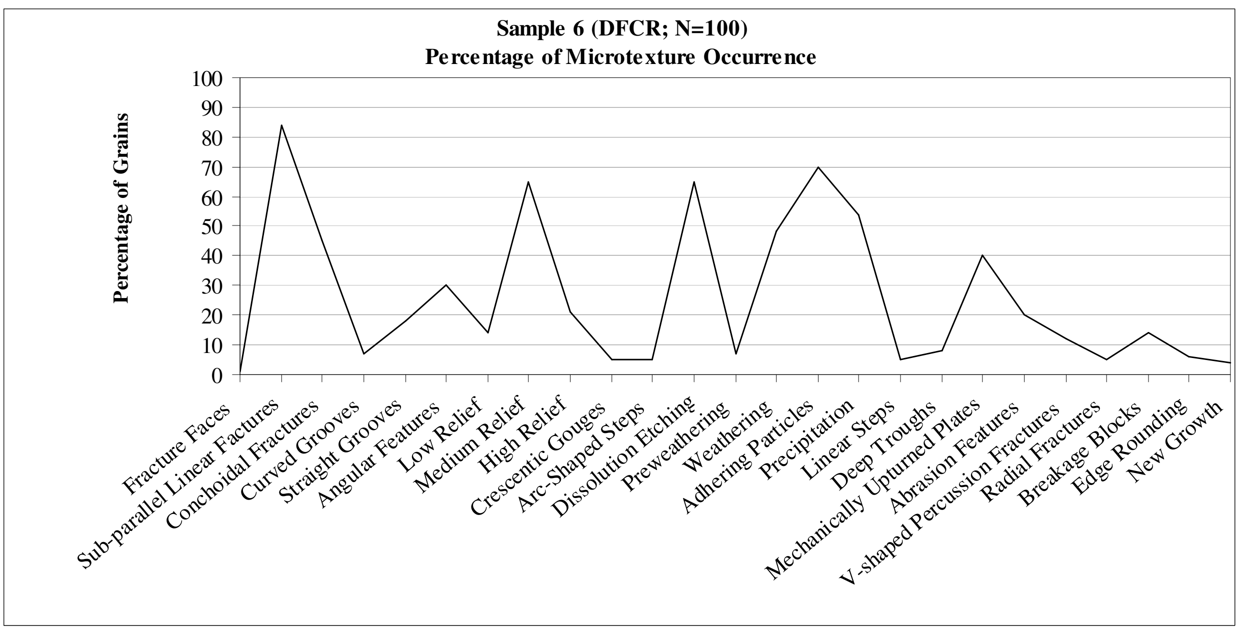

Figure 16. Results for sample 6 (debris flow, Costa Rica)

features when compared with samples 7 and 9 (Figures 17 and 18). Curved grooves and step-like features are found on less than 20% of grains from each sample.

Independence tests for sample 6 revealed that breakage blocks are found only on grains with medium-to-high relief, a relationship seen in other samples. The independence test results for sample 7 showed that conchoidal fractures tend to occur on grains without sharp, angular features; this relationship is not seen in the other Costa Rica samples. In sample 9, deep troughs are often paired on grains with curved grooves; along with sample 4, sample 9 has one of the highest percentages, 40.0%, of grains with curved grooves.

4.1.2 Dominican Republic Samples

The same microfeatures typically considered diagnostic of glacigenesis found on Costa Rican grains (Figure 4), such as sub-parallel linear and conchoidal fractures, curved grooves, and step-like features, are also found within the Dominican Republic samples (Figure 19). The microtextural signatures of the Dominican Republic samples (Figure 20) are remarkably alike, even more so than the resemblance between Costa Rican samples (Figure 3). Sub-parallel linear fractures are again the most common feature. Conchoidal fractures (Figure 21) occur with greater frequency on the Dominican Republic grains, while a considerably higher percentage of Costa Rican quartz grains have precipitation features. Mechanically upturned plates are seen on a comparable number of grains among sample from Costa Rica and the Dominican Republic. Straight and curved grooves (Figure 22) did not occur with any marked difference in frequency. V-shaped percussion fractures occur on only a minor number of Dominican Republic grains. Sample 11, a Macutico terrace diamicton sample, has the highest incidence of weathering among all Costa Rican and Dominican Republic samples. Linear and arc-shaped steps are found on less

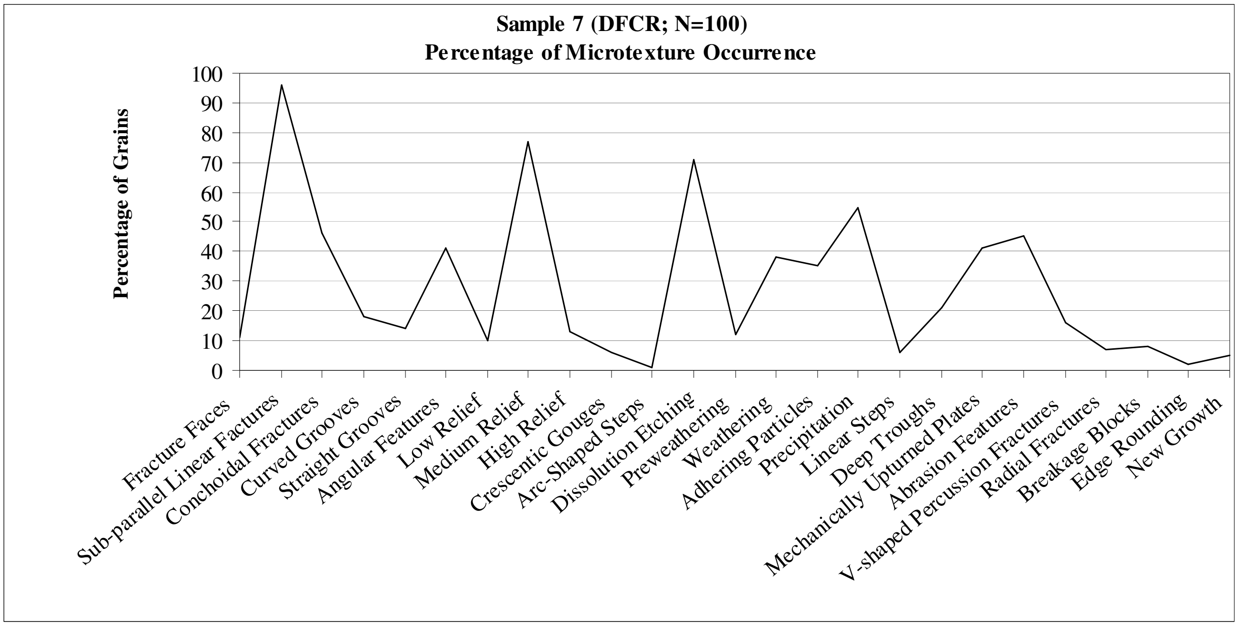

Figure 17. Results for sample 7 (debris flow, Costa Rica)

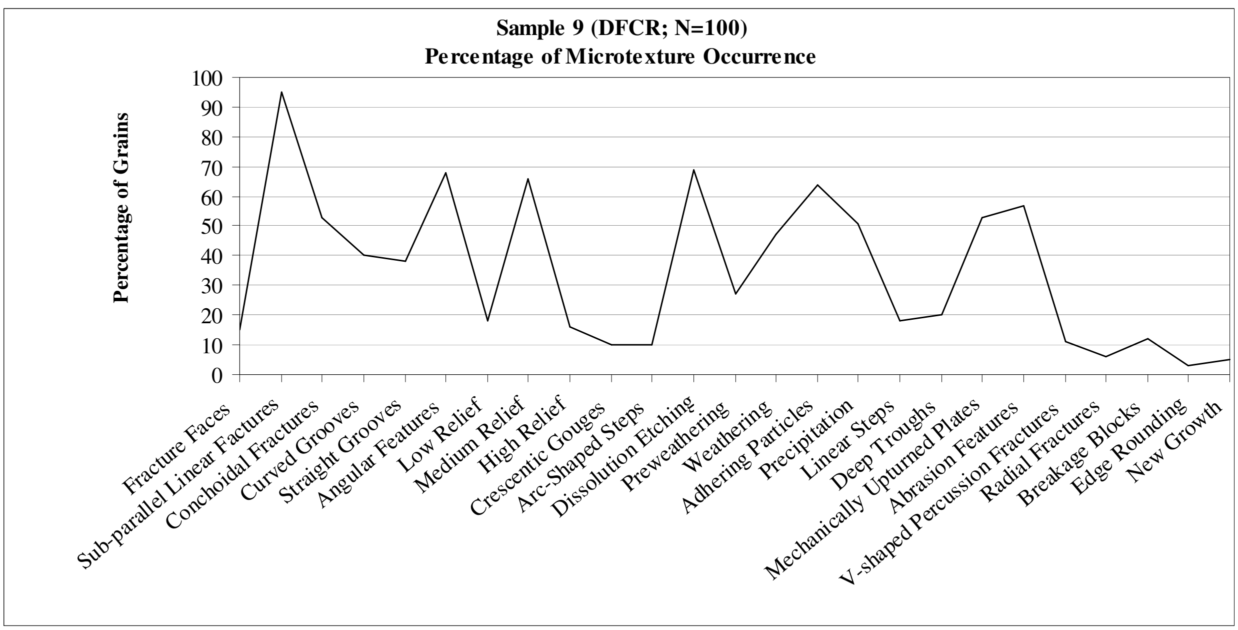

Figure 18. Results for sample 9 (debris flow, Costa Rica)

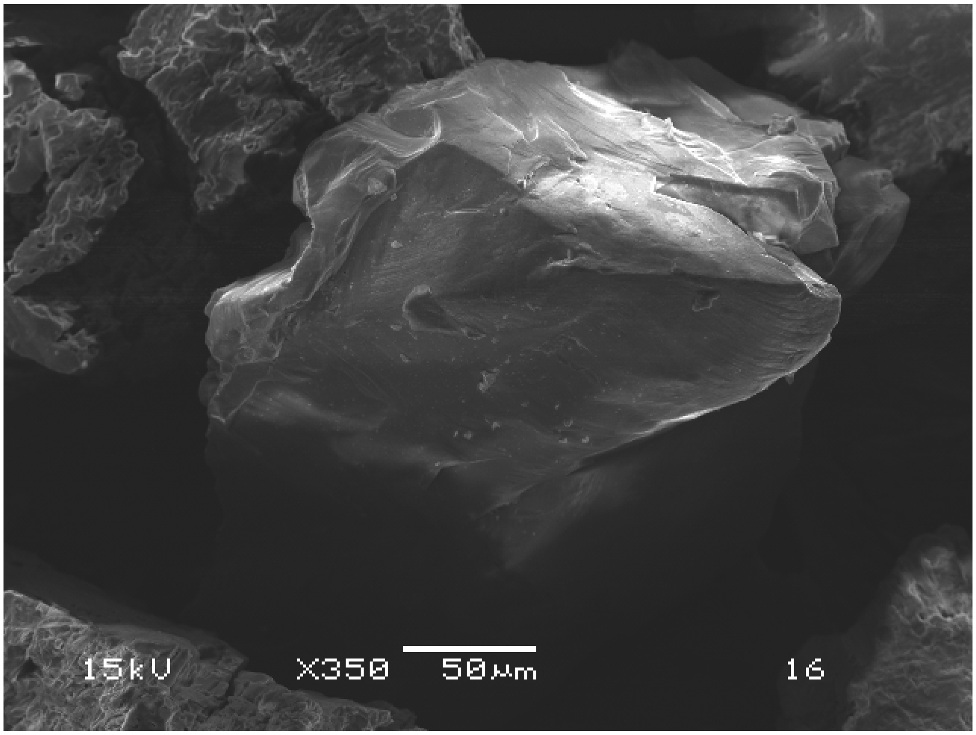

Figure 19. Example grain, sample 16 (PGDR[5]), Dominican Republic

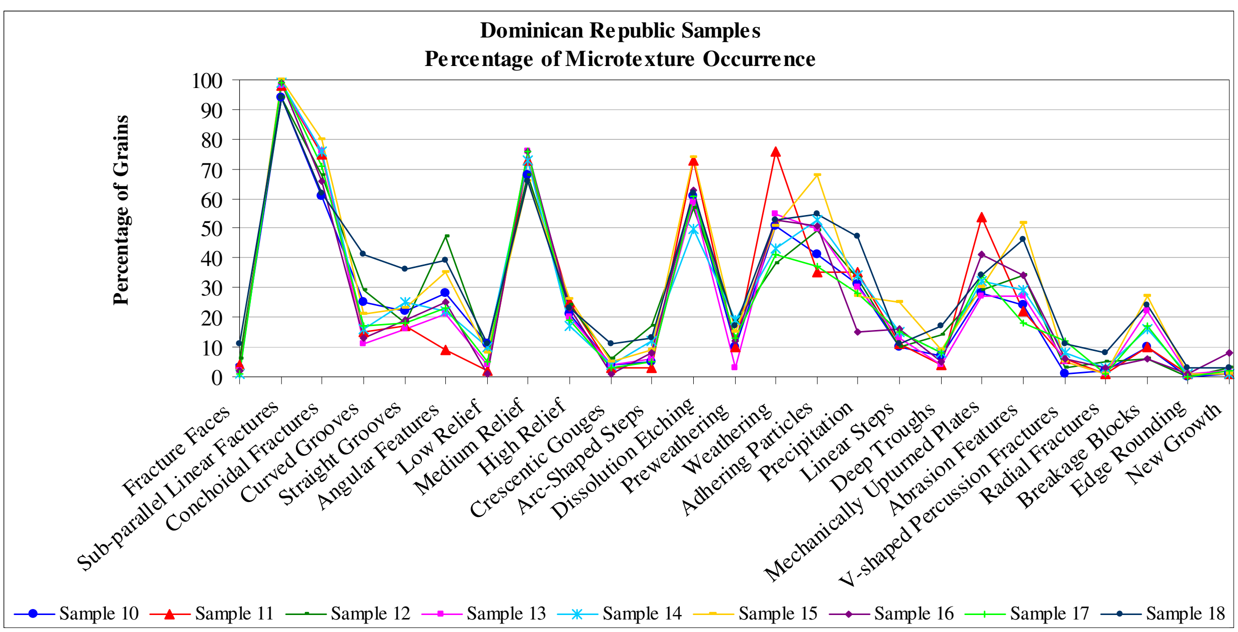

Figure 20. Results for Dominican Republic samples 10–18

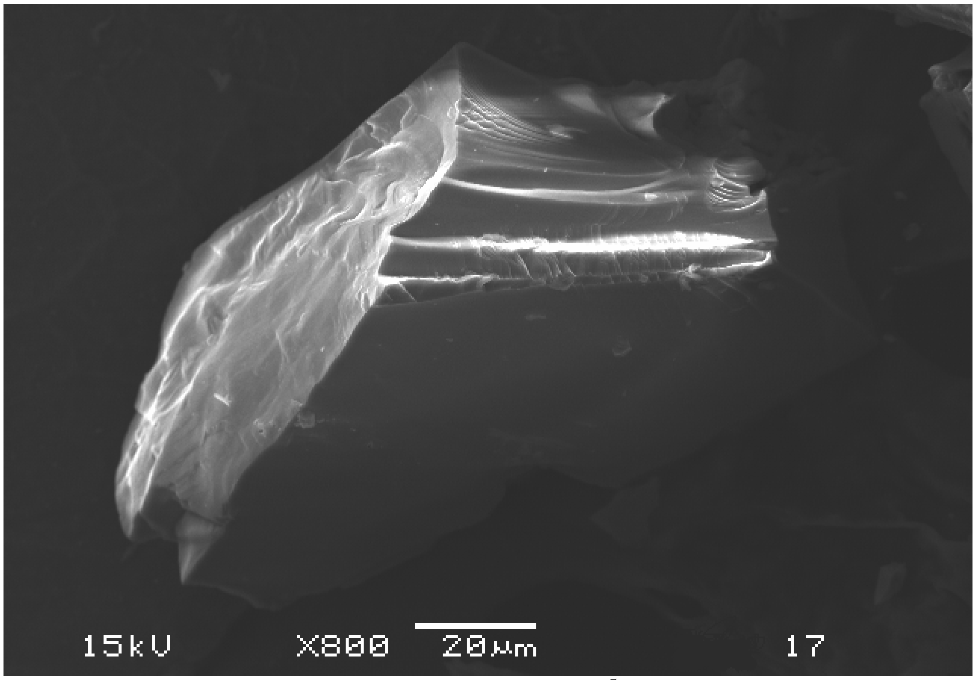

Figure 21. Microtexture examples, sample 17 (LTMDR[5]): deep troughs, curved and straight grooves, sub-parallel linear fractures

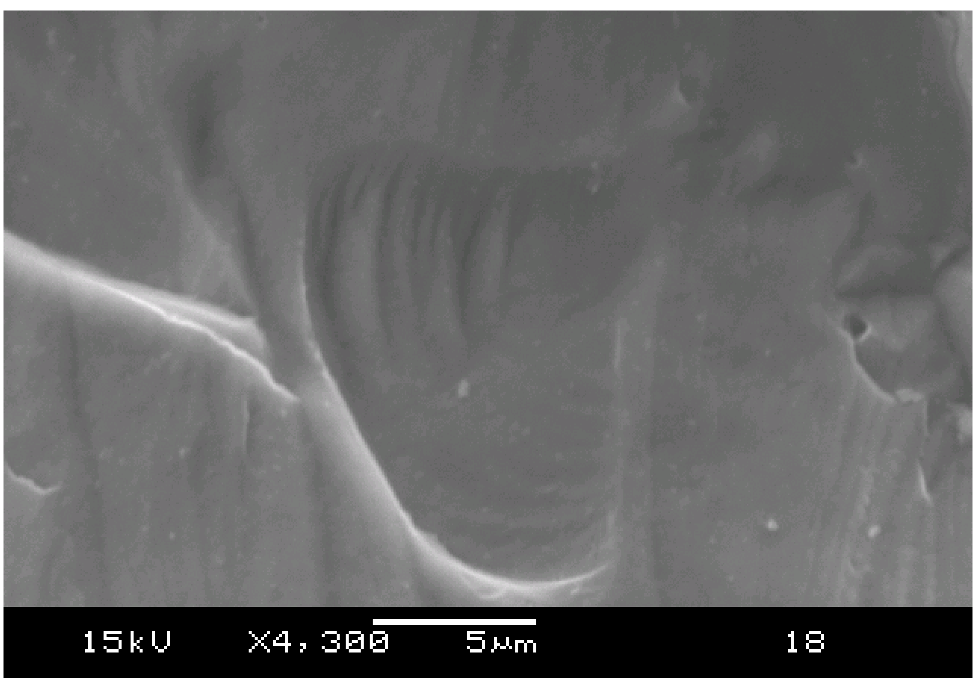

Figure 22. Microtexture examples, sample 18 (LTMDR[5]): conchoidal and sub-parallel linear fractures

than 15% of Dominican grains, which again is similar to the percentage of Costa Rican grains. I did not find substantial differences between the Macutico samples and the Valle de Bao sample (Table 8).

Suspected Proglacial Lacustrine

Samples 12–16 are possible proglacial lacustrine sediments that were collected from coring Laguna Grande de Macutico in the Macutico region of the Cordillera Central, Dominican Republic. These sediments are suspected pro-glacial outwash flood clastics laid down in an incipient lacustrine environment dammed behind a flood-deposited levee (Orvis, pers. comm.). Overall, the microtextural signature patterns of these five individual samples are very similar (Figures 23–28). Most grains display medium-to-high relief, sub-parallel fracturing, dissolution etching, and adhering particles. Conchoidal fractures are found on more than 60% of all grains in each sample. With the exception of sample 12, a much smaller portion of these sediments have angular features than other Dominican Republic samples. Overall, sample 15 has the highest incidence of conchoidal fracturing (80.0%) and sub-parallel linear fractures (100%). New growth is seen on only a small number of grains; the highest occurrence of new growth is 8.0% for sample 16. The greatest deviation among these samples' microtextural patterns occurs with the presence of breakage blocks. Samples 13, 14, and 15 contain a substantially higher number of grains with breakage blocks, compared to samples 12 and 16 or with all of the Costa Rican samples.

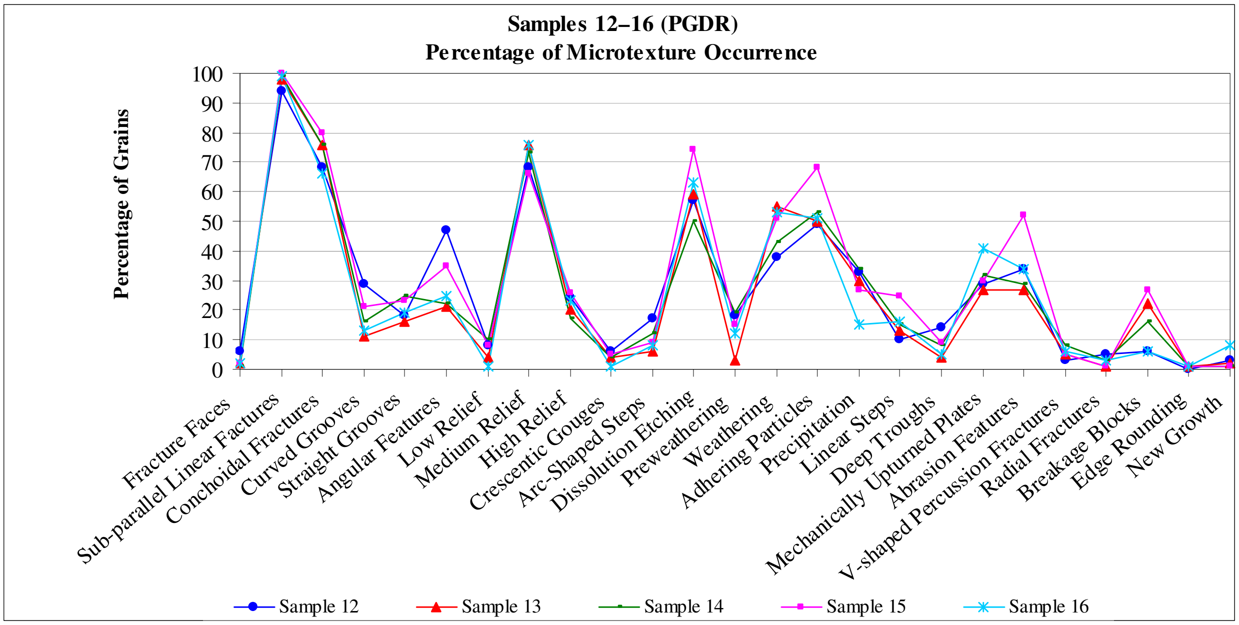

Figure 23. Results for samples 12–16 (suspected proglacial lacustrine, Dominican Republic)

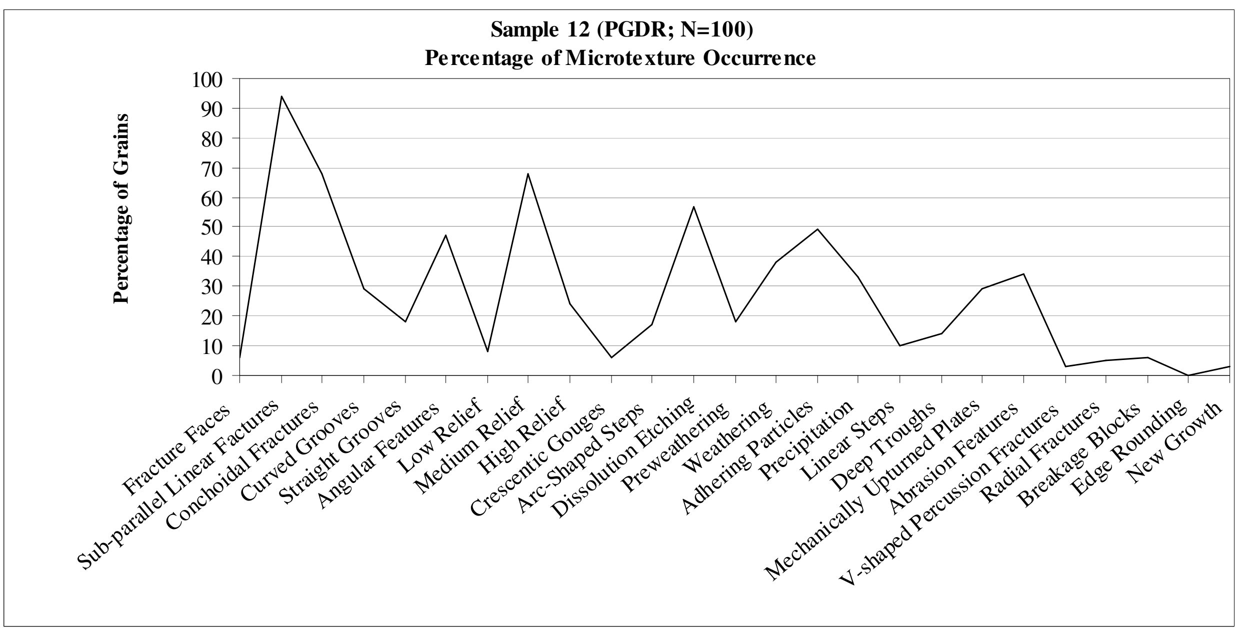

Figure 24. Results from sample 12 (suspected proglacial lacustrine, Dominican Republic)

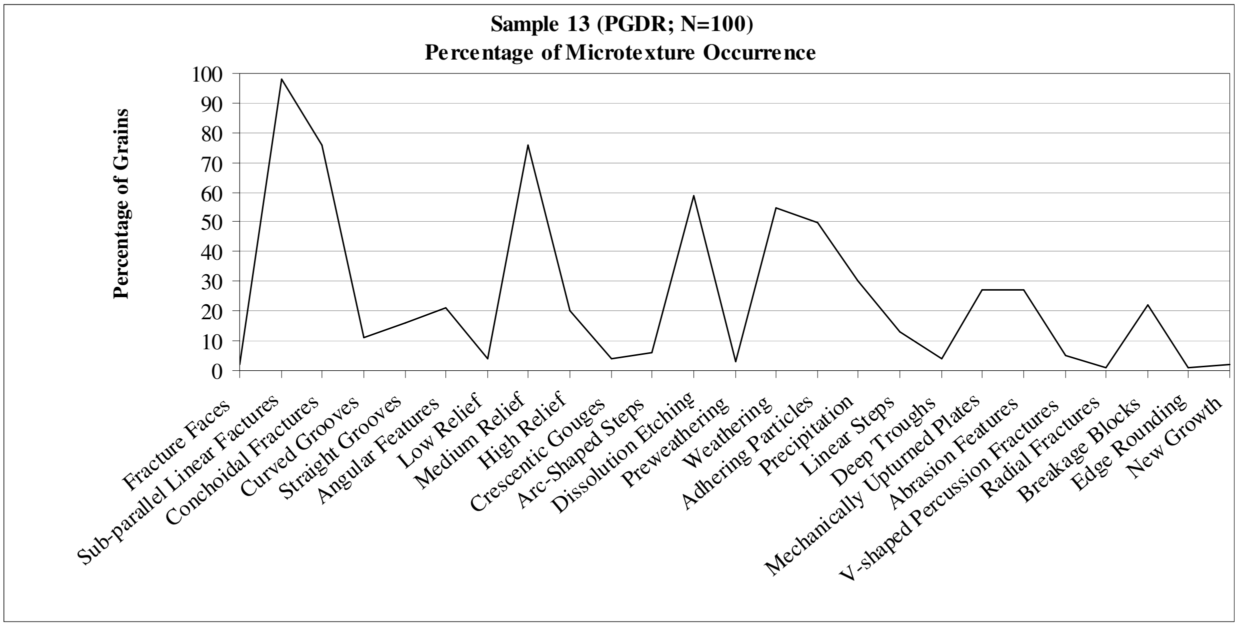

Figure 25. Results from sample 13 (suspected proglacial lacustrine, Dominican Republic)

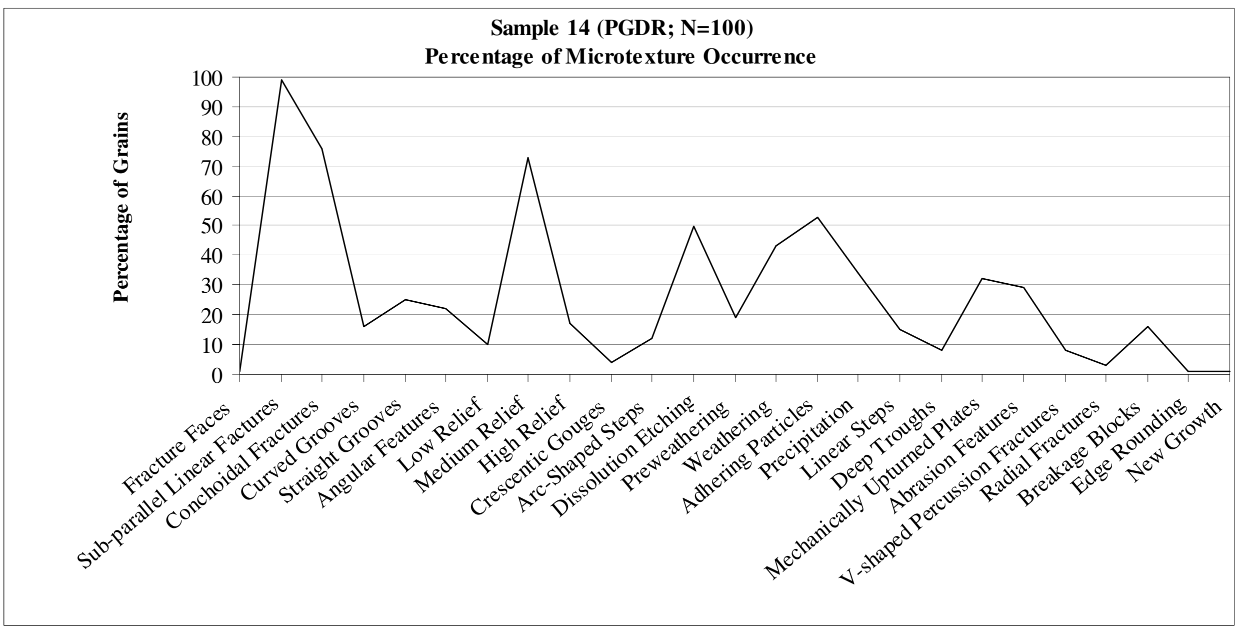

Figure 26. Results from sample 14 (suspected proglacial lacustrine, Dominican Republic)

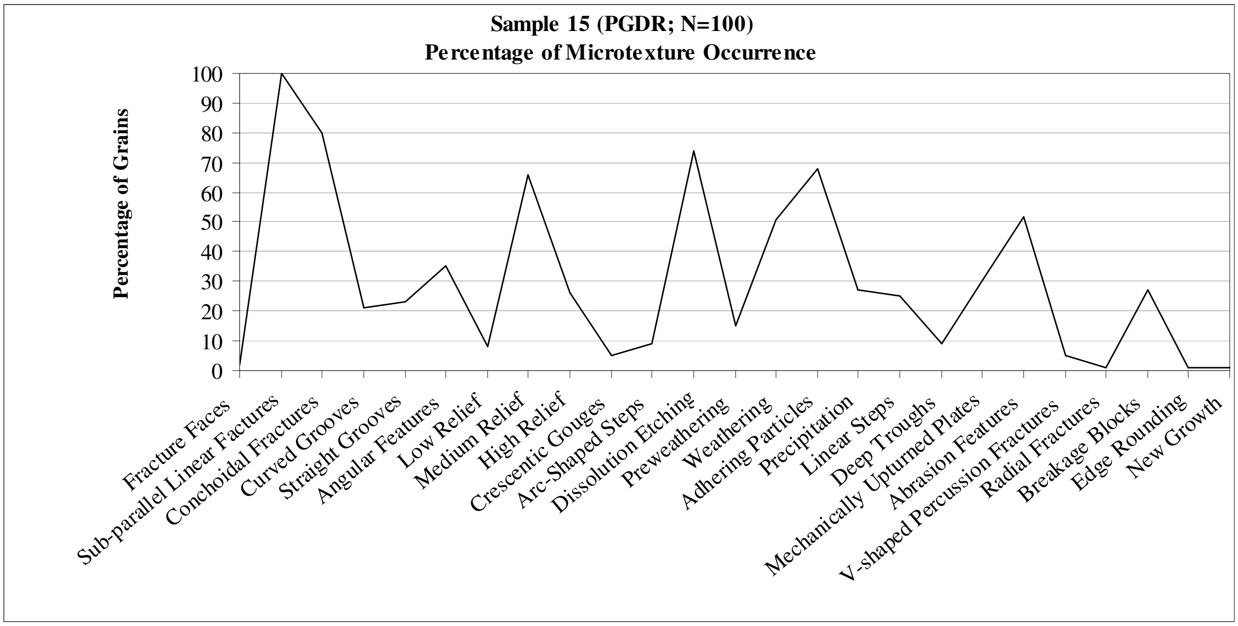

Figure 27. Results from sample 15 (suspected proglacial lacustrine, Dominican Republic)

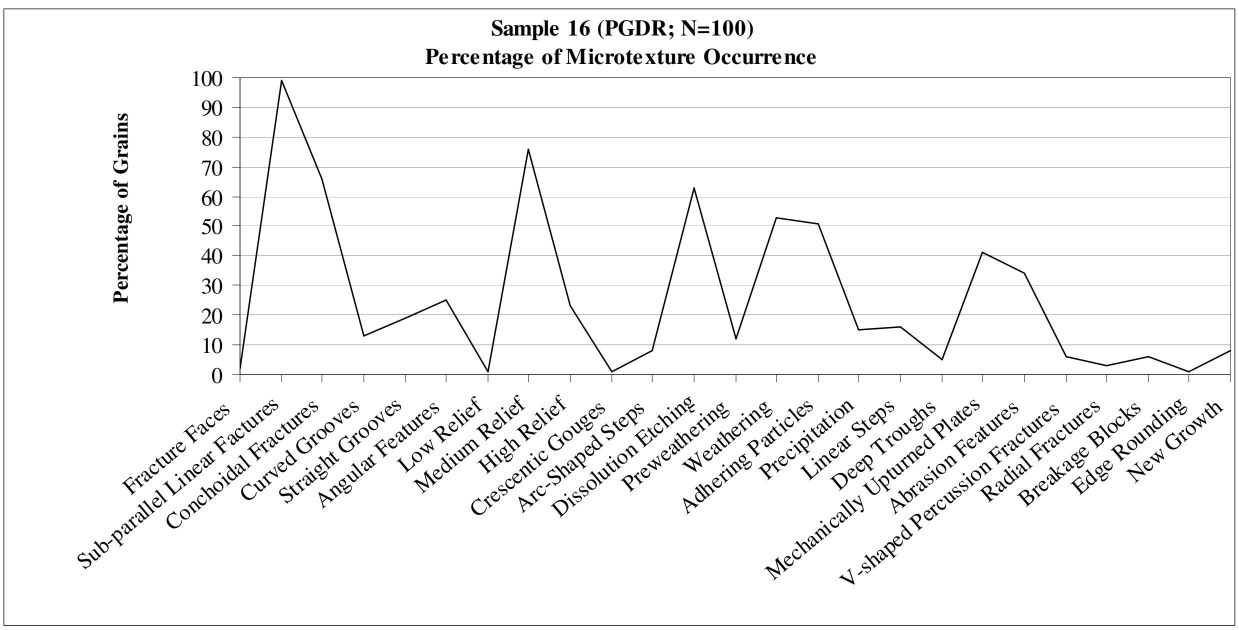

Figure 28. Results from sample 16 (suspected proglacial lacustrine, Dominican Republic)

Independence testing for sample 12 revealed a number of possible microtexture relationships. Grains with dissolution etching tend to not have any groove-like or step-like features. The majority of quartz sand grains with breakage blocks are also classified as high relief, an association found in other samples. Arc-shaped steps are rarely found with v-shaped percussion fractures among the grains of sample 12.

For sample 13, conchoidal fractures and v-shaped fractures are almost mutually exclusive. Conversely, curved grooves are found only on those grains that also have conchoidal fracturing. Independence testing also showed that conchoidal fractures tend to occur on grains with sub-parallel linear fracturing, a relationship seen in two other samples. Precipitation is seen more often on quartz sand grains lacking evidence of abrasion. The same can be said for sample 14. Independence testing for sample 15 uncovered no significant measures of independence or dependence among microtextures. In sample 16 grains that display linear step-like features substantially lack evidence of either weathering or dissolution etching.

Suspected Ground Moraine

A typical quartz sand grain from sample 10, collected near the base of a diamicton suspected to have been deposited beneath an ablating glacier tongue, has medium relief, sub-parallel and conchoidal fractures, and displays evidence of dissolution etching (Figure 29). Curved and straight grooves are seen on approximately 25% of the total number of grains. Nearly one-third of these grains have angular features and mechanically-upturned plates. A single measure of significance was found during independence testing: arc-shaped steps, while found on only a minority of grains, did not occur on grains with dissolution etching.

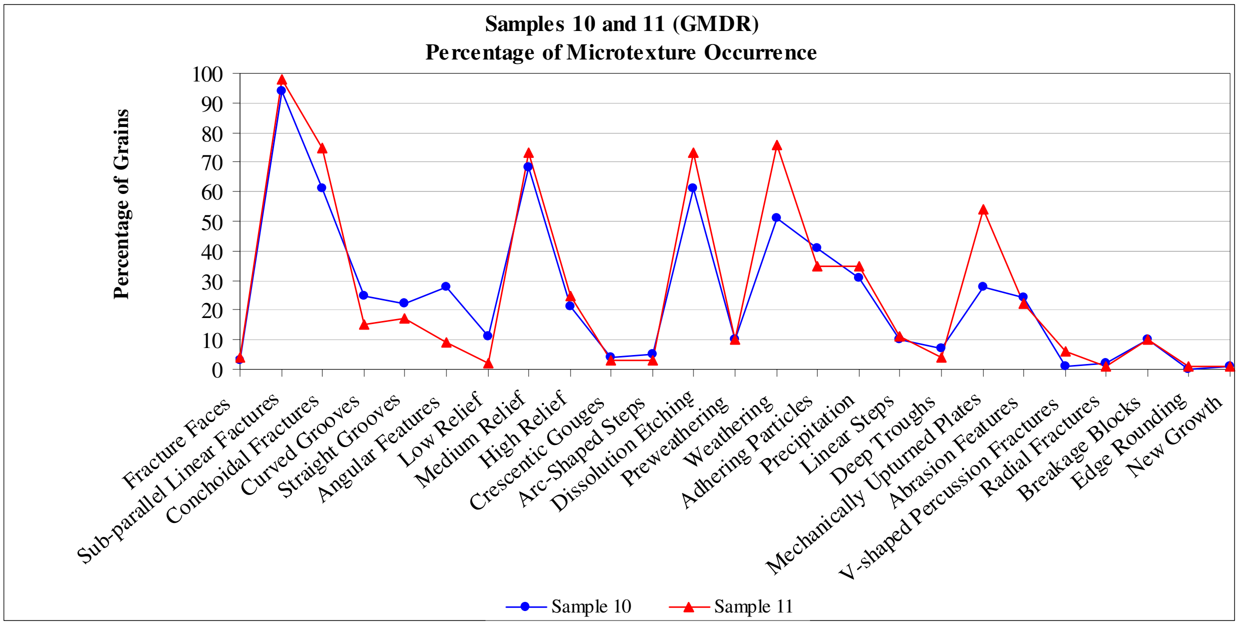

Figure 29. Results from samples 10 and 11 (suspected ground moraine, Dominican Republic)

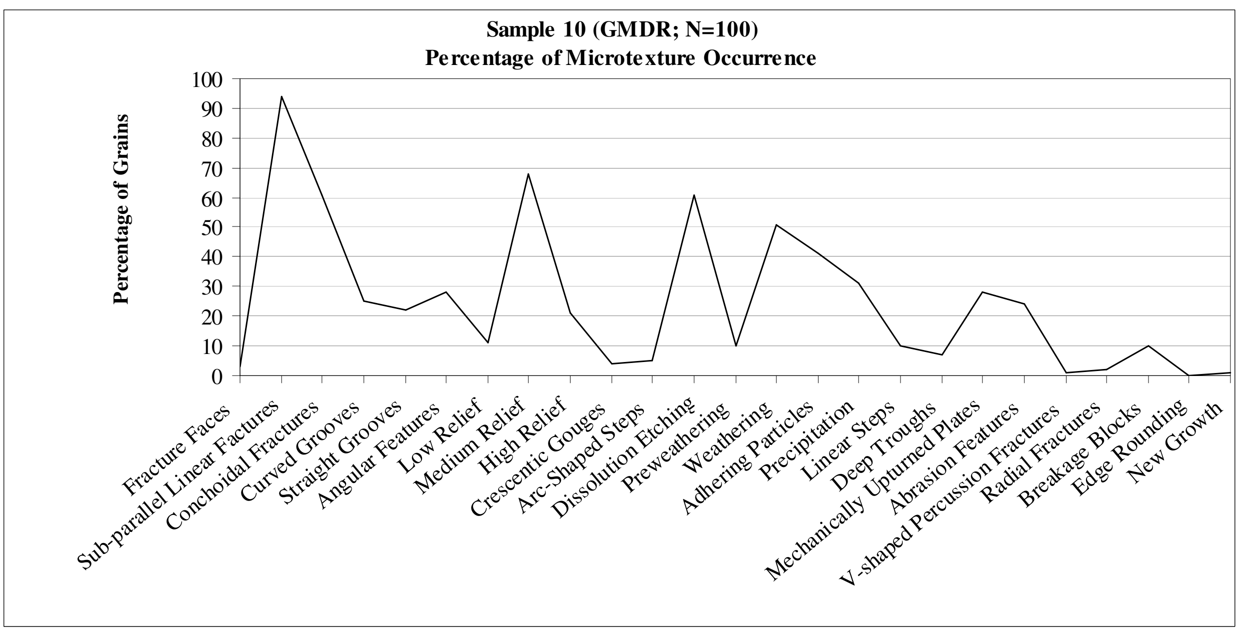

Figure 30. Results from sample 10 (suspected ground moraine, Dominican Republic)

Samples 10 and 11 (Figure 30) have fairly similar microtextural signatures, but some key differences do exist. Less than 10% of grains in sample 11, collected from a deposit similar to sample 10, have angular features, while more than 50% have mechanically-upturned plates. Sample 11 also has a much higher occurrence of grains with evidence of weathering and dissolution etching (Figure 31). Groove-like features, including deep troughs, are seen on a substantially smaller number of grains in sample 11 as well. Independence testing showed a strong association between conchoidal and sub-parallel linear fractures, and that the majority of grains with mechanically-upturned plates also have conchoidal fractures. No other relationships were found.

Suspected Lateral-to-Terminal Moraine

Samples 17 and 18 (Figure 32) are samples collected from suspected lateral-to-terminal moraines, sample 17 from a remnant transverse diamicton across Río Macutico near Sabana Macutico, and 18 from a suspected recessional moraine in a Valle de Bao headwater drainage. The grains from sample 17 have what has been shown to be a very typical microtexture signature of Dominican Republic grains: medium-to-high relief, sub-parallel and conchoidal fractures, and evidence of weathering and dissolution etching (Figure 33). Mechanically-upturned plates occur on 34.0% of grains, which is on par with the other Dominican Republic samples. The percentages of occurrence for other microtextures are unremarkable. Independence testing did not reveal any significant relationships among microtextures.

Certain microtextures are found on a greater number of grains from sample 18 than any other Dominican Republic sample (Figure 34). Fracture faces, which are large, clean fractures across 25% of a grain's surface (Mahaney 2002), grooves and deep troughs, crescentic gouges, and arc-shaped steps all occur on a considerably higher quantity of grains than in other samples.

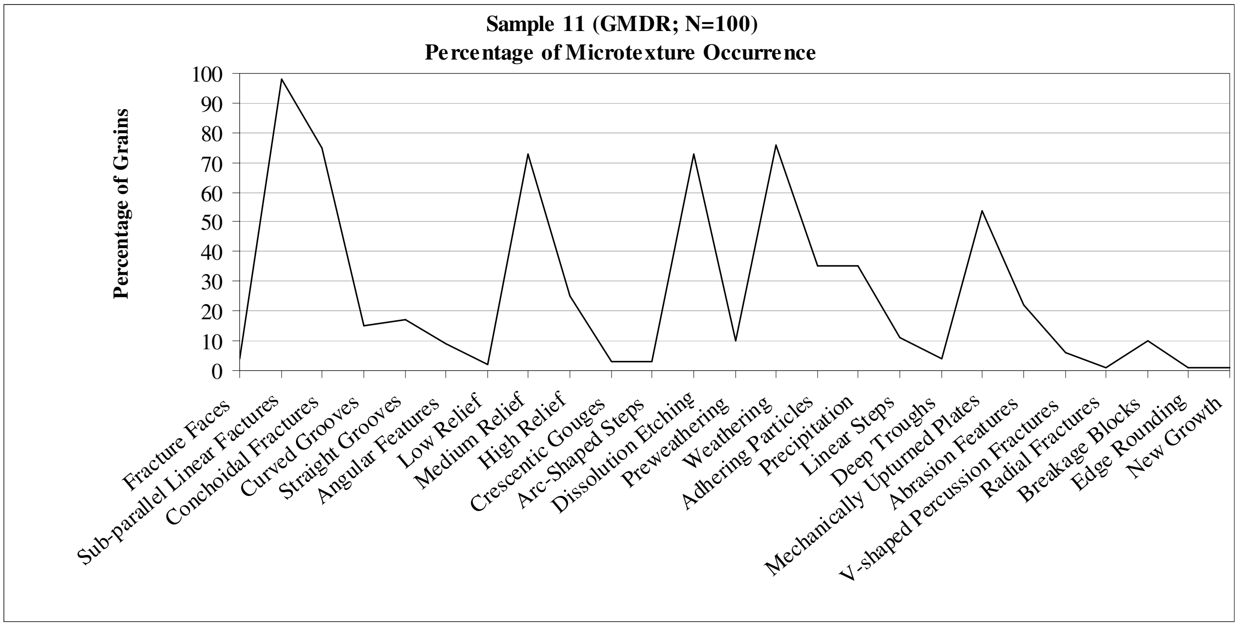

Figure 31. Results from sample 11 (suspected ground moraine, Dominican Republic)

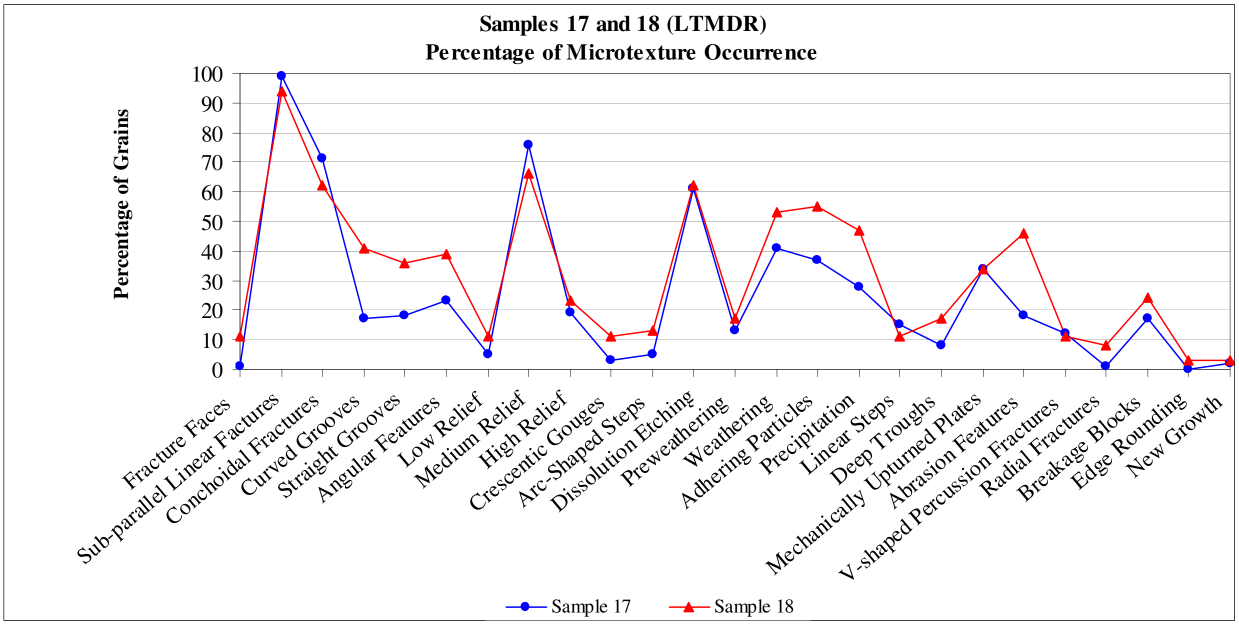

Figure 32. Results from samples 17 & 18 (suspected lateral-to-terminal moraine, Dominican Republic)

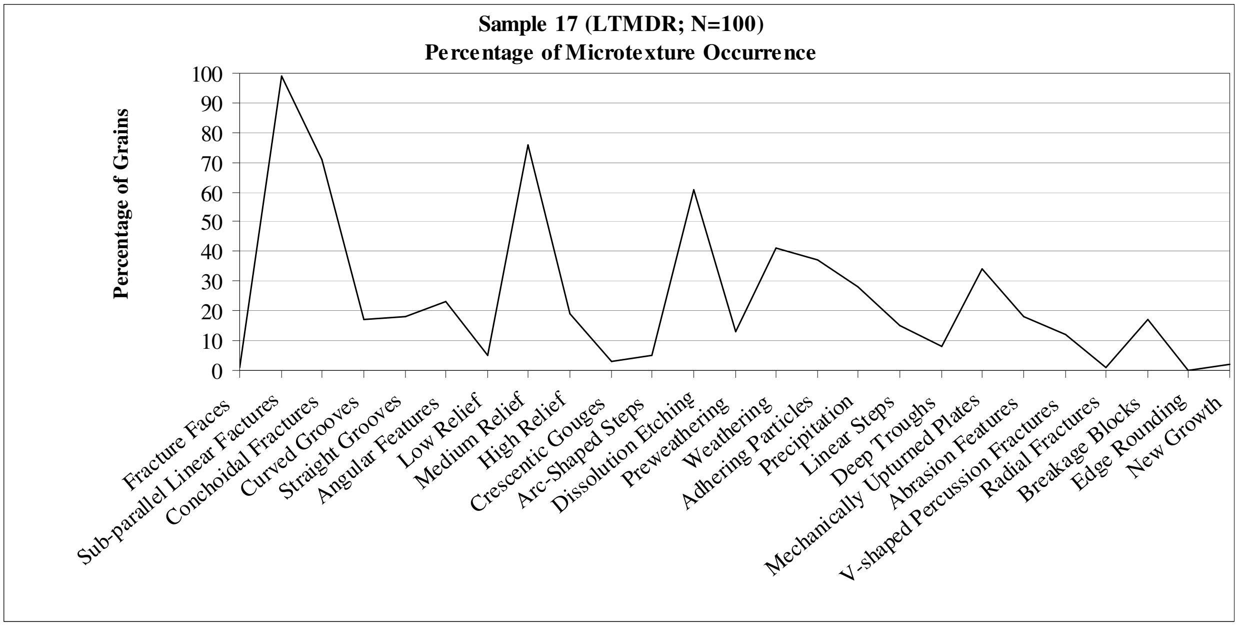

Figure 33. Results from sample 17 (suspected lateral-to-terminal moraine, Dominican Republic)

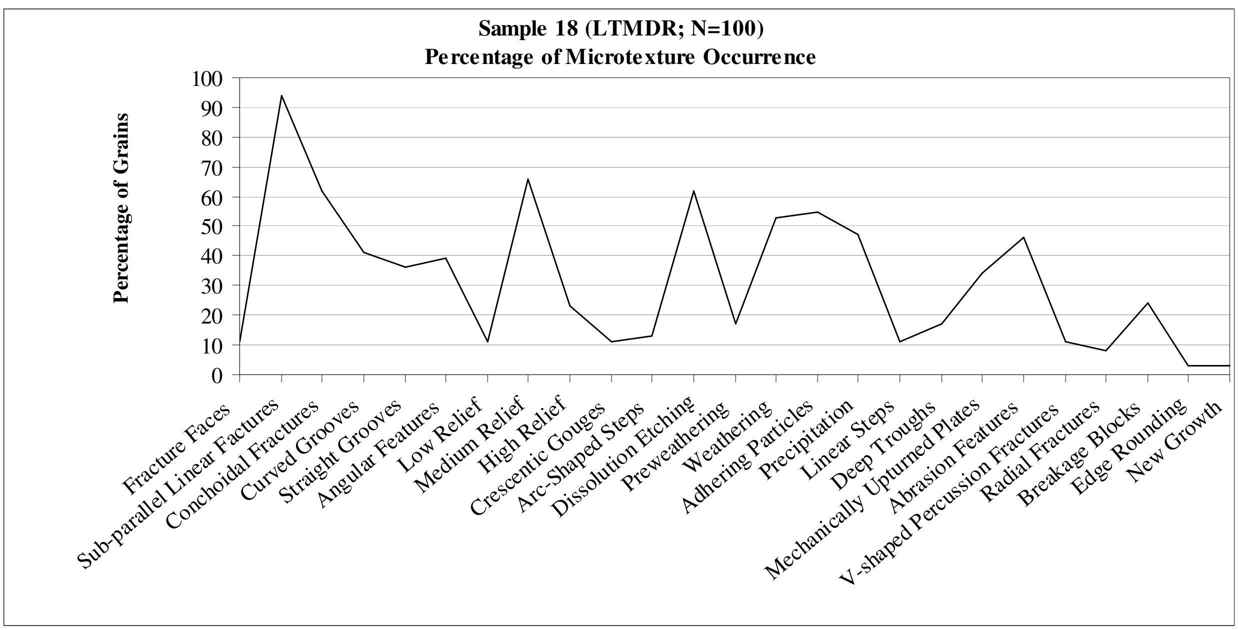

Figure 34. Results from sample 18 (suspected lateral-to-terminal moraine, Dominican Republic)

Approximately 40% of quartz grains in sample 18 have angular features. Sub-parallel and conchoidal fractures occur in typically high numbers, and the majority of grains have medium-to-high relief with evidence of dissolution etching and weathering. No significant measures of dependence or independence among microtextures were found.

4.2 Confidence Intervals

Confidence intervals were calculated for all samples at the 99% level via statistical bootstrapping. I analyze my results in the context of calculated confidence intervals below and compare samples by deposit area (Figures 35–58). Later in the thesis, I will discuss degrees of real similarity and difference between the Costa Rica and Dominican Republic samples. One important point to note is that our statistical bootstrapping thus far ignores both positive and negative correlation among microtexture occurrences. We have seen above that there appear to be some, although they may be inconsistent across samples. Our bootstrapping approach at present also ignores the larger question of comparing microtexture *spectra* between samples. The confidence intervals that we have calculated refer only to the individual microtextures independently. Analyzing them as combined spectra would be more than a trivial task and is left for future research.

4.2.1 Costa Rica Samples, by Deposit Type

Glacio-Lacustrine, Sample 1

Sample 1 is the only known glacio-lacustrine sample among the Costa Rican samples and therefore cannot be compared with others of the same deposit type (Figure 35). I found that sample 1 is most similar to sample 3 (ground moraine) and sample 6 (debris flow) at the 99% confidence level. The confidence intervals for sample 1 overlap those of samples 3 and 6 at every microtexture and so cannot be said to be significantly different.

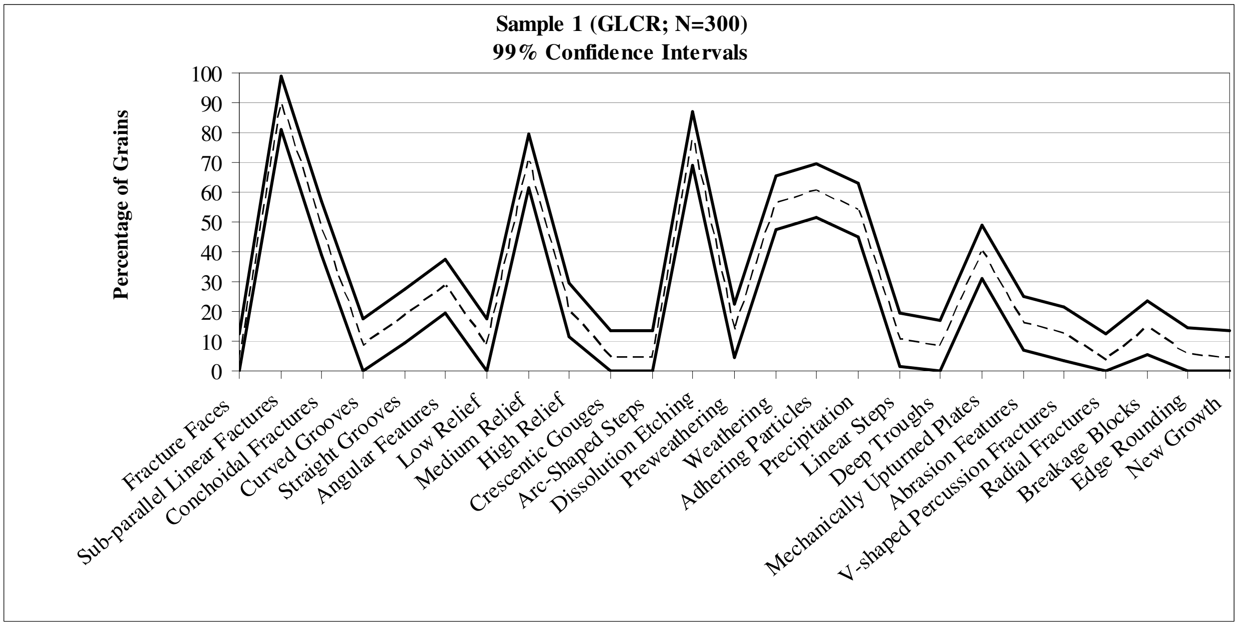

Figure 35. Confidence interval results for sample 1 (glacio-lacustrine, Costa Rica)

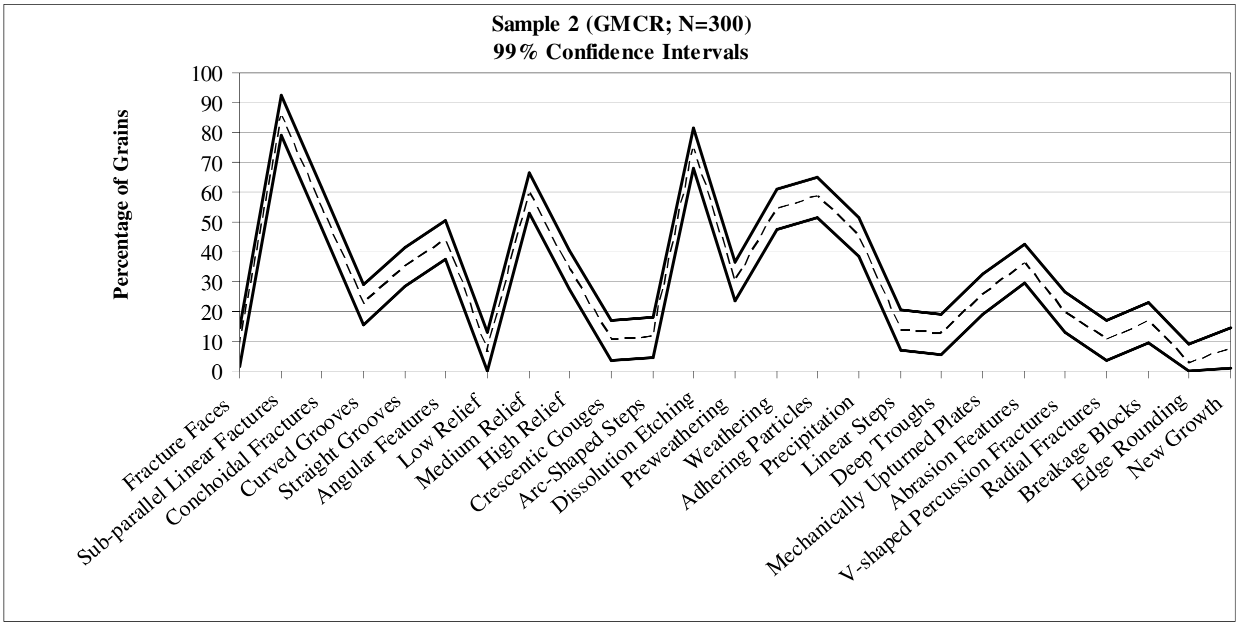

Figure 36. Confidence interval results for sample 2 (ground moraine, Costa Rica)

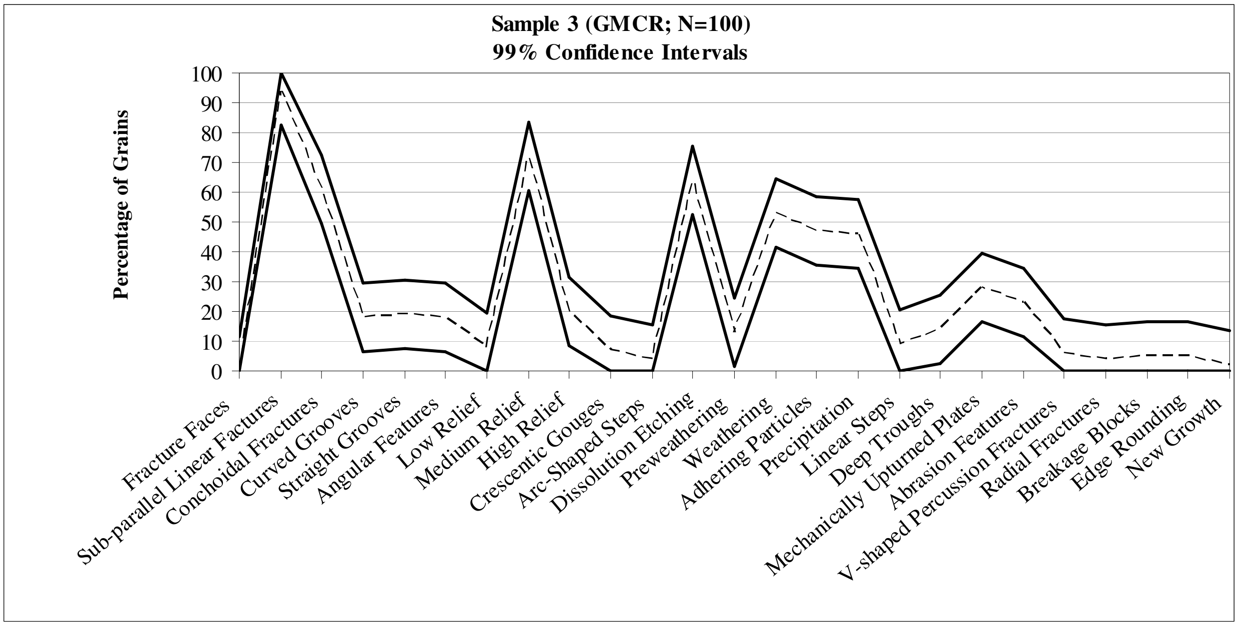

Figure 37. Confidence interval results for sample 3 (ground moraine, Costa Rica)

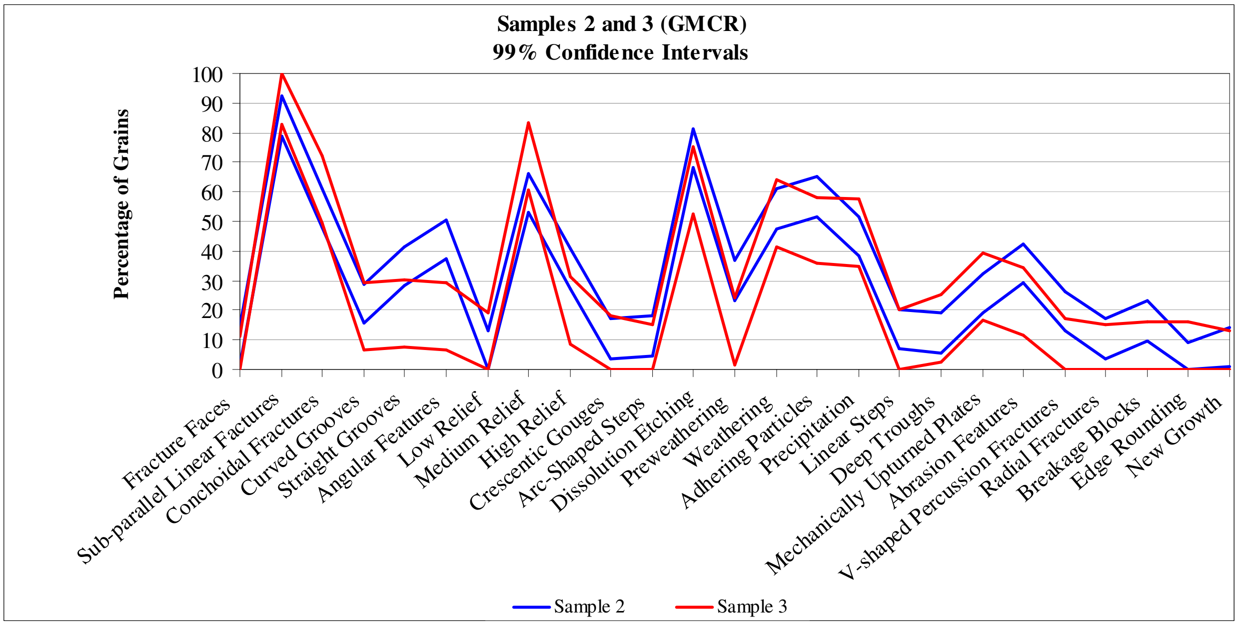

Figure 38. Confidence interval results for samples 2 & 3 (ground moraine, Costa Rica)

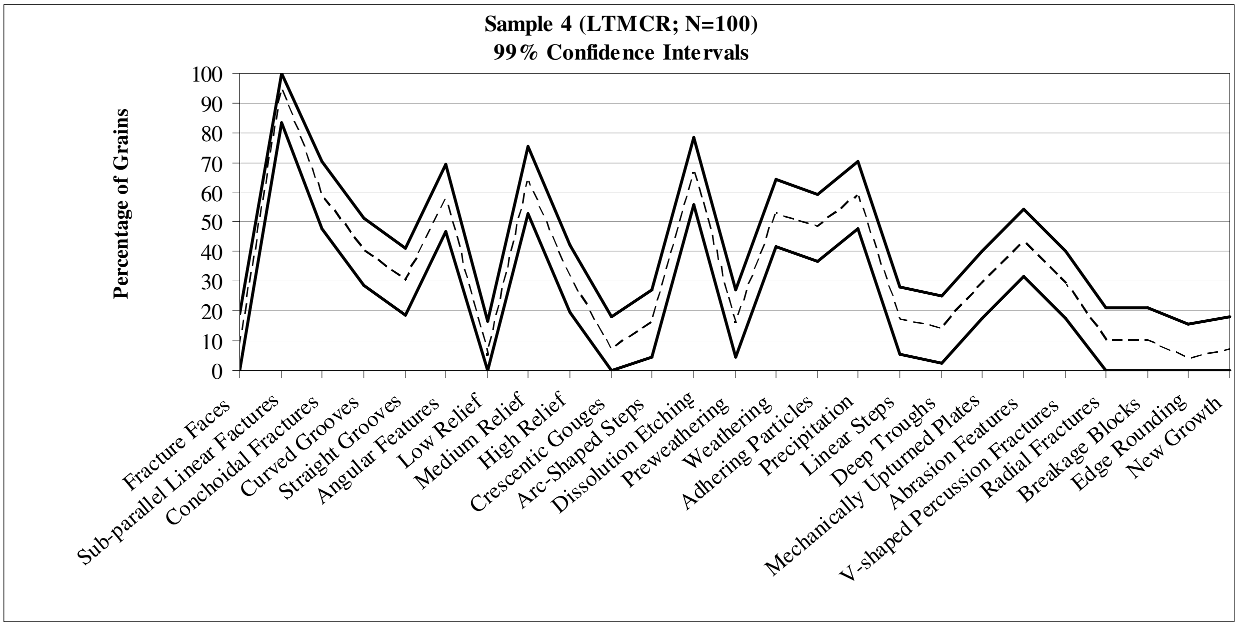

Figure 39. Confidence interval results for sample 4 (lateral-to-terminal moraine, Costa Rica)

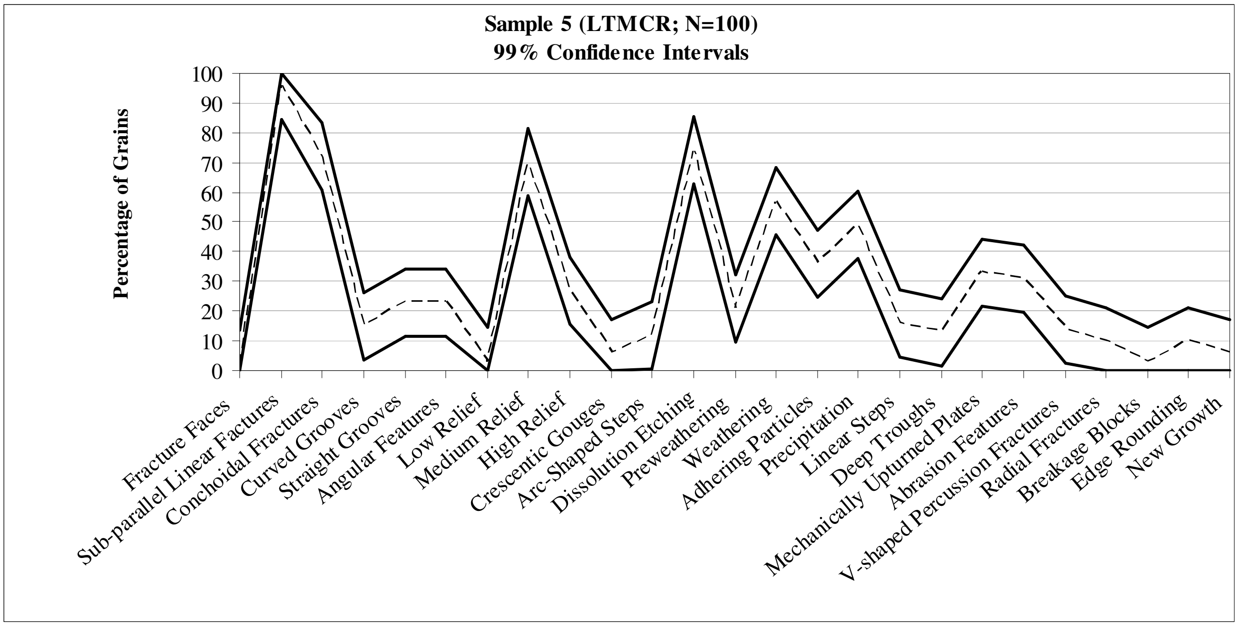

Figure 40. Confidence interval results for sample 5 (lateral-to-terminal moraine, Costa Rica)

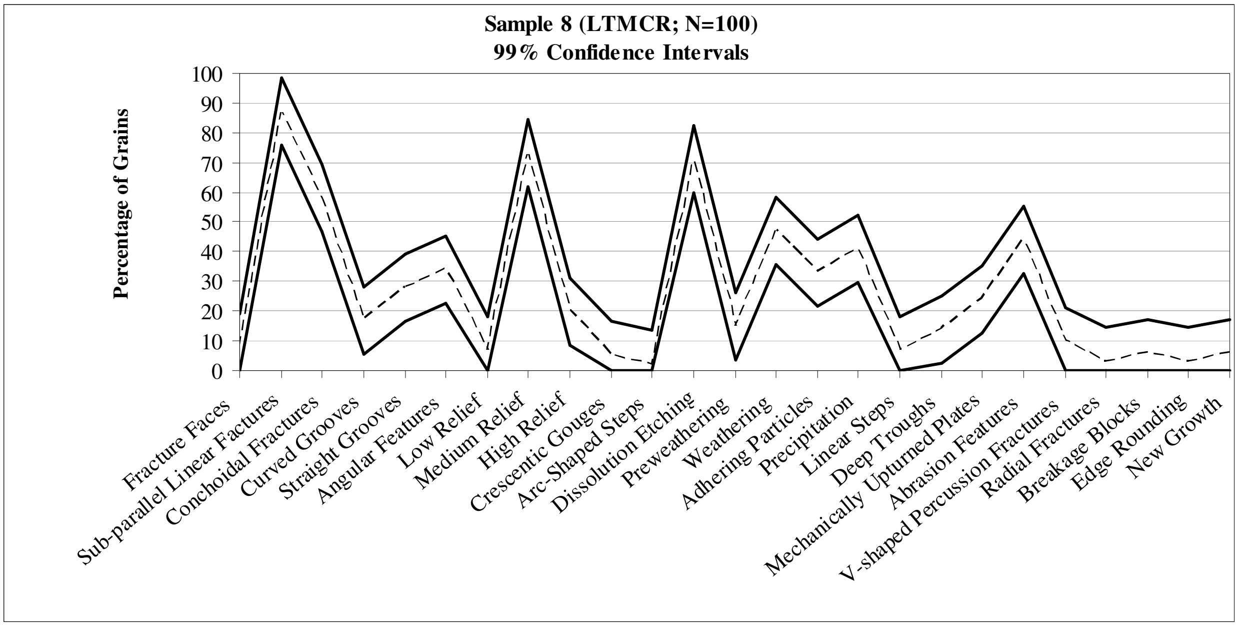

Figure 41. Confidence interval results for sample 8 (lateral-to-terminal moraine, Costa Rica)

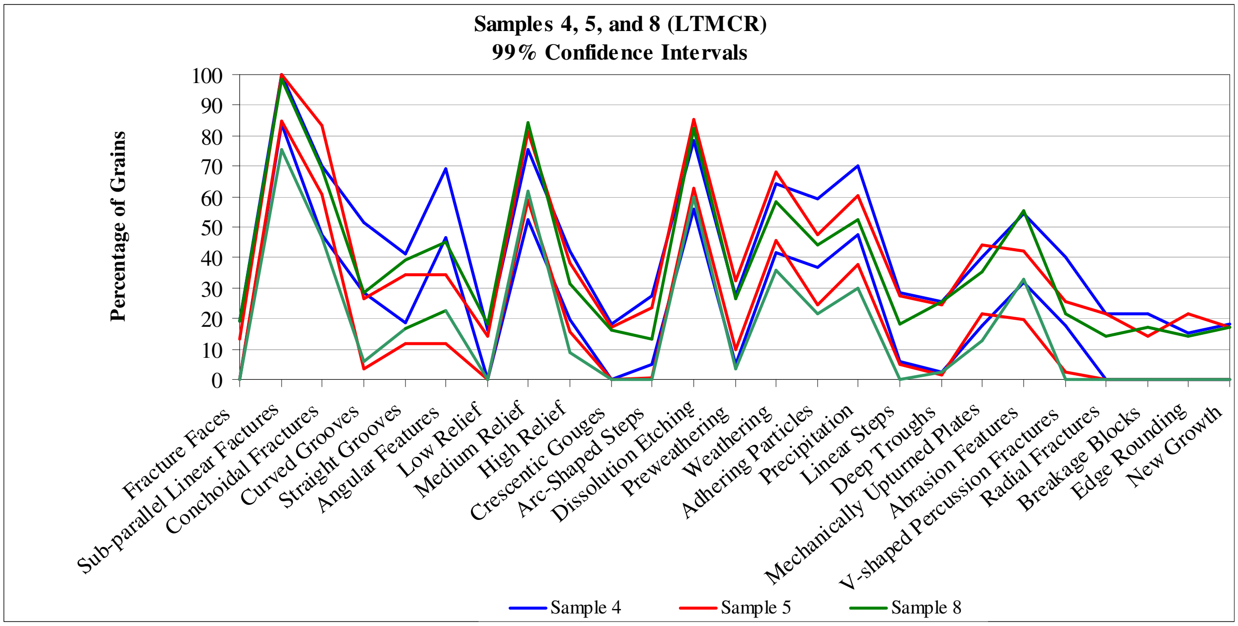

Figure 42. Confidence interval results for samples 4, 5, & 8 (lateral-to-terminal moraine, Costa Rica)

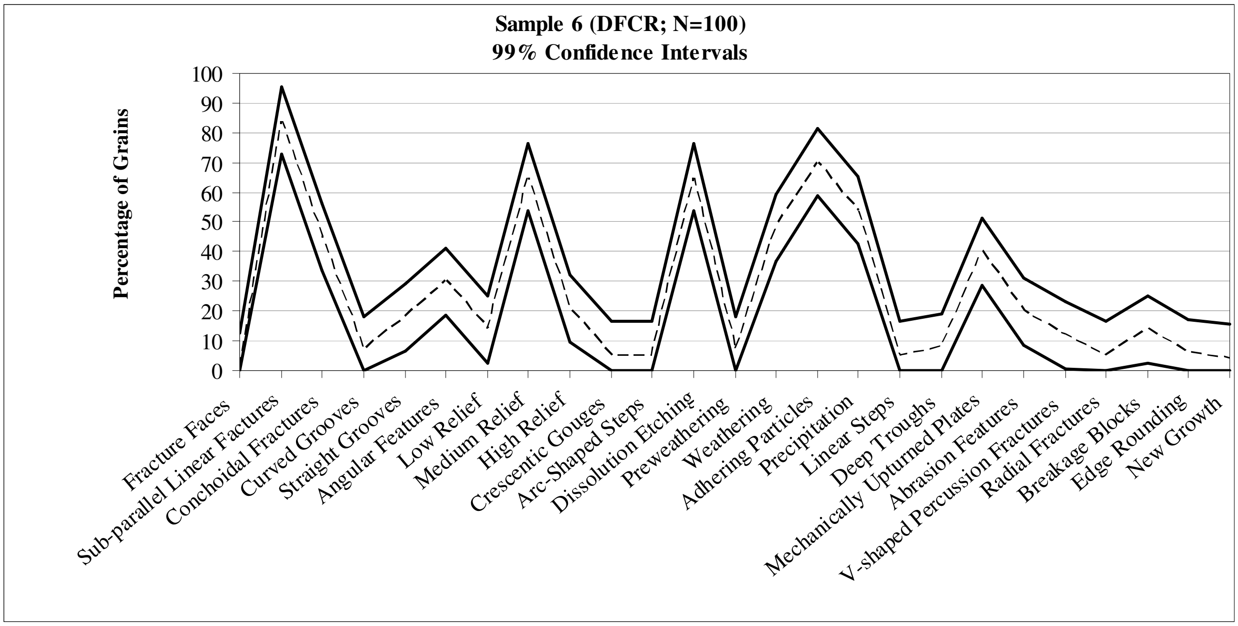

Figure 43. Confidence interval results for sample 6 (debris flow, Costa Rica)

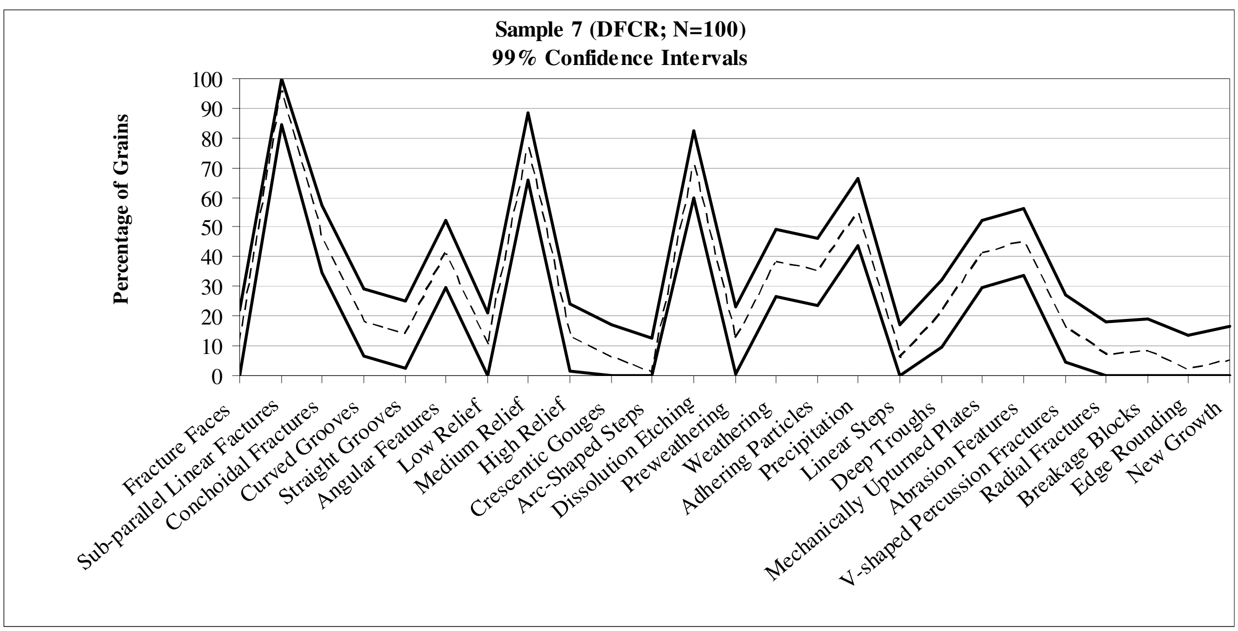

Figure 44. Confidence interval results for sample 7 (debris flow, Costa Rica)

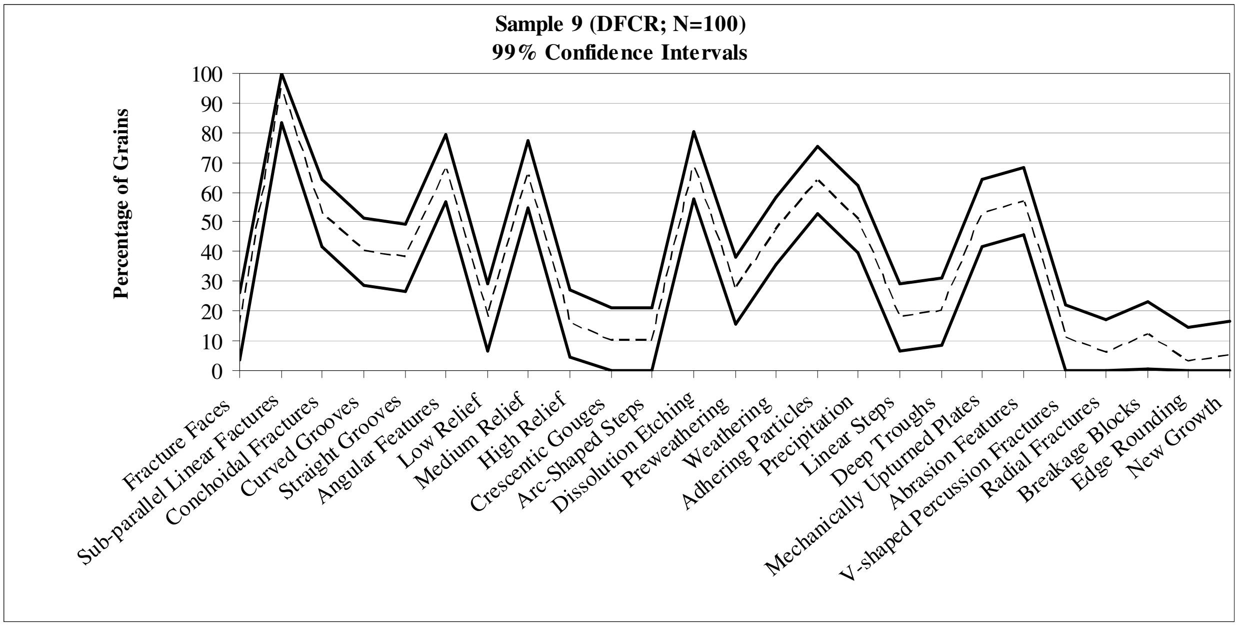

Figure 45. Confidence interval results for sample 9 (debris flow, Costa Rica)

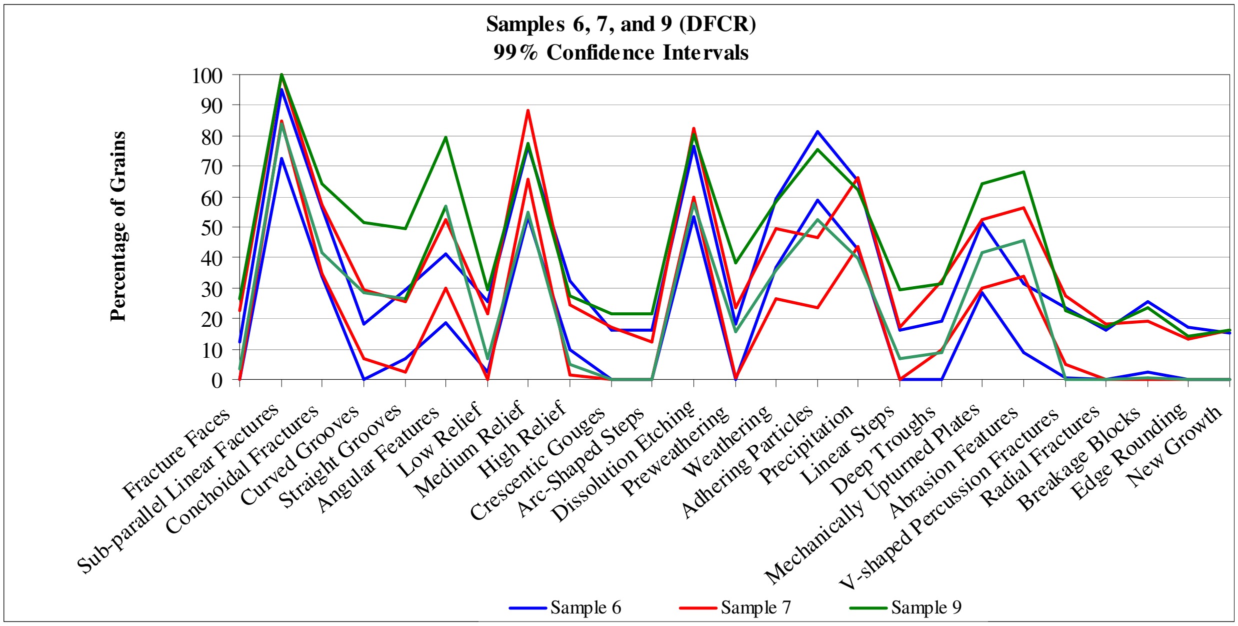

Figure 46. Confidence interval results for samples 6, 7, & 9 (debris flow, Costa Rica)

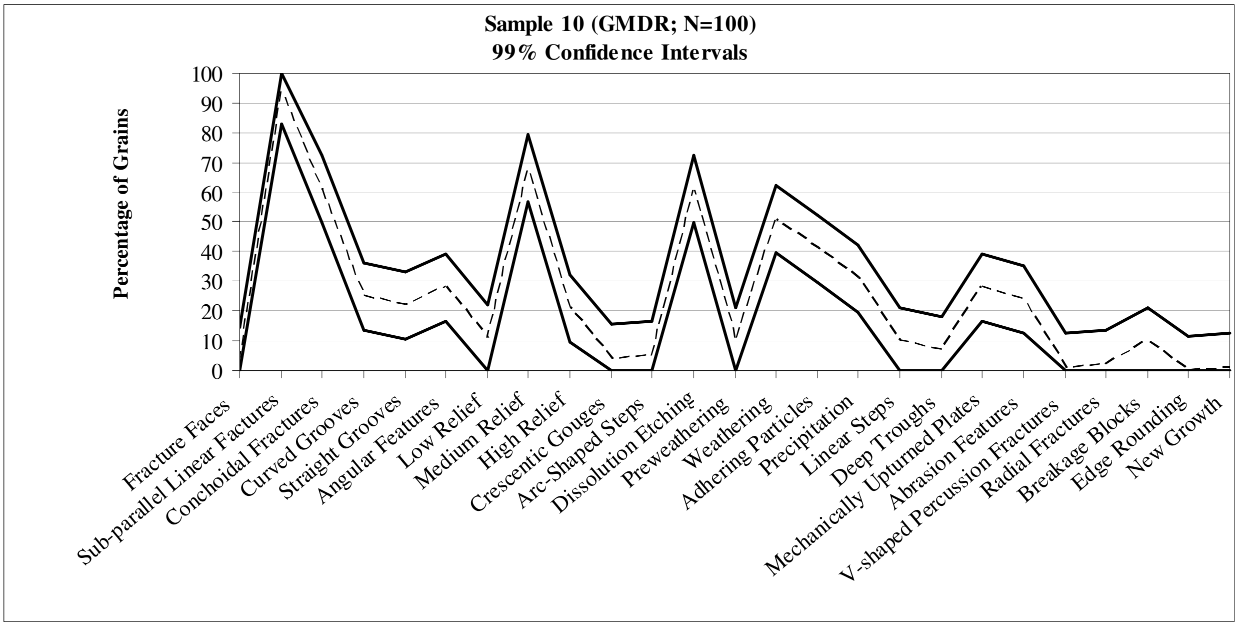

Figure 47. Confidence interval results for sample 10 (suspected ground moraine, Dominican Republic)

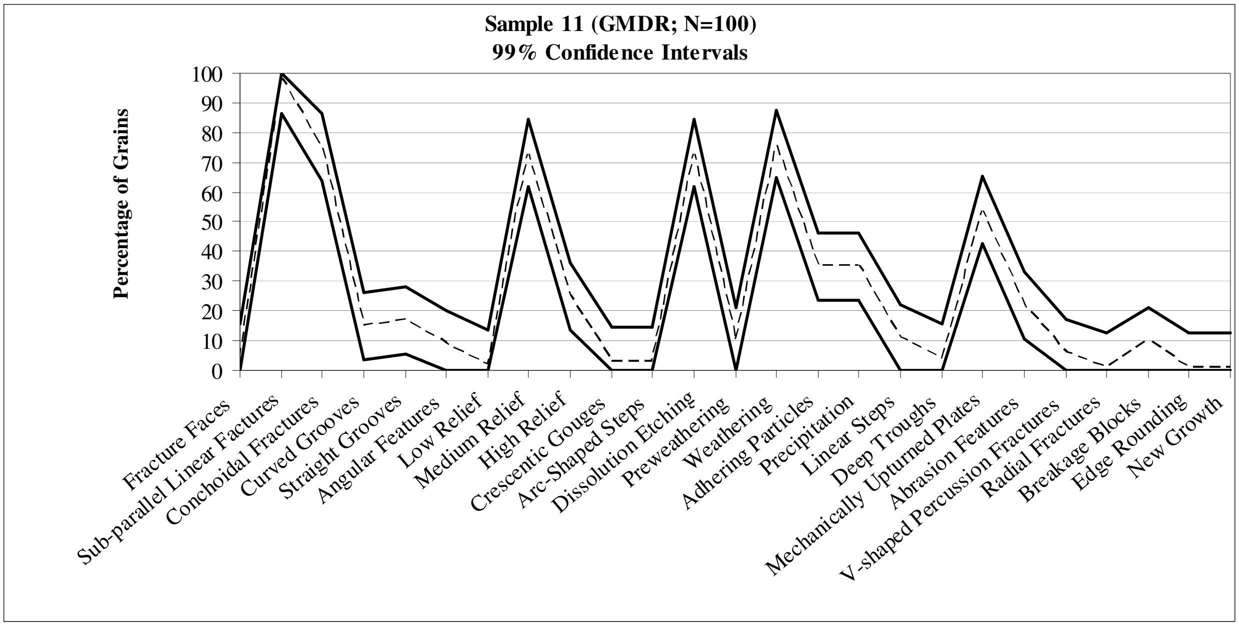

Figure 48. Confidence interval results for sample 11 (suspected ground moraine, Dominican Republic)

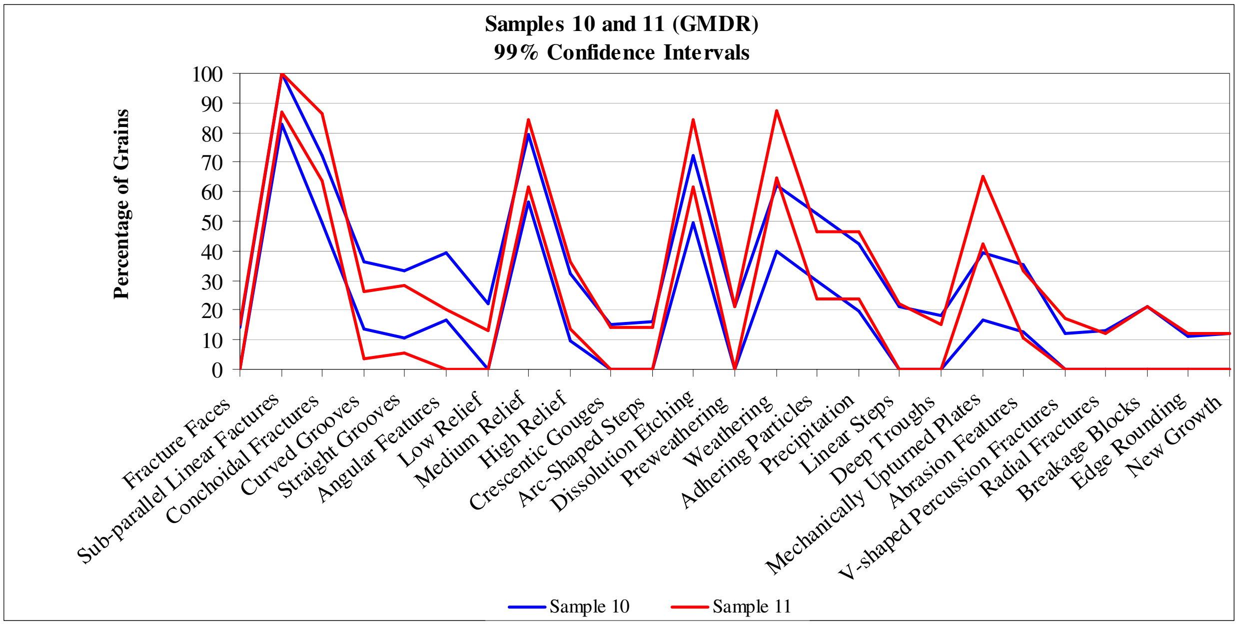

Figure 49. Confidence interval results for samples 10 & 11 (suspected ground moraine, Dominican Republic)

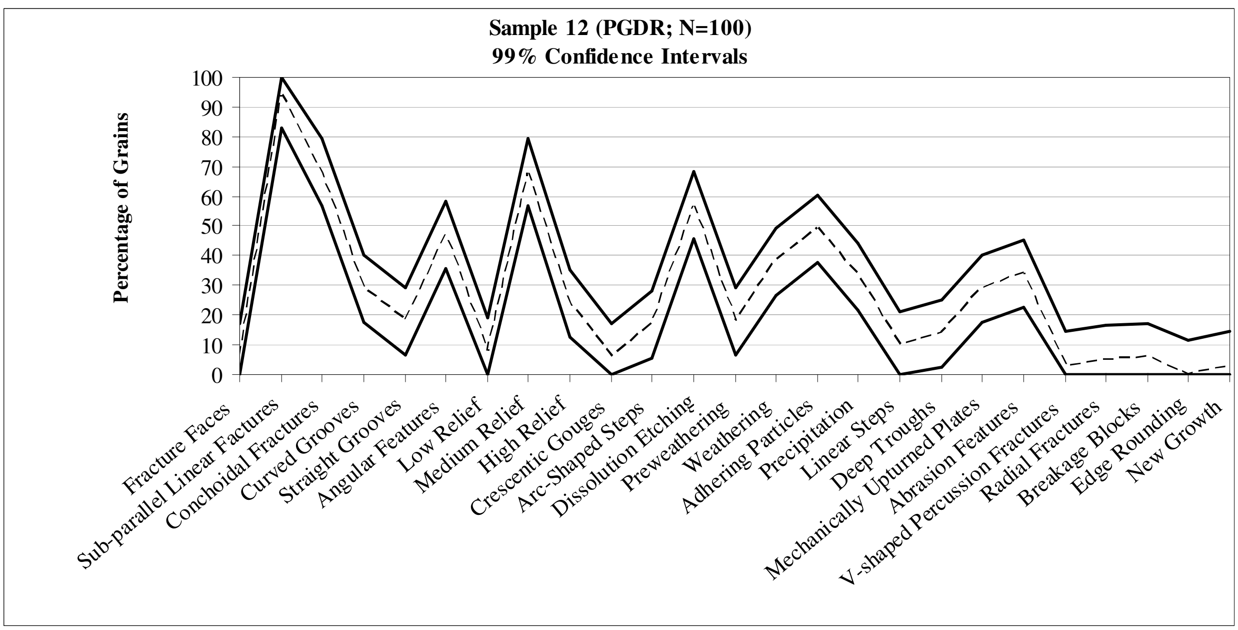

Figure 50. Confidence interval results for sample 12 (suspected proglacial lacustrine, Dominican Republic)

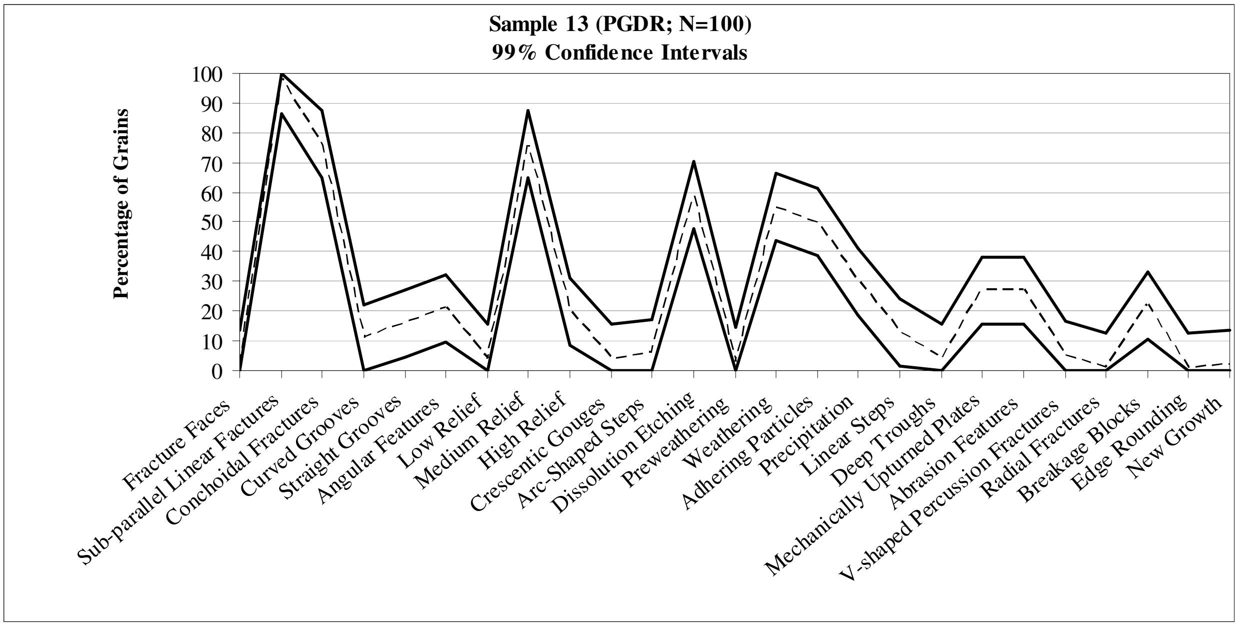

Figure 51. Confidence interval results for sample 13 (suspected proglacial lacustrine, Dominican Republic)

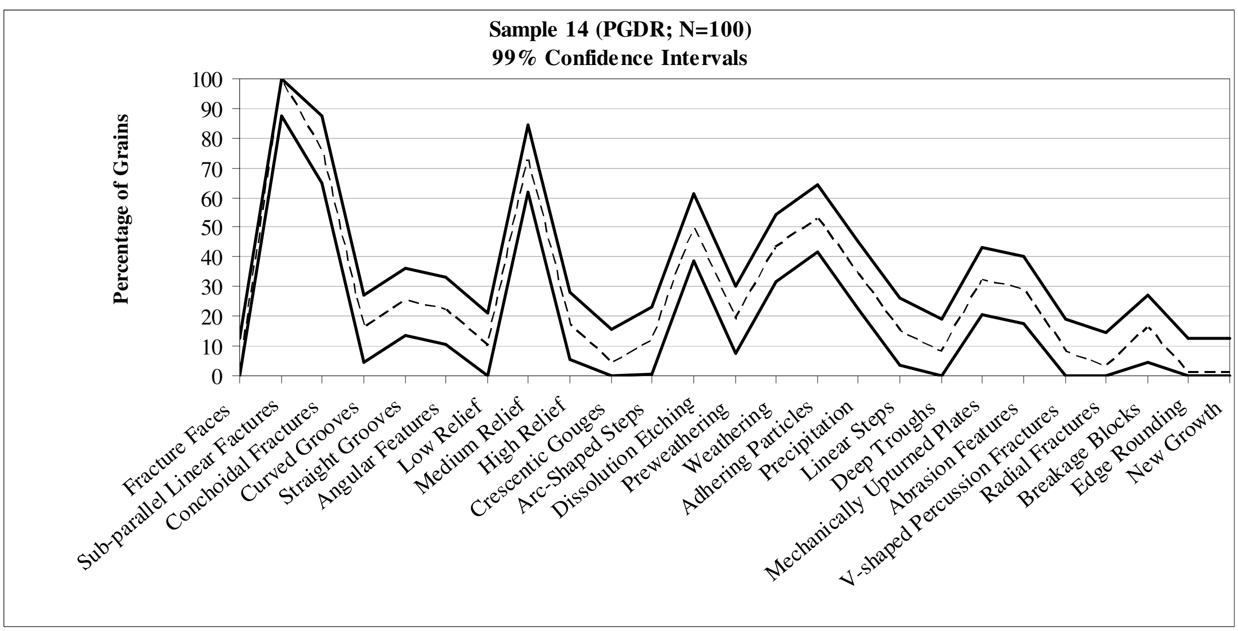

Figure 52. Confidence interval results for sample 14 (suspected proglacial lacustrine, Dominican Republic)

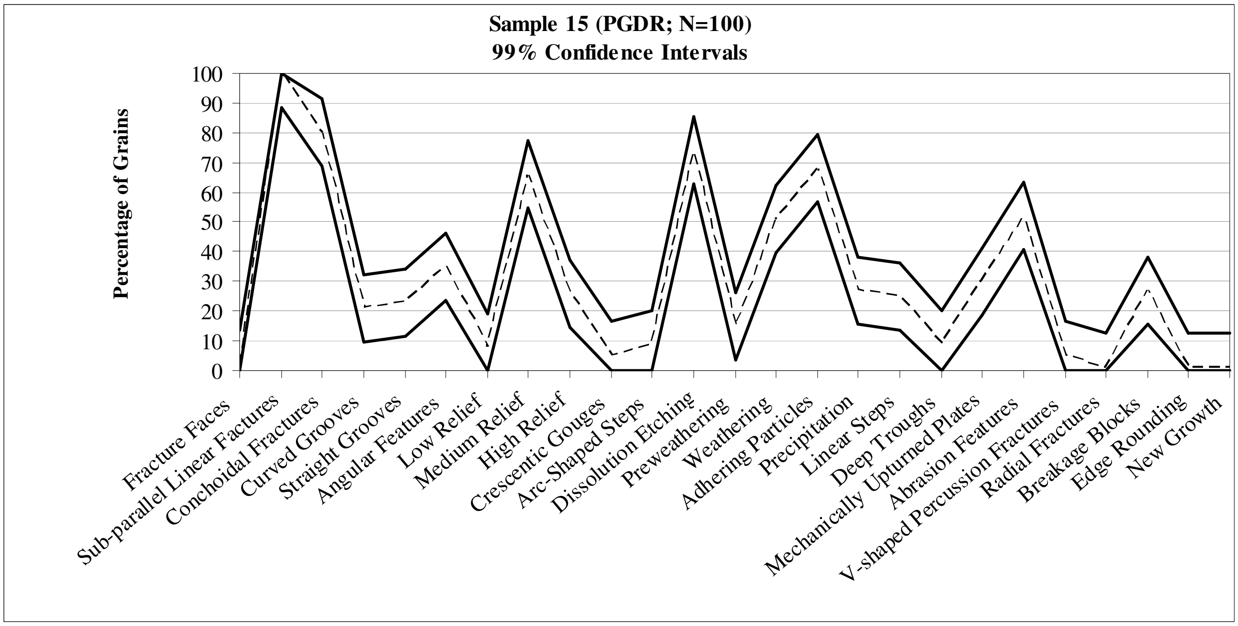

Figure 53. Confidence interval results for sample 15 (suspected proglacial lacustrine, Dominican Republic)

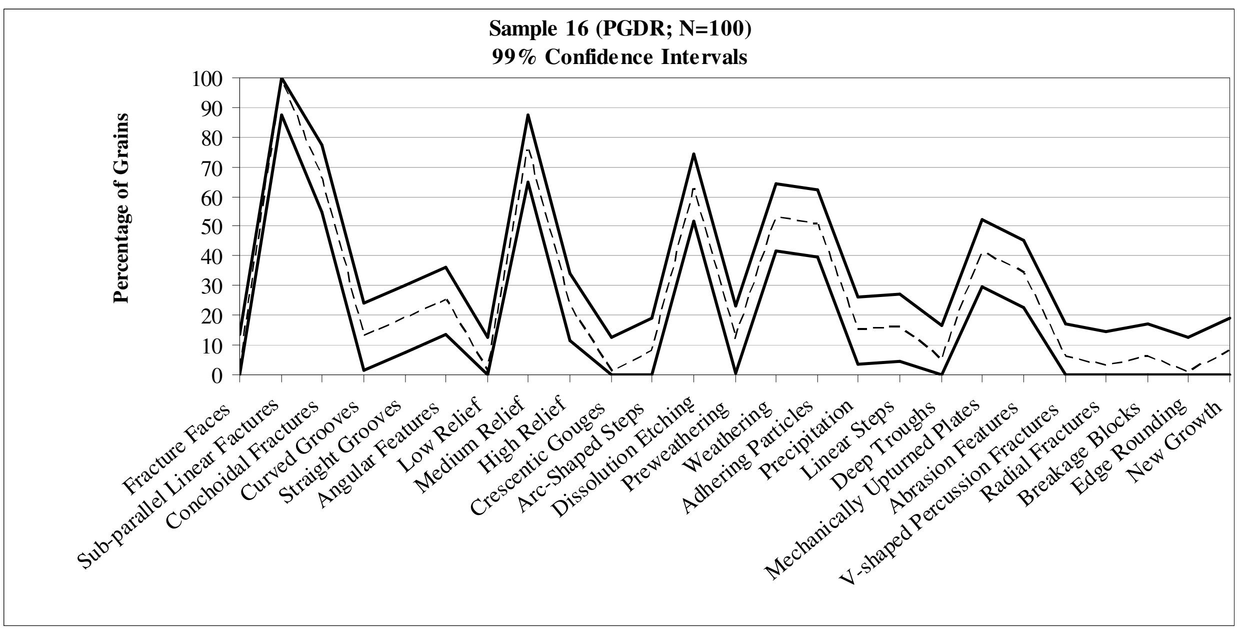

Figure 54. Confidence interval results for sample 16 (suspected proglacial lacustrine, Dominican Republic)

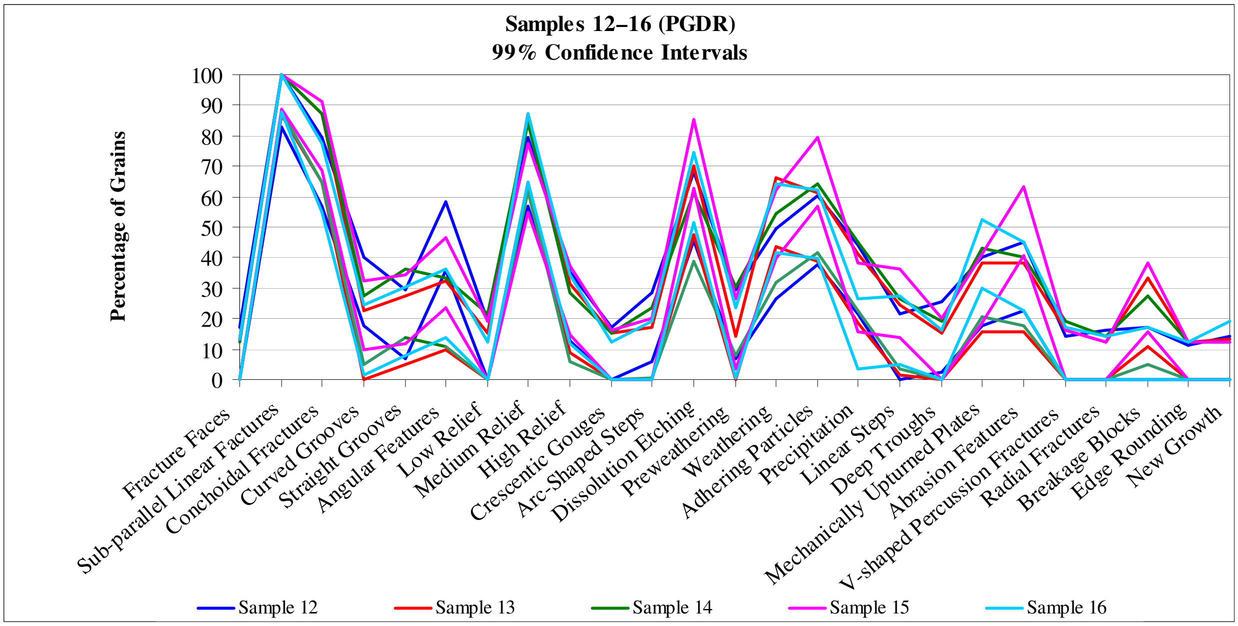

Figure 55. Confidence interval results for samples 12–16 (suspected proglacial lacustrine, Dominican Republic)

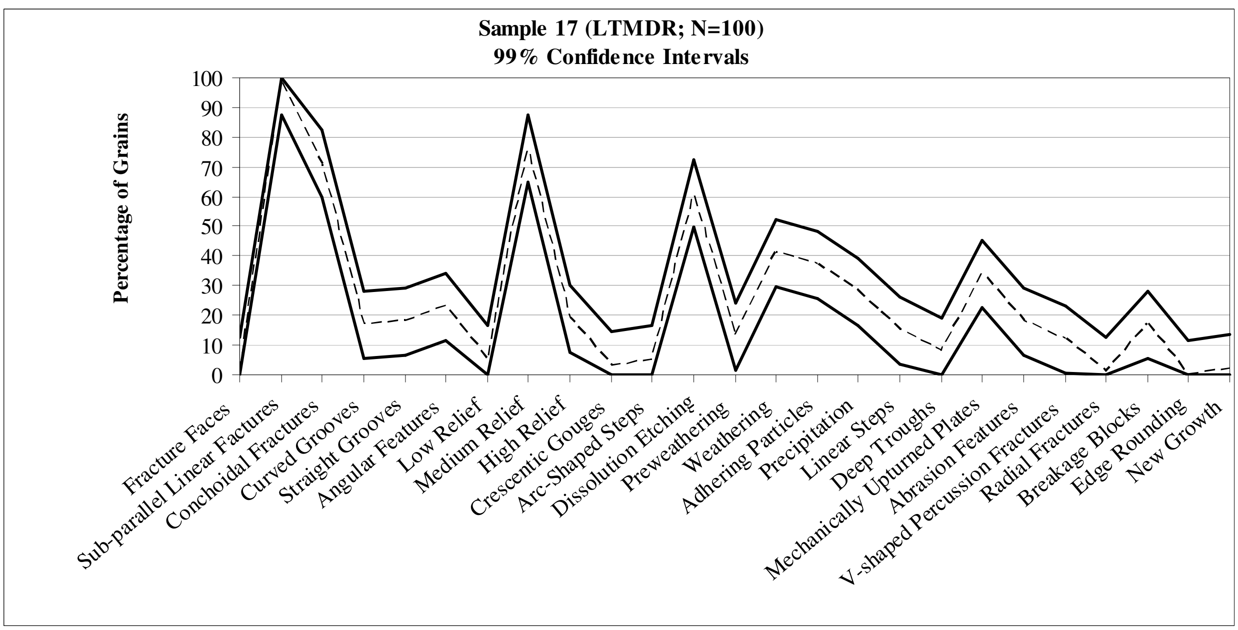

Figure 56. Confidence interval results for sample 17 (suspected lateral-to-terminal moraine, Dominican Republic)

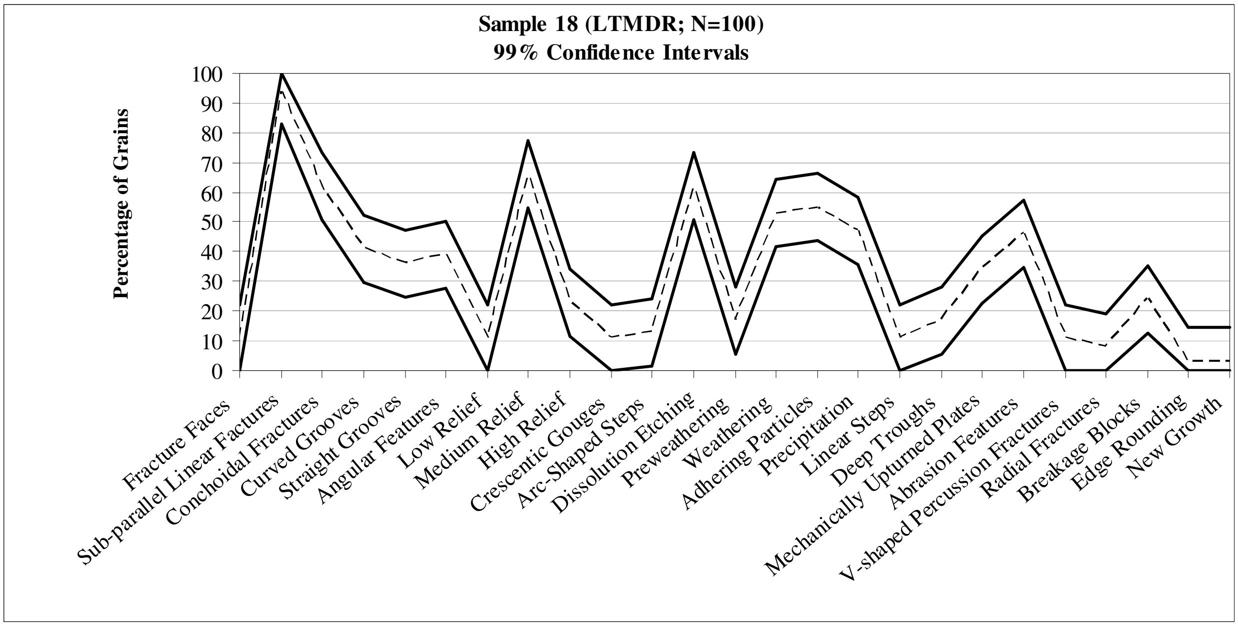

Figure 57. Confidence interval results for sample 18 (suspected lateral-to-terminal moraine, Dominican Republic)

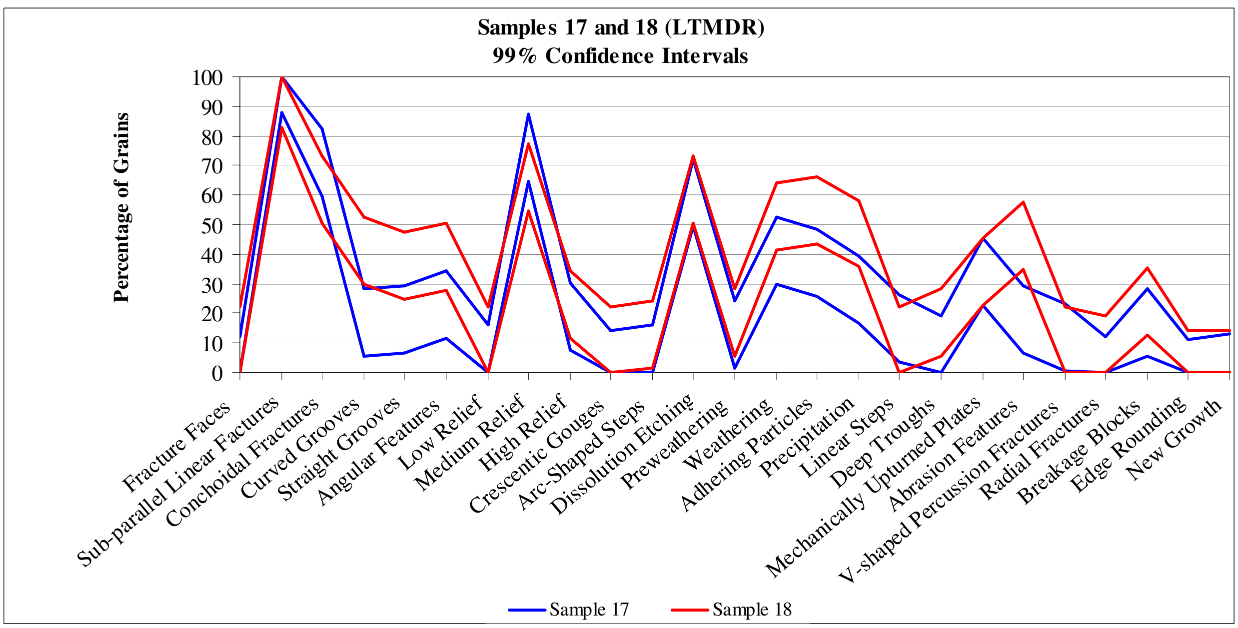

Figure 58. Confidence interval results for samples 17 & 18 (suspected lateral-to-terminal moraine, Dominican Republic)

Ground Moraine, Samples 2 & 3

At the 99% confidence level, the two Costa Rican ground moraine samples differ only in the occurrence of a single microtexture (Figures 36 and 37). As discussed above, the samples were collected contiguously in the field, so their degree of difference may inform interpretation of differences among other individual samples. Our confidence intervals were calculated on a single-microtexture basis, ignoring the probabilistic behavior of multiple-texture results. Sample 2 has a higher number of quartz sand grains displaying angular features; for this microtexture, the lower limit of sample 2 and the upper limit of sample 3 are separated by less than 10%. Given the confidence intervals of the remaining microtextures, the two samples are otherwise statistically indistinguishable (Figure 38).

Lateral-to-Terminal Moraine, Samples 4, 5, & 8

The lateral-to-terminal moraine samples are not statistically different at the 99% confidence level (Figures 39–41). A single microtexture in sample 4 exists as an outlier: it has a substantially higher incidence of grains with angular features, meaning its confidence limits for that microtexture do not overlap with those of the other two samples. The lower confidence limit of angular features recorded in sample 4 is 1.4% higher than the upper limit of sample 8. The confidence intervals overlap for all three samples at the remaining microtextures (Figure 42).

Glacial-Periglacial Debris Flow, Samples 6, 7, & 9

Overall I found that samples 6, 7, and 9 are fairly similar to each other at a 99% confidence level (Figures 43–45). The only microtextures for which these samples seriously differ are angular features, evidence of abrasion, and adhering particles. In each instance, two out of three samples overlap and the third is an outlier. Sample 9 has a much higher number of grains with angular features; sample 7 has fewer grains with adhering particles; and sample 6 has the least amount of abrasion features among debris flow samples. For these microtextures, the gap between confidence intervals of the three samples varies between 2.0 and 14.0%. The remaining 22 microtextures have complete overlap at the 99% confidence level (Figure 46).

4.2.2 Dominican Republic Samples, by Deposit Type

Suspected Ground Moraine, Samples 10 & 11

Samples 10 and 11 are statistically very similar and differ only at a single microtexture at the 99% confidence interval (Figures 47 and 48). A higher number of quartz sand grains in sample 11 display evidence of weathering, but the confidence intervals are separated by less than 3%. The confidence intervals of the remaining microtextures are not markedly different (Figure 49).

Suspected Proglacial Lacustrine Sediments, *Samples 12–16*

At the 99% confidence level, I inferred no significant difference between these five possible proglacial lacustrine samples (Figures 50–54). The lower limits of angular features in sample 12 are above the upper limits for samples 13 and 14; the same is true for the confidence bounds for abrasion features recorded in sample 15. These differences, however, are less than 5% in both cases. The confidence intervals of the remaining microtextures overlap across all samples (Figure 55).

Suspected Lateral-to-Terminal Moraine, Samples 17 & 18

Samples 17 and 18 are very similar at the 99% confidence level (Figures 56 and 57). A single microtexture (curved grooves) prevents 100% overlap. Sample 18 has a higher occurrence of curved grooves, but the confidence intervals of the two samples are separated by only 1.4% (Figure 58).

4.3 Comparison of Costa Rica and Dominican Republic Samples

The samples collected in Costa Rica are known glacial sediments, while the Dominican Republic samples are suspected glacial sediments. I first compared percentage of microtexture occurrence for all Dominican Republic samples as a group to all Costa Rican samples as a group. I then compared Dominican Republic samples to Costa Rican samples as subsets from similar deposit types. Samples 2 & 3 and 10 & 11 are known (Costa Rica) versus suspected (Dominican Republic) ground moraine samples. Samples 1 and 12–16 are known glacio-lacustrine versus suspected proglacial lacustrine sediments. Samples 4, 5, & 8 and 17 & 18 are known versus suspected lateral-to-terminal moraines. No suspected till-debris-flow samples were included in the Dominican Republic samples because no similar topography that might engender them exists there.

4.3.1 Raw Results Comparison

As a whole, the tropical highland sediments from both Costa Rica and the Dominican Republic analyzed in this thesis produced very similar results (Figure 59). The incidences of sub-parallel linear fracturing are high across all samples. Conchoidal fractures and medium-to-high relief are also common in all samples. The occurrences of other microtextures considered glacially diagnostic, step-like and groove-like features in particular, appear in clusters of samples with similar results; while not found on a substantial number of grains, these microtextures occur nonetheless—and clusters whose results are similar are as apt to include samples from both countries as not. Costa Rican and Dominican Republic samples also have similar number of grains with evidence of dissolution etching and weathering, microfeatures associated with pre- and post-glacial environments. Microtextures exhibiting the greatest contrast between Costa Rican and Dominican Republic samples, such as angularity, abrasion and adhering particles,

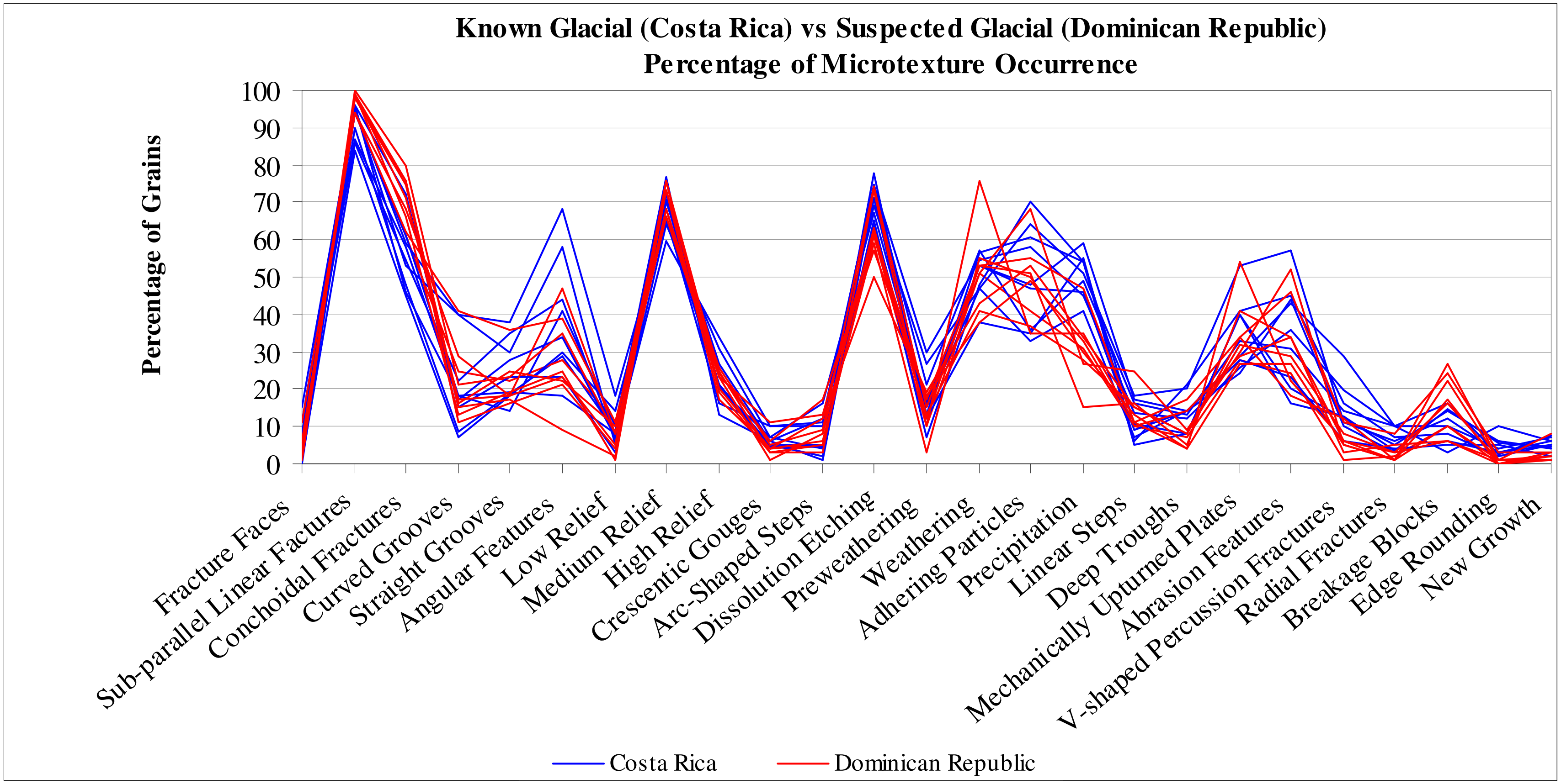

Figure 59. Comparison of results of Costa Rican and Dominican Republic samples

differ in percentage of occurrence, not mere presence; the question is not do any grains carry these features, but how many. Overall, the microtextural signature patterns of known glaciated sediments of Costa Rica largely overlap the patterns of sediments of unknown provenance from the Dominican Republic; the overlap is even more evident when one compares sediments by deposit type.

4.3.2 Deposit Type Comparisons

Known Glacio-Lacustrine and Suspected Proglacial Lacustrine

The suspected (Dominican Republic) proglacial lacustrine sediments, samples 12–16, are remarkably similar to sample 1 (Costa Rica) at the 99% confidence level. For each microtexture, the confidence limits of sample 1 overlap either all, or at a minimum two, samples. The three microtextures for which the limits of sample 1 do not overlap all of the corresponding samples are conchoidal fractures, abrasion, and dissolution etching. The lower confidence limits of samples 13–15 fall above the upper limit of sample 1 for conchoidal fractures—a more strongly glacigenic signal than in sample 1. At the 99% level, the lower limit of confidence for dissolution etching in sample 1 is substantially higher than the upper limit of sample 14. Lastly, the confidence interval for abrasion features in sample 15 is substantially higher than the range of confidence for sample 1.

Known and Suspected Ground Moraine

Sample 10 (Dominican Republic) is statistically indistinguishable from samples 2 and 30 Costa Rica) at the 99% confidence level; overlap occurs at every microtexture. Sample 11 differs somewhat more. The confidence limits of angular features and of adhering particles for sample 11 fall below those of sample 2 for the same microtextures. Conversely, the confidence intervals of sample 11 for weathering and mechanically upturned plates fall above the limits of samples 2 and 3 (and also, as noted earlier, those of sample 10). The confidence limits of the remaining 21 microtextures for sample 11 overlap the limits of samples 2 and 3.

Known and Suspected Lateral-to-Terminal Moraines

Sample 17 (Dominican Republic) is similar to Costa Rican samples 4, 5, and 8, but not identical. The confidence limits of three microtextures fall outside the limits of the other samples. For angular features, the upper limit of sample 17 falls short of the lower limits of sample 4 by more than 10%. Results for precipitation microtextures contrast similarly: sample 17 falls below the limits of sample 4 by approximately 8%. The upper confidence limit of abrasion features for sample 17 is considerably less than those of samples 4 and 8. Sample 18 (Dominican Republic), however, is statistically indistinguishable from samples 4, 5, and 8 at the 99% confidence level; the confidence levels overlap for every microtexture.

CHAPTER 5. DISCUSSION

5.1 Introduction to Discussion

The results of this research indicate that a common microtextural fingerprint exists among various tropical highland glacigenic sediment samples. As described in the previous chapter, the Costa Rican samples share, in similar proportions, a number of microtextural characteristics: medium-to-high relief, evidence of abrasion and weathering, sub-parallel and conchoidal fractures as well as the presence of groove and step-like features. The limited degree of dissimilarity between Costa Rican samples and the prevalence of microtextures shown to be glacigenic in the literature suggest that the Costa Rican samples may be typical representatives of tropical highland glacigenic sediments. The microtextural signature that emerged in the putatively glacigenic Dominican Republic samples is comparable to that of the Costa Rican samples. Outliers, for particular microtextures in particular samples, do exist in both groups, but percentages of microtexture occurrences for the majority of samples cluster. Based on the commonality of microtextural characteristics of the known glacigenic samples and the suspected glacigenic samples, I conclude that the Dominican Republic quartz sand grains analyzed in this thesis are indistinguishable from the known glacigenic samples from Costa Rica.

During analysis of the 99% confidence intervals generated for every sample, I attempted to answer a series of questions: Do samples that should be similar resemble each other? Do samples that are known to be glacial in origin resemble each other? Do downslope diamict deposits from Costa Rica resemble each other enough to infer that they are equivalent in origin? Do downslope diamict deposits from Costa Rica seem to bear a glacial imprint? Do any Dominican Republic samples resemble the known glacial samples from Costa Rica? Do any Dominican Republic samples bear no resemblance whatsoever to samples from Costa Rica? In the sections below I discuss my findings on the comparisons of Costa Rican and Dominican Republic samples. In general, if the confidence intervals of individual microtextures largely overlap between samples and any that do not are separated by relatively small gaps, I concluded that the samples were not significantly different. The logic of making such inferences is informed in part by the results for sample 2 and sample 3, which were collected literally contiguously in the field from the same deposit, yet for which the 99% confidence intervals of one microtexture, angular features, did not overlap.

5.2 Microtextural Signature Pattern

The pattern that emerged after analysis of known tropical highland glacigenic sediments (Costa Rican) is as follows: Quartz sand grains in the Wentworth Fine Sand size class (250–125 µm) from the Costa Rican samples have a high incidence of sub-parallel linear and conchoidal fractures. These glacierized sediments tend to have angular features with medium-to-high relief along with abraded features and adhering particles. Although not found on a majority of grains, a small but consistent subset of grains from the Costa Rican suite have step-like features, curved and straight grooves (ranging from light grooves to deep troughs), as well as breakage blocks and mechanically upturned plates. The presence of these microtextures and the aforementioned ubiquitous sub-parallel linear and conchoidal fractures would, absent other lines of evidence such as geomorphology, provide microtextural evidence of glacigenesis for the Costa Rican samples. I also found extensive evidence of weathering and precipitation, both of which occur in pre- and post-glacial environments, on a substantial number of grains. This is expected, as these microtextures have also been shown in numerous studies to be diagnostic of glacial environments (e.g., Krinsley and Donahue 1968; Margolis and Kennett 1971; Krinsley and

Doornkamp 1973; Higgs 1979; Bull 1986; Mahaney 1991; Helland and Holmes 1997; Helland et al. 1997; Mahaney and Kalm 2000; Mahaney 2002).

The microtextural signature pattern of the Dominican Republic samples is very similar to the known glaciated sediments of Costa Rica. A high number of quartz sand grains exhibit sub-parallel linear and conchoidal fractures, angular features, dissolution etching, and medium-to-high relief. Within every Dominican Republic sample I found a subset of grains with step-like features, breakage blocks, and grooves as well as evidence of abrasion and adhering particles. Again, based on the microtextural pattern and the similarity to known glacial sediments both from other studies and herein, these results indicate that the Dominican Republic samples are indistinguishable from the glacierized sediments of Costa Rica.

The greatest range of percent of occurrence for a single microtexture among Costa Rican samples is 50%; 68% of quartz sand grains in sample 9 (a debris-flow deposit) have angular features, while only 18% are classified as angular in sample 3 (ground moraine). For the Dominican Republic, the greatest variation in microtexture occurrence is 38%, in two different microtextures. Sample 12 has 38% more quartz sand grains with angular features and adhering particles than sample 11. Again, these two samples are from different deposit types. Sample 11 is suspected ground moraine and sample 12 is suspected proglacial lacustrine material.

While the Dominican Republic samples are statistically somewhat more similar to one another than the Costa Rican samples are to each other, I attribute this to the difference between the upland and downslope Costa Rican deposits. The upland deposits from Costa Rica all share similar attributes as a group, as do the downslope. No debris-flow deposits are among the Dominican Republic samples and therefore a direct comparison can not be made. However, the unknown-provenance samples collected from the Dominican Republic are as similar to the upland known glacial sediments of Costa Rica as the Costa Rican samples are to each other.

The microtextures with the most variance across samples, in terms of percent of occurrence, in Costa Rica are straight grooves, angular features, adhering particles, mechanically upturned plates, and abrasion. For the Dominican Republic, angular features, adhering particles, and abrasion have the greatest variation in percent of occurrence between samples. These features may tend to naturally vary in glacigenic sediments due to microvariations in sediment history in terms of the morphogenic processes to which the grains were exposed. Precipitation, weathering, straight grooves, and mechanically upturned plates all have outlying samples within the Dominican Republic suite, but the majority of samples fall into clusters of percent occurrence for these microtextures.

5.3 Upland and Downslope Samples

The nine samples from Costa Rica divide into upland and downslope groupings. The upland deposits, samples 1–5 and 8, are from Valle de las Morrenas. Samples 6, 7, and 9 are downslope diamict deposits from probable glacial debris flow matrix collected at San Gerardo. While 100% overlap does not occur between the upland and downslope samples at the 99% confidence level, or within either group, similar characteristics exist nonetheless, despite differences in deposit type—this, paired with the prevalence of microtextures considered diagnostic of glacial transport, led me to conclude that all Costa Rican samples are glacierized. In the following sections I discuss the similarity among the upland deposits, the similarity between upland and downslope deposits, and how the Dominican Republic samples compare to both the upland and downslope Costa Rican samples.

5.3.1 Upland Deposits, Costa Rica

At the 99% confidence level, samples 1–5 and 8, the known glacial deposits, are highly similar. Overlap of the confidence limits occurs at every microtexture, if not for every sample. Total overlap between all six samples does not occur for only two microtextures, angular features and evidence of abrasion. This may have to do with differences in the transport and grinding mechanics and distances of sediments deposited into ground moraines, lateral-to-terminal moraines, and glaciolacustrine environments. Both samples 2 and 4 are at the higher end of the spectrum of percent occurrence for quartz sand grains with angular features. As for the other exceptional microtexture, abrasion, the limits of sample 1 fall below those of samples 2, 4, and 8. Sample 1 consists of glaciolacustrine sediments which may not have been subjected to the same degree of abrasive grinding as the more distal moraine deposits; the lake from which these samples were collected is fairly high within the valley. This sample also has the highest proportion of pyroclastic, rather than granodioritic, makeup, and this may facilitate the crumbling off of SiO_2 grains. The limits of each sample overlap completely for the remaining microtextures, and overall, based on the results for samples 2 and 3, the upland deposits appear to be statistically indistinguishable at the 99% confidence level.

5.3.2 Upland versus Downslope, Costa Rica

When compared at the 99% confidence level, the upland glacial deposits and downslope diamict deposits have fairly similar microtextural signatures. Confidence limits overlap at every microtexture, but not necessarily for every sample at every microtexture. As discussed in an earlier section, the downslope deposits, samples 6, 7, and 9, do not have 100% overlap with each other at every microtexture, but present a similar pattern nonetheless. The observed partial divergence between upland and downslope samples occurs with adhering particles, abrasion, and angular features. Substantial overlap occurs at these three microtextures, but certain samples, such as sample 9, which overlaps only with sample 4 for angular features, fall outside the limits of the others. Again, variations in the prevalence of these microtextures may occur naturally due to differences in localized processes to which the sediments were subjected.

Upland sample 1 is a glaciolacustrine sample collected immediately below the deglaciation horizon. Samples 2–5 and 8 were collected from ground moraines and lateral moraines in Valle de las Morrenas, which, as mentioned earlier, Orvis and Horn (2000) describe as a well-developed glacial trough. The origins of the downslope debris-flow deposits are not so obvious, but Orvis (pers. comm.) hypothesized that the material that comprises the terraces from which the sediments were collected moved down the mountain from areas of glacial activity. Orvis (pers. comm.) further describes why these Costa Rican debris-flow deposits are hypothesized to be glacigenic:

> Many cirques on the Chirripó Massif of the Cordillera de Talamanca open down-valley into the expected glacial troughs complete with remnants of lateral and terminal moraines. For example, the Valle de Las Morrenas compound-cirque floor ends at a rock step just below Morrenas Lake 4 (the collection site for samples 2 & 3), and the valley downstream takes more than 2.5 km to drop 480 meters in elevation (a slope of 11˚ or 19%). That stretch of valley is dominated by portions of several large extant moraine complexes that are visible on 1:50000-scale topographic maps. In contrast, a number of cirques that head drainages flowing down the western flank of the massif open down-valley onto near-cliff-like slopes. For example, the cirque on the south flank of Cerro Ventisqueros heads a drainage of the Río Bosin, a tributary of the Río Chirripó Pacifico that runs through San Gerardo. Below the lip of the cirque, the stream that issues from it takes only 0.77 km to drop 480 meters in elevation (a slope of 32˚ or 62%). In these drainages, even the massively glacierized drainage of the headwaters of Río Chirripó Pacifico, little or no evidence of moraines is visible on topographic maps below the point at which these steep slopes are reached.
>
> Orvis, Harden, and Horn hypothesize that glacial ice advancing, and till and outwash deposits building, on these steep slopes were inherently unstable, not least because the elevation of the zero-degree isotherm would have been at a

> similar elevation and melting ice would have contributed to instability. We suspect that periodic failures of ice-and-sediment buildup occurred, generating debris flows that came to rest about 10 km distant and 2000 m lower in elevation, where drainages approach the Cordillera's foothills. What remains today is terraces perched above the modern river (the village of San Gerardo is spread along several such terrace surfaces) that are primarily composed of minimally-weathered silt-rich matrix supporting rounded but unweathered gravel, cobbles, and boulders up to 10 m and more in their long dimension. For this reason, it seems reasonable to suspect that the debris-flow sediments might still exhibit glacial imprints despite their presumed subsequent rapid transport down the mountain flank.

The limited amount of difference between the upland and downslope samples and a strong showing of microtextures described as diagnostic of glacigenesis in the relevant literature suggest that all of the Costa Rican samples are glacigenic, which in turn supports the Orvis-Harden-Horn hypothesis of steep-slope instability of glaciers and their sediments, and the glacigenicity of San Gerardo and similar foothill terraces perched above modern streams that head in the uplands.

5.3.3 Upland and Downslope Comparisons to Dominican Republic

While the Dominican Republic sediments do bear some resemblance to the downslope diamicts of Costa Rica, as a whole the Dominican Republic samples are more similar to the upland Costa Rican samples. The confidence limits of the Dominican Republic microtextural signature patterns tend to fall within the middle of the range of limits of the Costa Rican samples. Sample 10 has almost a 100% overlap with the upland samples; the only exception being the high number of grains within sample 4 that display angular features. Sample 4 has the highest number of grains with angular features in all of the Costa Rican samples, and similarly differs from the Dominican Republic samples, but as described above, this microtexture appears to vary naturally. The similarity between sample 10 and the known glacial sediments of Costa Rica constitutes strong evidence that this Dominican Republic sample can be characterized as glacigenic.

Sample 11 is perhaps the most different of all of the Dominican Republic samples. Its overall appearance more closely resembles the upland samples, but its low degree of angularity and its high number of grains with evidence of weathering match neither upland nor downslope Costa Rican samples. The occurrences of mechanically upturned plates are most similar to sample 9 (downslope), but its higher number of grains with conchoidal fractures resembles samples 1, 3, and 5 (upland). Compared to Dominican Republic samples as a whole, sample 11 has the highest amount of adhering particles, weathering, and mechanically upturned plates. However, these few variations in microtexture occurrence compared to the entirety of other analyzed samples are not extensive enough to dissuade my conclusion that sample 11 is glacigenic. The overall microtextural signature of sample 11 very much resembles that of known glacial Costa Rican sediments and the other previously suspected glacial sediments of the Dominican Republic. A more likely inference might be that, in the barely-glacierized Dominican Republic highlands, the glacier that deposited sample 11 happened to entrain more soft regolith or saprolite and less unweathered basement than was the case for other samples.

Sample 12 falls within the middle of the confidence limits for the upland samples and also exhibits some similarities with the downslope. With the exception of lower limits for precipitation and dissolution etching, samples 13 and 14 are remarkably similar to the upland deposits. Considering that both precipitation and dissolution etching occur in pre- and post-glacial environments, and that the Holocene climates of the two regions contrast, differences in occurrence are not substantial enough to discourage a conclusion of general glacigenesis. Sample 15 overlaps with all but 3 microtextures in the upland samples; for breakage blocks, adhering particles, and evidence of abrasion, sample 15 overlaps with all downslope diamict samples. Sample 16 and 17 are, again, remarkably similar to the upland samples, but the values of precipitation (again, perhaps a function of Holocene climate) fall outside the limits of both upland and downslope samples. Lastly, sample 18 tends to follow the upper confidence limits of the upland samples, but overlap occurs with greater frequency here than with downslope samples.

The Dominican Republic samples, then, share many characteristics with both the upland and downslope diamict Costa Rican samples, but in general have more in common with the upland samples. The similarity in topography and lithology between the Dominican Republic sites and the upland Costa Rican sites is one contributing answer as to why these two sediment suites are similar; however, I believe this similarity and the indistinguishability between the Dominican Republic samples as a group and the known glacigenic samples bolsters the evidence suggesting that the Dominican Republic sands have been glacierized.

5.4 Conclusions

The results of this thesis indicate that a unique microtextural fingerprint exists for tropical highland glacigenic sediments, which can largely survive overprinting by debris-flow transport and subsequent downslope (ca. 1400-m elevation) Holocene weathering. Furthermore, based on this common microtexture signature pattern, I conclude that the Dominican Republic sediments can be characterized as glacigenic. This inference is further supported by the shared characteristics between the Dominican Republic samples and the upland, known glacierized sediments of Costa Rica.

5.4.1 Sample Size

The results of this research are based on SEM analysis of a much higher number of sand grains than has been the typical case in previous studies. I studied multiple samples from each locale, and for every sample, I analyzed in detail a minimum of 100 quartz sand grains. The decision to study sample sizes much larger than those recommended by the relevant literature was based on my desire to be unequivocally robust in answering my research questions. By analyzing a minimum of 100 quartz sand grains and recording microtextures individually for each grain, I was able to generate detailed data on the trends of microtextural pattern development with increasing *N,* of tropical highland glacigenic sediments. A larger sample size allowed me to clearly and repeatably discern a common microtextural signature pattern within the tropical highland glacial sediment suites. I also carried two samples to even larger sample sizes. By analyzing 150 grains in sample 1 and 300 grains in sample 2, I hoped to elucidate how the microtexture signature would stabilize as samples become larger. In separate work that paralleled this study, we found that the signatures of these two samples were remarkably similar to the other known glaciated samples with sample sizes of N=100, and compared well with 100-grain subsets chosen pseudo-randomly from the larger samples. Based on this evidence and the equivalent similarity of the Dominican Republic microtextural signature patterns, I deduced that N=100 is an adequate sample size for classifying purportedly glacigenic tropical highland sediments environmental provenance.

A sample size of 20–30, or even 50, grains, as recommended in the relevant literature, would not have yielded the same results. In related collaborative work with Dr. Orvis, bootstrapping results yielded a 99% confidence interval of ±15% for samples of 50 grains, ±21% for samples of 30 grains, and ±25% for samples of 20 grains, making it extremely difficult to infer that seemingly contrasting samples are in fact statistically distinguishable. With a lower confidence interval of 95%, the difficulty would increase. Within glacial environments, when one considers the diversity of microtextures found on glacierized sediments, and the relative rarity of some of them, a sample size of only 20–30 grains can not accurately represent its parent population.

This conclusion contradicts the general trend of sample size selection in the literature (Tovey and Wong 1978; Bull 1981; Mahaney 2002; Alekseeva 2005). In studies with a limited time-frame or comparatively primitive SEM equipment, one could argue for the utility of a smaller sample size in providing a generalized picture of fracture type and relative frequency. Certain sediments, such as those in a littoral environment, will exhibit a consistent, and small, set of microfeatures; this consistency allows for a smaller sample size, but a number of environments, particularly glacial, can generate a wide array of microtextures. Increased diversity in microtextures requires an increase in sample size to properly characterize their incidence.

Furthermore, the presence of one or two diagnostic microtextures can hardly be said to provide enough evidence of environmental provenance. In order to determine environmental provenance based on a microtextural signature, one must include a sample size and microtextural suite that will be robust for the sample with the greatest variance. Based on evidence from work parallel to this study, that sample size is on the order of 100 grains for tropical highland sediments.

5.4.2 Microtexture Relevance

Glacial grains have potential to carry the widest variety of surface microtextures of sediments in any environment; these include microtextures that were generated before, during, and after glaciation (Mahaney 2002). The 25 microtextures (Table 3) included in my analyses were taken from multiple studies and compiled with the sheer diversity of glacial textures in mind. This list of 25 microtextures was actually pruned down from 30 during the reconnaissance phase of my research; I decided to remove five textures (chattermarks; overprinting; parallel ridges; craters; lattice shattering) from my list when it became apparent that these features were not at all common in the tropical highland sediments I studied. Most are likely to be more common in cold-based glaciers; overprinting may be more common with longer englacial transport distances. I took care to note when I did eventually find a microtexture not included in my list, but none occurred often enough to warrant mention in this study.

A few microtextures that were included in the thesis did not provide much evidence as to environmental provenance; their prevalence was not substantial enough to truly affect the signature pattern that emerged. For the sediments studied in this thesis, features such as radial fractures, edge rounding, new growth, fracture faces, v-shaped percussion fractures, and crescentic gouges were extremely rare. Nevertheless, I found that the presence, and absence, of several of these provided important information regarding the environmental history of the sediments. Edge rounding and v-shaped percussion fractures are indicators of fluvial transport; edge rounding also occurs in glacial environments as abrasive grinding erases sharp edges. Radial fractures are linear fractures that radiate from an impact point, such as that might occur when grains come into contact with one another in debris-rich shearing zones of ice. Mahaney and Kalm (2000) also noted the absence of crescentic gouges within the suite of sediments they studied, specifically because this texture has been described as ubiquitous to glacial sediments (Folk 1975; Bull et al. 1980). In all likelihood, the lack of fracture faces is the result of less later glacial crushing and further fracturing after an initial, larger fracture, in these short-transport-distance tropical highland glacial systems. While not exhaustive, the microtextures analyzed in this study nevertheless comprise a wide-ranging list of the types of fractures and other microtextures generated in glacial environments.

5.4.3 Microvariation among Known Glacial Sediments

Samples 2 and 3 were contiguous in the field, both collected from highly dewatered basal material deposited in a ground moraine. Sample 2 was slightly nearer (by 4–6 cm) than sample 3 to the modern exposure surface. The higher percentage of angular grains in sample 2 might be explained by the relative difference in distance from the modern surface. Considering that grains in sample 3 do not have as high a degree of relief as those in sample 2, it is conceivable that post-depositional processes could have dulled some of this type of evidence of glacial transport within sample 3. However, this singular difference does not diminish the obvious level of similarity between these two adjacent samples.

Samples 4 and 5 were similarly collected from the same lateral moraine, but were not adjacent to each other; they were from less than 5 m apart and sampled contrasting visible textures of moraine matrix. The intentional differences between the two material types are reflected in the minor differences in microtextures. Sample 4 was collected from a depth well below any obvious pedogenesis horizons and subsequently has fewer grains than sample 5 with microfeatures associated with post-depositional environments (weathering and dissolution etching). Sample 5 has a slightly smaller number of grains with apparent glacial crushing features, such as grooves and abraded surfaces, when compared to sample 4. Sample 5 comprises fine sediments that settled or were emplaced by water transport near and under a large boulder—post-depositional weathering, especially if it remained a subsurface channel for water, may have erased the more obvious signs of glacial transport, more so at least than in sample 4.

Alternatively, sample 5 might not have been subjected to the same history of grinding and crushing as sample 4; or sample 4 may have endured further modification as subsequent sediments were deposited above it. Despite these minor variations, both lateral moraine samples display strong microtextural evidence of glacigenesis.

A comparison of basal till (samples 2 and 3) to lateral/terminal till (samples 4, 5, and 8) did not reveal much difference between the two deposit types, at least in this particular tropical alpine glacial system. The signatures are fairly similar and further analysis of additional till samples would be necessary to make any inference towards identifying distinct microvariations between ground moraine and lateral/terminal moraine sediments. The debris-flow deposits differ seriously from the moraine sediments only in the number of grains with mechanically upturned plates, which are plates that have been partially torn loose from mineral surfaces after impact (Mahaney 2002). The higher incidences of this texture could be related to fracturing that occurred during transport as the material was dislodged and flowed downhill several kilometers to the San Gerardo site.

5.4.4 Degree of Glacigenicity

The Dominican Republic samples as a whole are remarkably similar to the Costa Rican samples as a whole. These tropical highland sediments look so similar that they might have been collected in the same valley. The microtextural signature revealed in this thesis is common across all samples, regardless of sediment deposit type. The degree to which sediments resemble each other within the two main sample groups is also noteworthy. Both upland and downslope deposits from Costa Rica are strikingly similar. This similarity gives further credence to the conjecture of Orvis, Harden, and Horn (Orvis, pers. comm.) that the downslope deposits consist of mostly glacierized sediments. Even more striking is the resemblance between sediments of unknown provenance with each other; the Dominican Republic samples are more similar to each other than the known-glacial-locale sediments are to one another. In all likelihood this higher degree of similarity has to do with the lack of Dominican Republic debris flow sediments, and it might be happenstance—studying more samples from both locations might yield a different degree of group similarity in each case. However, I believe that the approach presented in this thesis is useful for obtaining a glacigenic fingerprint for unknown samples. While I did not compare presumed non-glacigenic samples, for example modern landslide deposits, from the Dominican Republic or Costa Rica to known glacierized sediments, I am confident that these results provide an accurate representation of the expected microtextural fingerprint from tropical highland glacigenic sediments.

I cannot undisputedly claim that one sample group looks more glacigenic than the other. Certain Dominican Republic samples had higher occurrences of diagnostically glacial microtextures, but the same can be said of certain Costa Rican samples. On average, 71% of Dominican Republic grains had conchoidal fractures, compared to the Costa Rican average of 55%. However, Costa Rican samples had more incidences of groove-like features. Both groups in their entirety have strong glacigenic microtextural signature patterns, and the strength of that evidence led to me to conclude that Dominican Republic sediments of previously unknown provenance can be characterized as glacigenic.

5.4.5 Broader Conclusions

In hindsight, the research conducted in this thesis could have been improved with further study at the onset into how specific microtextures are generated and additional "practice" with the SEM. The time necessary to catalogue a single sample decreased as I became more confident in my ability to recognize relevant microtextures, but the bulk of effort went into recording microtextural data. The addition of an energy-dispersive spectrometer (EDS) to the SEM would have been an improvement as well. EDS allows users to identify adhering substances and coatings on sand grains (Mahaney 2002), and also serves as a further defense against accidental inclusion of non-SiO_2 grains in the study. It provides chemical elemental information only, not mineralogical, but when paired with standard SEM practices, EDS can generate a wealth of useful data.

After conducting an extensive amount of research with a scanning electron microscope, I believe the SEM is a useful tool for sediment analysis. It provides insight that might otherwise not be revealed, into the various environmental processes to which sediments have been subjected. As with any scientific research tool, possibilities for error and user bias do exist. Misidentification of microtextures can lead to inaccurate conclusions about the environmental provenance of sediments. Culver et al. (1983) conducted a study on user bias and found that various SEM users came to different conclusions regarding the same set of samples. User bias might be an unavoidable aspect of scanning electron microscopy, but steps can be taken by the SEM user to inhibit that type of error and therefore should not diminish the overall usefulness of SEM to sediment analysis. Similar issues have been documented in palynology and other fields, but the larger overall patterns on which inferences are based have proved repeatable.

The most difficult task in this research proved to be the development of the 99% confidence intervals. The sheer amount of data necessary to generate accurate confidence intervals without an applicable established statistical technique was daunting. However, now that we have established confidence intervals specific to this class of problem through bootstrapping (in collaborative work), subsequent statistical analyses of other sediments can be undertaken with confidence. Measuring and comparing samples at the 99% confidence level allowed me to infer a microtextural fingerprint that was common even to samples with the greatest variance. For example, sample 11 carries an obvious glacigenic signature, but is not as similar to other Dominican Republic samples as those samples are to each other. However, I believe the microtextural signature pattern uncovered in this thesis will prove to be common to a wide variety of tropical highland glacial sediments.

This thesis is one part of a larger project whose goal is to establish protocols for distinguishing between glacigenic and non-glacigenic sediments, and to eventually test for glacigenicity among diverse sediments in Costa Rica, the Dominican Republic, and elsewhere. I believe that the methods employed in this thesis can be applied in other studies attempting to distinguish tropical highland glacigenic samples from sediments of non-glacial provenances from the same region. This is the next logical step: further SEM analysis of a variety of Dominican Republic samples to determine provenance. This study could be bolstered, for example, by the analysis of non-glacigenic sediments from Dominican Republic landslide samples. The microtextural signature of non-glacigenic samples could be compared to the signature revealed in this thesis to see how the contrasting provenance types differ (or do not differ) at the microtextural level. My contribution to the larger project will hopefully allow the completion of its remaining goals, specifically the aim to make suitable inferences about the presence or absence of glaciers in the Dominican Republic within the last 45,000 yr B.P.

LIST OF REFERENCES

Alekseeva, V.A., 2005. Micromorphology of quartz grain surface as indicator of glacial sedimentation conditions: Evidence from the Protva River Basin. *Lithology and Mineral Resources*, 40(5), pp. 420–428.

Baker, Jr., H.W., 1976. Environmental sensitivity of submicroscopic surface textures on quartz sand grains—A statistical evaluation. *Journal of Sedimentary Petrology*, 46(4), pp. 871–880.

Benn, D.I. and Evans, D.J.A., 1998. *Glaciers and Glaciation*. New York: Arnold, 734pp.

Bernet, M. and Bassett, K., 2005. Provenance analysis by single-quartz-grain SEM-CL/Optical microscopy. *Journal of Sedimentary Research*, 75(3), pp. 492–500.

Birks, H.J.B. and Birks, H.H., 1980. *Quaternary Paleoecology*. London: Edward Arnold, 289pp.

Bolay, E., 1997. *The Dominican Republic: A Country Between Rain Forest and Desert. Contributions to the Ecology of a Caribbean Island*. Weikersheim, Germany: Margraf, 456pp.

Bozzola, J.J. and Russell, L.D., 1998. *Electron Microscopy, 2nd edition*. Sudbury, MA: Jones and Bartlett Publishers, 670pp.

Bull, P.A., 1986. Procedures in environmental reconstruction by SEM analysis. In: Sieveking, G. de G., and Hart, M.B. (eds.), *The Scientific Study of Flint and Chert: Proceedings of the Fourth International Flint Symposium, Polytechnic*. 10–l5 April 1983, Cambridge: Cambridge University Press, pp. 221–226.

Bull, P.A., 1981. Environmental reconstruction by electron microscopy. *Progress in Physical Geography*, 5, pp. 368–397.

Bull, P.A., Culver, S.J., and Gardner, R., 1980. Chattermark trails as paleoenvironmental indicators. *Geology*, 8, pp. 318–322.

Clark, G.M., Horn, S.P., and Orvis, K.H., 2002. High-elevation savanna landscapes in the Cordillera Central, Dominican Republic, Hispaniola: Dambos in the Caribbean? *Mountain Research and Development*, 22(3), pp. 288–295.

Clement, R.M. and Horn, S.P., 2001. Pre-Columbian land-use history in Costa Rica: A 3000-year record of forest clearance, agriculture and fires from Laguna Zoncho. *The Holocene*, 11(4), pp. 419–426.

Culver, S.J., Bull, P.A., Campbell, S., Shakesby, R.A., and Whalley, W.B., 1983. Environmental discrimination based on quartz grain surface textures: a statistical investigation. *Sedimentology*, 30, pp. 129–136.

Denyer, P., and Kussmaul, S. (compilers), 2003. *Geología de Costa Rica*. Cartago, Costa Rica: Instituto Tecnológica de Costa Rica, 515pp.

Doornkamp, J.C., 1974. Tropical weathering and the ultra-microscopic characteristics of regolith quartz on Dartmoor. *Geografiska Annaler. Series A, Physical Geography*, 56(1–2), pp. 73-82.

Dowdeswell, J.A., 1982. Scanning electron micrographs of quartz sand grains from cold environments examined using Fourier shape analysis. *Journal of Sedimentary Petrology*, 52(4), pp. 1315–1323.

Driese, S.G., Orvis, K.H., Horn, S.P., Li, Z.H., and Jennings, D.S., 2007. Paleosol evidence for Quaternary uplift and for climate and ecosystem changes in the Cordillera de Talamanca, Costa Rica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 248, pp. 1–23.

Drummond, M.S., Bordelon, M., De Boer, J.Z., Defant, M.J., Bellon, H., and Feigenson, M.D., 1995. Igneous petrogenesis and tectonic setting of plutonic and volcanic rocks of the Cordillera de Talamanca, Costa Rica–Panama, Central American arc. *American Journal of Science*, 295, pp. 875–919.

Folk, R.L., 1975. Glacial deposits identified by chattermark tracks in detrital grains. *Geology*, 3, pp. 475–479.

Fritts, H.C., 2001. *Tree Rings and Climate*. Caldwell, NJ: The Blackburn Press, 545pp.

Gomez, B. and Small, R.J., 1983. Genesis of englacial debris within the lower Glacier de Tsidjiore Nouve, Valais, Switzerland, as revealed by scanning electron microscopy. *Geografiska Annaler. Series A, Physical Geography*, 65(1–2), pp. 45–51.

Graefe, K., 1998. Exhumation and thermal evolution of the Cordillera de Talamanca (Costa Rica); constraints from fission track analysis, ^{40}Ar/^{39}Ar, and ^{87}Rb/^{87}Sr chronology. *Tübinger Geowissenschaftliche Arbeiten*, 39.

Hambry, M., 1994. *Glacial Environments*. Vancouver: UCL Press Limited, 296pp.

Helland, P.E. and Holmes, M.A., 1997. Surface textural analysis of quartz sand grains from ODP Site 918 off the southeast coast of Greenland suggests glaciation of southern Greenland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 135, pp. 109–121.

Helland, P.E., Huang, P.-H., and Diffendal, Jr., R.H., 1997. SEM analysis of quartz sand grain surface textures indicates alluvial/colluvial origin of the Quaternary "glacial" boulder clays at Huangshan (Yellow Mountain), east-central China. *Quaternary Research*, 48, pp. 177–186.

Higgs, R., 1979. Quartz-grain surface features of Mesozoic-Cenozoic sands from the Labrador and western Greenland Continental Margins. *Journal of Sedimentary Petrology*, 49, pp. 599–610.

Horn, S.P., 1993. Postglacial vegetation and fire history in the Chirripó Páramo of Costa Rica. *Quaternary Research*, 40, pp. 205–225.

Horn, S.P., 1990. Timing of deglaciation in the Cordillera de Talamanca, Costa Rica. *Climate Research*, 1, pp. 81–83.

Horn, S.P., Orvis, K.H., Kennedy, L.M., and Clark, G.M., 2000. Prehistoric fires in the highlands of the Dominican Republic: evidence from charcoal in soils and sediments. *Caribbean Journal of Science*, 36(1–2), pp. 10–18.

Horn, S.P., Kennedy, L.M., and Orvis, K.H., 2001. Vegetation recovery following a high elevation fire in the Dominican Republic. *Biotropica* 33, pp. 701–708.

Horst, O.H., 1992. Climate and the "encounter" in the Dominican Republic. *Journal of Geography*, 91(5), pp. 205–210.

JEOL, 2006. *Scanning Electron Microscope Operations.* Manual for a short course held 13–17 November 2006. Peabody, MA: The JEOL Institute, 245pp.

Kennedy, L.M., Horn, S.P., and Orvis, K.H., 2006. A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 231, pp. 271–290.

Kennedy, L.M., Horn, S.P., and Orvis, K.H., 2005. Modern pollen spectra from the highlands of the Cordillera Central, Dominican Republic. *Review of Palaeobotany and Palynology*, 137(1–2), pp. 51–68.

Krinsley, D.H. and Donahue, J., 1968. Environmental interpretation of sand grain surface features by electron microscopy. *Geological Society of America Bulletin*, 79(6), pp. 743–748.

Krinsley, D.H. and Doornkamp, J.C., 1973. *Atlas of Quartz Sand Surface Textures*. Cambridge: Cambridge Univ. Press, 91 pp.

Kwon, Y.I. and Boggs, S., 2002. Provenance interpretation of Tertiary sandstones from the Cheju Basin (NE East China Sea): a comparison of conventional petrographic and scanning cathodoluminescence techniques. *Sedimentary Geology*, 152, pp. 29–43.

League, B.L. and Horn, S.P., 2000. A 10,000 year record of páramo fires in Costa Rica. *Journal of Tropical Ecology*, 16, pp. 747–752.

Mahaney W.C., 2002. *Atlas of Sand Grain Surface Textures and Applications*. Oxford: Oxford Univ. Press, 237 pp.

Mahaney, W.C., 1998. Scanning electron microscopy of Pleistocene sands from Yamal and Taz peninsulas, Ob River estuary, northwestern Siberia. *Quaternary International*, 45/46, pp. 49–58.

Mahaney, W.C., 1995. Pleistocene and Holocene glacier thickness, transport histories and dynamics inferred from SEM microtextures on quartz particles. *Boreas*, 24, pp. 293–304.

Mahaney, W.C., 1991. Glacially-crushed quartz grains in late Quaternary deposits in the Virunga Mountains, Rwanda—Indicators of wind transport from the north? *Boreas*, 91(1), pp. 81–89.

Mahaney, W.C., Dirszowsky, R., Milner, M.W., Menzies, J., Stewart, A., Kalm, V., and Bezada, M., 2004. Quartz microtextures and microstructures owing to deformation of glaciolacustrine sediments in the northern Venezuelan Andes. *Journal of Quaternary Science*, 19, pp. 23–33.

Mahaney, W.C., Stewart, A., and Kalm, V., 2001. Quantification of SEM microtextures useful in sedimentary environmental discrimination. *Boreas*, 30, pp. 165–171.

Mahaney W.C. and Kalm V., 2000. Comparative SEM study of oriented till blocks, glacial grains and Devonian sands in Estonia and Latvia. *Boreas*, 29, pp. 35–51.

Mahaney, W.C., Campbell, I.A., and Claridge, G., 1996. Microtextures on quartz grains in tills from Antarctica. *Palaeogeography, Palaeoclimatology and Palaeoecology*, 121, pp. 89–103.

Mahaney, W.C., Vortisch, W., and Julig, P., 1988. Relative differences between glacially crushed quartz transported by mountain and continental ice—Some examples from North America and East Africa. *American Journal of Science*, 288, pp. 810–826.

Margolis, S.V. and Kennett, J.P., 1971. Cenozoic paleoglacial history of Antarctica recorded in subantarctic deep sea cores. *American Journal of Science*, 271, pp. 1–36.

Mazzullo, J. and Ritter, C., 1991. Influence of sediment source on the shapes and surface textures of glacial quartz sand grains. *Geology*, 19, pp. 384–388.

Menzies, J. (ed.), 2002. *Modern & Past Glacial Environments*. Oxford: Butterworth-Heinemann, 543 pp.

Northrop, L.A. and Horn, S.P., 1996. Pre-Columbian agriculture and forest disturbance in Costa Rica: Palaeoecological evidence from two lowland rainforest lakes. *The Holocene*, 6(3), pp. 289–299.

Orvis, K.H. and Horn, S.P., 2000. Quaternary glaciers and climate on Cerro Chirripó, Costa Rica. *Quaternary Research*, 54, pp. 24–37.

Orvis, K.H., Clark, G.M., Horn, S.P., and Kennedy, L.M., 1997. Geomorphic traces of Quaternary climates in the Cordillera Central, Dominican Republic. *Mountain Research and Development*, 17, pp. 323–331.

Pidwirny, M., 2006. Landforms of glaciation. *Fundamentals of Physical Geography, 2nd Edition*. January 12th, 2009. Accessed March 1st, 2009 at url: http://www.physicalgeography.net/fundamentals/10af.html.

Schubert, C., and Medina, E., 1982. Evidence of Quaternary glaciation in the Dominican Republic: Some implications for Caribbean paleoclimatology. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 39, pp. 281–294.

Seyedolali, A., Krinsely, D.H., Boggs., JR., O'Hara, P.F., Dypvik, H., and Goles, G.G.,1997. Provenance interpretation of quartz by scanning electron microscope-cathodoluminescence fabric analysis. *Geology*, 25, pp. 787–790.

Simonov, Yu.G., 1999. *Ob"yasnitel'naya morfometriya rel'efa* (Explanatory Morphometry of Relief), Moscow: Mosk. Gos. Univ., 263pp.

Strand, K., Passchier, S., and Näsi, J., 2003. Implications of quartz grain microtextures for onset Eocene/Oligocene glaciation in Prydz Bay, ODP Site 1166, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 198, pp. 101–111.

Towner, R.H., 2007. Dendroarchaeology. In: Elias, S.A. (ed.), *Encyclopedia of Quaternary Science*, 3. New York: Elsevier, pp. 2307–2315.

Tovey, N.K. and Wong, K.Y., 1978. Preparation, selection, and interpretation problems in scanning electron microscope studies of sediments. In: Whalley, W.B. (ed.), *Scanning Electron Microscopy in the Study of Sediments*. Norwich, Geo Abstracts, pp. 181–199.

Whaley, W.B. and Krinsley, D.H., 1974. Scanning electron microscope study of surface textures of quartz grains from glacial environments. *Sedimentology*, 21, pp. 87–105.

Wunsch, O., Calvo, G.,Willscher, B., Seyfried, H., 1999. Geologie der alpinen Zone des Chirripó-Massives (Cordillera de Talamanca, Costa Rica, Mittelamerika). *Profil*, 16, pp. 193–210.

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