Controls on gravel composition in a proglacial environment, Kaunertal, Austria

Research Thesis
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Geological Sciences in the undergraduate colleges of
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By

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Abstract

Proglacial environments, the settings in front of glaciers, are increasingly targeted for study as global climate change affects many of the world's glaciers. This study focuses on a proglacial environment in Kaunertal, Austria, located in the drainage basin of the Gepatschferner Glacier, one of the biggest glaciers in Austria (Baewert and Morche, 2013). Effects of transport in proglacial drainage systems like this one are hypothesized to influence the distribution patterns of different rock types supplied by glacial erosion. The main goals of this project are to: 1) describe the composition of gravel-sized clasts along an ~4 km length of the Fagge River, the proglacial stream that drains the Gepatschferner Glacier in order to test the results presented in similar research; and 2) interpret the spatial changes in gravel composition in terms of the distribution of bedrock types in the area and the effects of transport, such as the greater persistence of stronger rock types during transport. Sixteen sites were sampled along the Fagge River, with ~50 grains collected at each site. Fifty grains were also taken from each major tributary or moraine. In addition, a sample was collected from each of 20 outcrops, distributed among the 3 lithologies in the study area. The composition of each grain was determined by visual examination with a hand lens and standard rock identification charts. The abundance of each rock type has been examined as a function of sampling location. The most abundant gravel compositions are "Orthogneiss," "Paragneiss" and "Ortho- or Paragneiss." There was a wide variation of abundances in all rock types throughout the length of the drainage basin. Although no significant trends were found, "Orthogneiss," "Amphibolite," and "Other" became somewhat more abundant downstream, while "Paragneiss," "Ortho- or Paragneiss" and "Jointed Gneiss" are still present.

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Introduction

Austria is home to some of the largest temperate glaciers in the world, and recent reduction of these glaciers due to global climate change emphasizes the need for studies regarding the effects global warming may have on the environment to which the glacier belongs. Proglacial environments, the setting in front of a glacier, are increasingly targeted for study as global climate changes. This study focuses on one proglacial setting affected by the melting of a glacier. Kaunertal, Austria is located in the drainage basin of the Gepatschferner Glacier, one of the biggest glaciers in Austria (Baewert and Morche, 2013). Proglacial areas, especially river channels, are highly unstable and contain channels, bars, water discharge and sediment input that can change within a day (Baewert and Morche, 2013; Marren, 2005; Ferguson et al. 1992). This leaves a proglacial basin system especially vulnerable to any increase in glacial meltwater. The Gepatschferner, in particular, is losing significant ice volume each year. The glacier terminus retreated about 450m between 1971 and 1990 (Keutterling and Thomas, 2006). This yields an average retreat of approximately 23m per year.

Gravel transport and gravel distribution patterns in a proglacial setting are affected by many variables. The hydraulic character of the drainage, including its size, gradient, and discharge characteristics, determines transport rate and distance, degree of recycling and weathering in transit, and ultimate survival of various lithologies (Lindsey et al. 2007). This study site is of particular interest because climate change, by affecting the rate at which the Gepatschferner retreats, may initiate or interrupt geomorphic cycles within the drainage basin (Lindsey et al. 2007). Gravel-sized grains were chosen because pebble counts are the method of choice for studying the provenance of coarse clastic deposits, because they yield specific information about source lithology (Lindsey et al. 2007).

Similar work has been done in order to find downstream trends in sediment composition. Lindsey et al. (2007) collected gravel samples from tributary fans and terraces of the Santa Cruz River in Arizona as well as from terraces of the Wind River in Wyoming. Pebble counts of lithology and roundness from terraces formed in response to climate change were analyzed in these two contrasting piedmont fluvial systems to see how provenance varies with drainage size (Lindsey et al. 2007). Plumley (1948) collected terrace gravels from three creeks in the Black Hills, Rapid Creek (~48 km), Battle Creek (~27 km), and Bear Butte Creek (~34 km). These studies found gravel composed of hard rocks will not develop obvious trends until 10 km or more downstream.

The main goals of this project are to 1) describe the composition of gravel-sized clasts along an ~4 km length of the Fagge River, the proglacial stream that drains the Gepatschferner Glacier in order to test the results presented in similar research; and 2) interpret the spatial changes in gravel composition in terms of the distribution of bedrock types in the area and the effects of transport, such as the greater persistence of stronger rock types during transport.

My working hypotheses are to 1) test the results found in Lindsey et al. (2007) and Plumley (1948) in the gravels in the ~4 km of the Fagge River; 2) see a higher diversity in gravel composition downstream; and 3) find a dominance of paragneiss in the gravel composition since the surrounding bedrock is dominated by gneiss.

Study Site

The Kaunertal valley is located in the Central Eastern European Alps of Tyrol, Austria. The study area consists of the catchment area of the Fagge River and its outlet, which is defined where the Fagge River enters the Gepatsch reservoir (at 1765 m a.s.l.) (Figure 1). The reservoir was built in the early 1960s and is operated by the Tiroler Wasserkraft AG (TIWAG) in order to generate power for the towns within the Kaunertal Valley, (Baewert and Morche, 2013). The area is characterized by high relief, as some of the highest peaks surrounding the area include Glockturm (3353 m), Weißseespitze (3518 m), Fluchtkogel (3497 m), Hochvernagtspitze (3535 m), and Hintere Ölgrubenspitze (3295 m) in the Ötztal Alps and are located within the watershed (Baewert and Morche, 2013; Figure 2). The tree line is located at about 2245 m (Nicolussi et al., 2005) and any land surface above this elevation is mostly covered by a large amount of unconsolidated sediments, suggesting an abundant supply of solid load to the Fagge River (Baewert and Morche, 2013).

The Fagge River extends about 4 km from the terminus of the glacier to the entrance of the reservoir. The bedrock lithology is part of the Austro-Alpine nappes which consists of crystalline rocks formed from various metamorphic events during the Variscan, Permo-Triassic, Cretaceous, and Tertiary. The Ötztal Alps are a part of the Ötztal-Bundschuh Nappe System which consists predominantly of biotite-plagioclase gneisses, mica schists, amphibolites and a wide range of orthogneisses, and occasionally migmatites and ecoglites (McCann, 2008, Figure 3). Paragneiss dominates the study site whereas amphibolite is present in scattered intrusions. The upper portion of the drainage basin is composed of orthogneiss, with an abrupt transition to amphibolites down drainage. Below a zone of alternating amphibolite and paragneiss, paragneiss dominates the bedrock. Paragneiss continues downvalley to a steep gorge which appears to expose another type of orthogneiss.

The valley area is 62.54 km^2 and contains the Gepatschferner and Weißseeferner glaciers, amounting to about 39% glacial cover (Baewert and Morche, 2013). With an area of about 22 km^2 the Gepatschferner ranks among the largest glaciers of the Eastern Alps (Keutterling and Thomas, 2006). The southernmost and highest margins of the glacier drain to the south of the central Alpine Ridge (into the southern Tyrol of Italy; Keutterling and Thomas, 2006), but the majority drains to the north into the Fagge River and into the Reservoir. Since 1965, glacier outflow has been collected in the Gepatsch Reservoir, which feeds the hydroelectric power station in Feichten (Keutterling and Thomas, 2006).

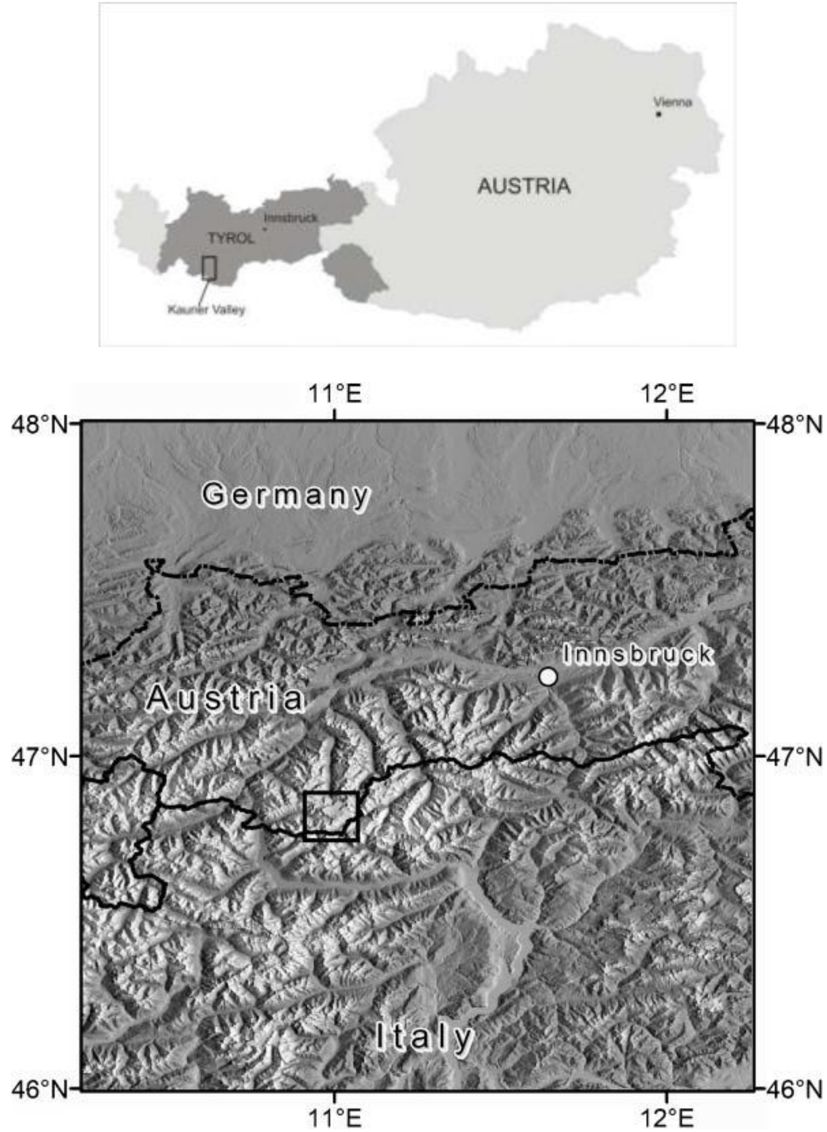


Figure 1: The study site is located in Kaunertal, Tyrol, Austria immediately north of the Austrian-Italian border.
From: Baewert and Morche, 2013; Keutterling and Thomas, 2006

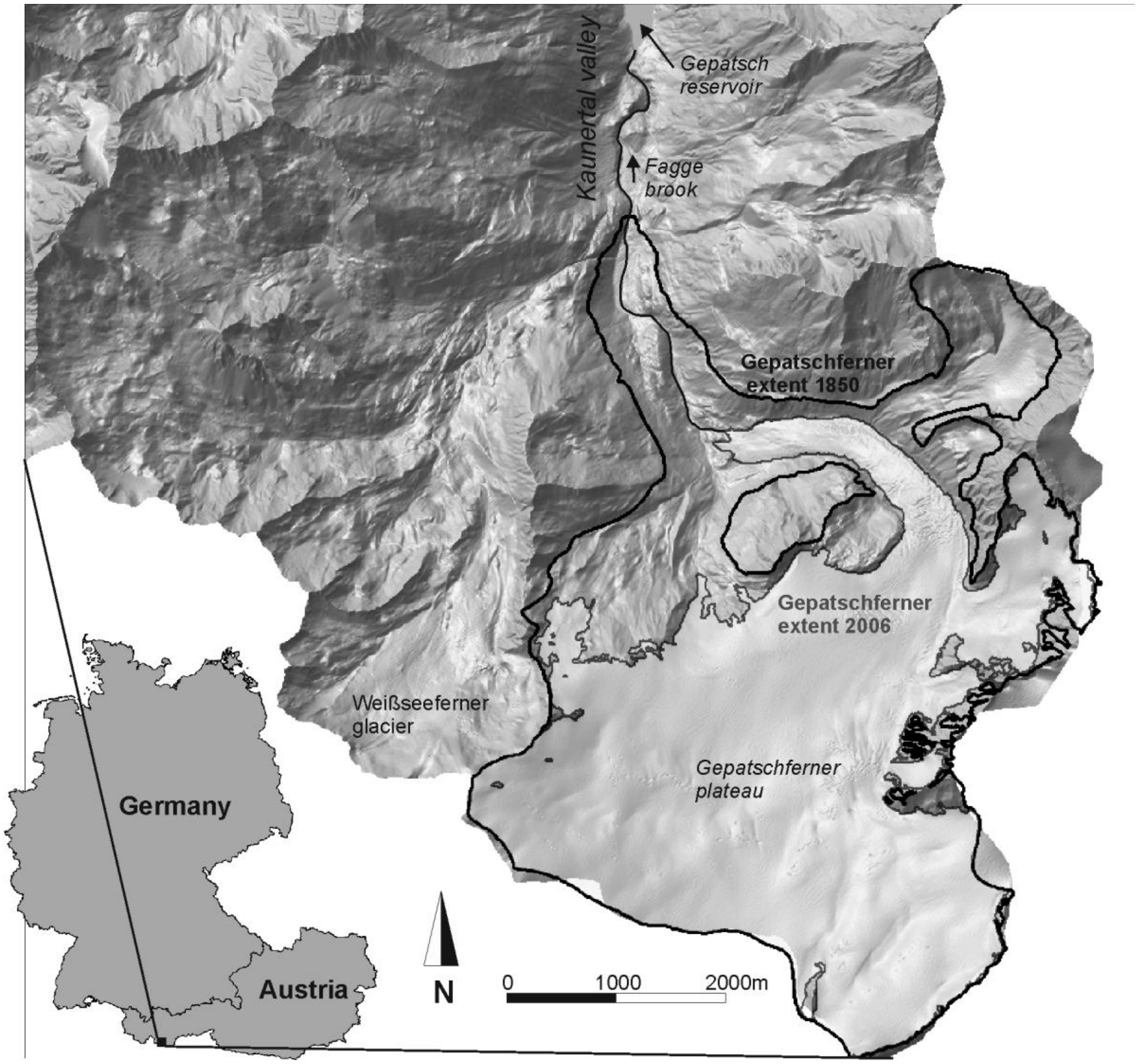


Figure 2: The Kaunertal Valley is the proglacial area inside the LIA moraines of the Gepatschferner and Weißseeferner glaciers. The LIA maximum and 2006 extent are shown. The shaded relief is from 10 m DEM.
From: Heckmann et al. 2012

As with many European Alpine glaciers, the Gepatschferner has been retreating rapidly since the Little Ice Age (LIA) in the 19th century, at rates up to 23 m per year. LIA moraines are present in the proglacial area and contribute sediment to the Fagge River.

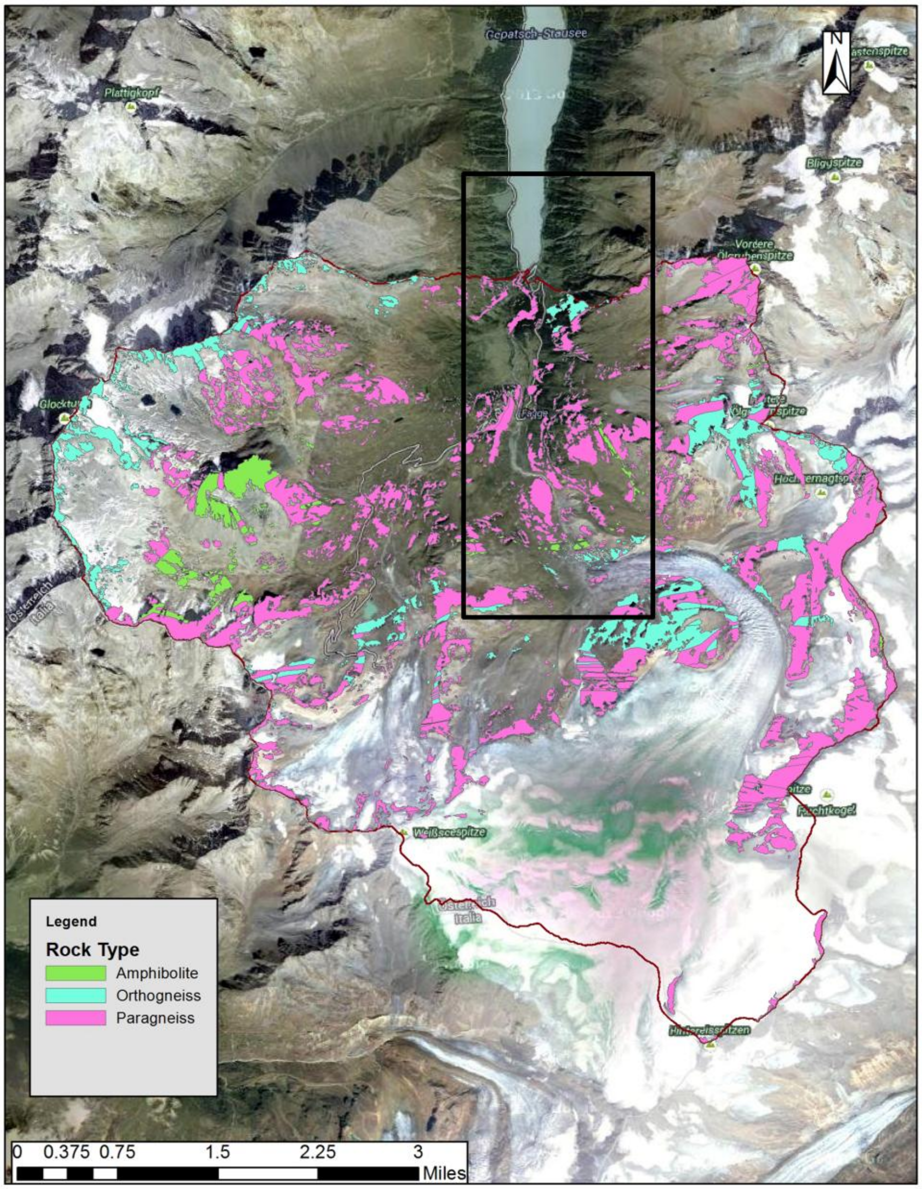


Figure 3: The bedrock geology of the study area and its surroundings, generalized into three main lithologies. The black rectangle indicates the study site.
From: Lucas Vehling, personal communication

Many research projects are ongoing in this study area. Other projects within the framework of PROSA (High-resolution measurements of morphodynamics in rapidly changing PROglacial Systems of the Alps) include quantifying fluvial sediment transport in the Fagge River and its main tributary, Riffler Bach (Baewert and Morche, 2013), mapping the surrounding geology, mapping the Pleistocene moraines, determining the sediment budget of the proglacial sediment cascade upstream of the Gepatsch Reservior (Heckmann et al. 2012), surveying short term storage to improve the understanding of coarse sediment dynamics in proglacial fluvial systems, and observing and quantifying the morphological changes of the Fagge River in response to glacial retreat and flood events.

Methods

The data for this study were collected in a small drainage basin system in Feichten Kaunertal, Austria. Gravel samples were collected along the main channel, named the Fagge River, the major tributaries or LIA moraines that supply sediment to the Fagge River, and the surrounding bedrock in the field site along the Fagge River. This type of sampling allows us to see how quickly a change in bedrock is reflected in sediment composition, and whether the contribution from that bedrock stays constant through the area of its outcrop.

Fifty grains were collected at sixteen sampling sites along the Fagge River, spaced ~250–300 m apart. An additional 50 grains were collected from 6 of the of the 16 sample sites in order to test reproducibility. Fifty grains were also collected from each of four major tributaries and two moraines (Figure 4). This sums to 28 total sample sites where a sample consists of 50 grains (Tables B2 and B3).

Grains of 5–10 cm length were hammered out of 20 outcrops from the surrounding bedrock. At least 1 sample was taken from each side of each contact between two different lithologies in the bedrock. This is to see the variations within the 3 major bedrock lithologies (Table B1).

Samples collected in the Fagge River were labeled FR for Fagge River, followed by the sample site number. FR-1 is the uppermost sample site (at the glacier terminus) and FR-15 is the lowermost sample site (at the entrance to the reservoir). One Fagge River sample is labeled “Gorge,” which was collected from the gorge that lies directly before the reservoir entrance. I subdivided the stream into

3 sections based on geology and regularity in the outcrops including: the upper portion (FR-1 through M1), the middle portion (FR-5 through FR-11) and the lower portion (RB through FR-15). Samples from major tributaries were labeled based on the tributary's name and/or sample number. Major tributaries include: BB (Bridge Bach), RB (Rifler Bach), LMT1 and LMT2 (Last Major Tributary). Moraines were labeled by sample site number: M1 and M2 (moraine 1 and moraine 2).

As a result, 1,106 grains were taken from the Fagge River, 304 grains were taken from the major tributaries and moraines, and 40 grains were taken from the surrounding bedrock. A total of 1,450 grains were collected from the study site. See Appendix B for grain counts.

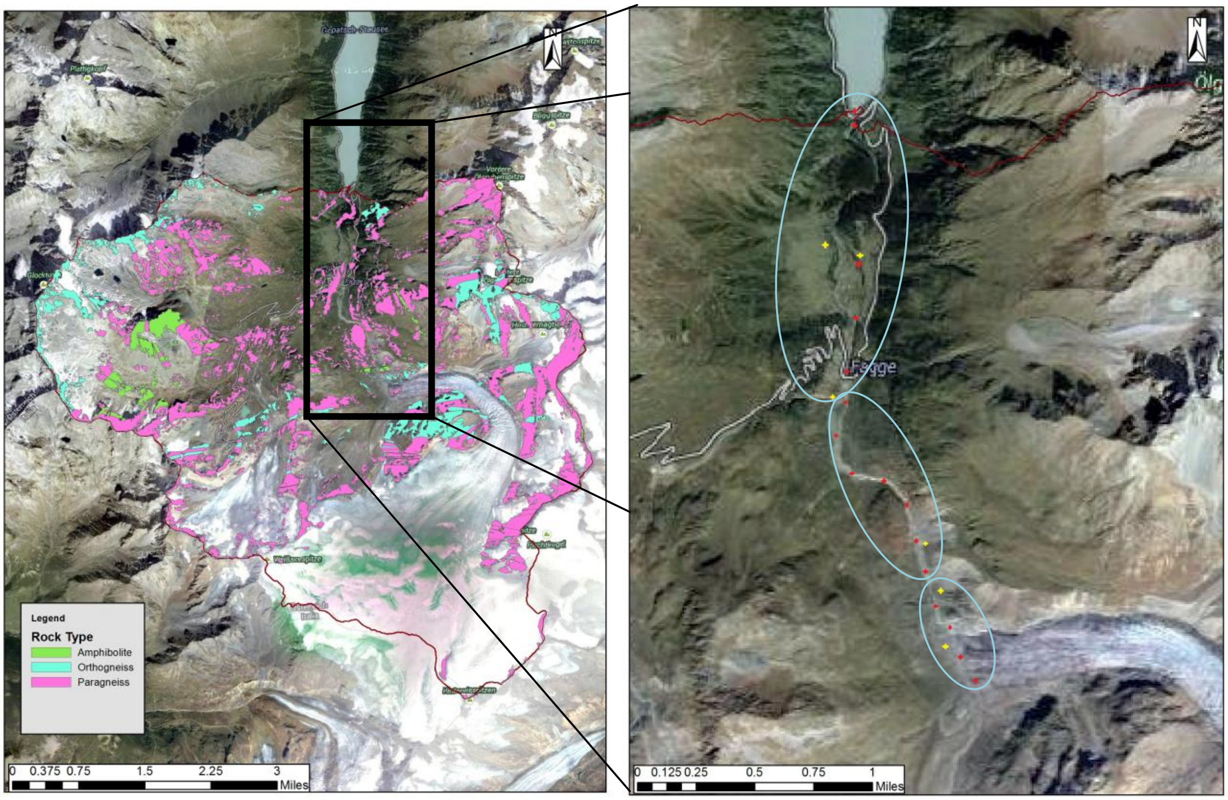
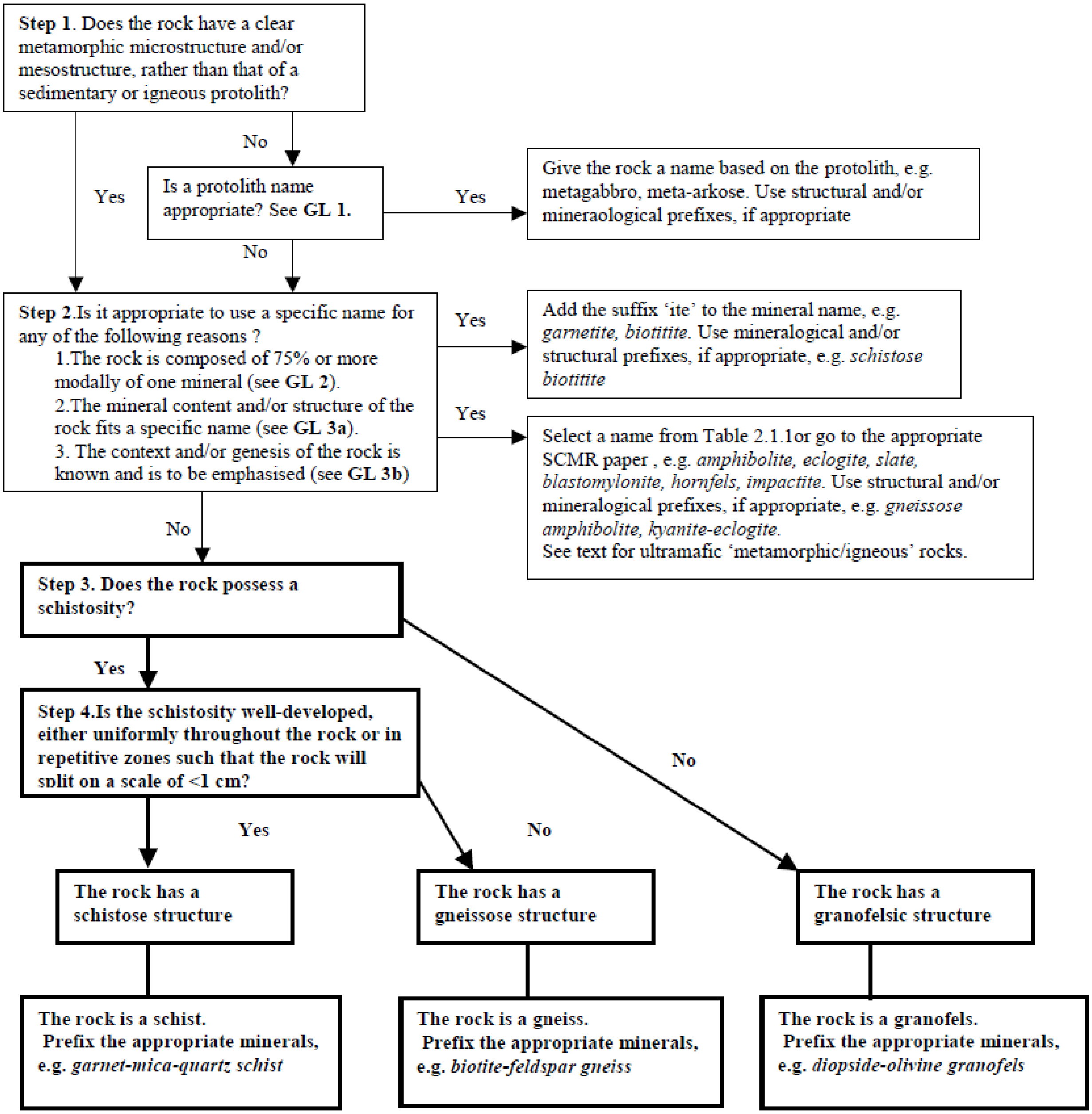


Figure 4: Location of the study area indicated by the black box and shown in detail on the right. Red dots indicate sample sites along the Fagge River (FR-1 at glacier, FR-15 at reservoir). Yellow dots indicate major tributaries and moraines (BB, M1, M2, RB, LMT 1 and 2). Blue ovals indicate 3 separate sections within the Fagge River.
From: Lucas Vehling, by personal communication

The distance between sampling sites varied due to accessibility, vegetation cover and eroded bedrock. Pebble-, cobble-, and boulder-sized grains were chosen at random, and were separated into their respective piles characterized by grain size. All clasts were subsampled by the use of a rock hammer and placed into labeled plastic bags stating the site number, date they were taken, and grain size (Figure 5). This made transportation parameters more reasonable.

Figure 5: Collecting and subsampling clasts at each site and separating each grain into different bags depending on its size (Pebble, Cobble, Boulder). Halil, top, assisted me in all field work.

Samples were shipped to The Ohio State University, organized, and analyzed to identify the lithology of each grain in each sample. A metamorphic rock identification flow chart from the British Geological Survey (Schmid et al. 2007, see Figure 6) was used to identify rock types, based on visual examination with a hand lens. The flow chart was mainly used for identifying schists, gneisses, and granofels in order to be able to tell them apart when it was not obvious. The definition of a schist given by Schmid et al. (2007) was used to help with identifications of schists.



Step 1. Does the rock have a clear metamorphic microstructure and/or mesostructure, rather than that of a sedimentary or igneous protolith?

Is a protolith name appropriate? See **GL 1**.

Give the rock a name based on the protolith, e.g. metagabbro, meta-arkose. Use structural and/or mineraological prefixes, if appropriate

Step 2.Is it appropriate to use a specific name for any of the following reasons ?
1.The rock is composed of 75% or more modally of one mineral (see **GL 2**).
2.The mineral content and/or structure of the rock fits a specific name (see **GL 3a**).
3. The context and/or genesis of the rock is known and is to be emphasised (see **GL 3b**)

Add the suffix 'ite' to the mineral name, e.g. *garnetite, biotitite*. Use mineralogical and/or structural prefixes, if appropriate, e.g. *schistose biotitite*

Select a name from Table 2.1.1or go to the appropriate SCMR paper , e.g. *amphibolite, eclogite, slate, blastomylonite, hornfels, impactite*. Use structural and/or mineralogical prefixes, if appropriate, e.g. *gneissose amphibolite, kyanite-eclogite*.
See text for ultramafic 'metamorphic/igneous' rocks.

Step 3. Does the rock possess a schistosity?

Step 4.Is the schistosity well-developed, either uniformly throughout the rock or in repetitive zones such that the rock will split on a scale of <1 cm?

The rock has a schistose structure

The rock has a gneissose structure

The rock has a granofelsic structure

The rock is a schist.
Prefix the appropriate minerals, e.g. ***garnet-mica-quartz schist***

The rock is a gneiss.
Prefix the appropriate minerals, e.g. ***biotite-feldspar gneiss***

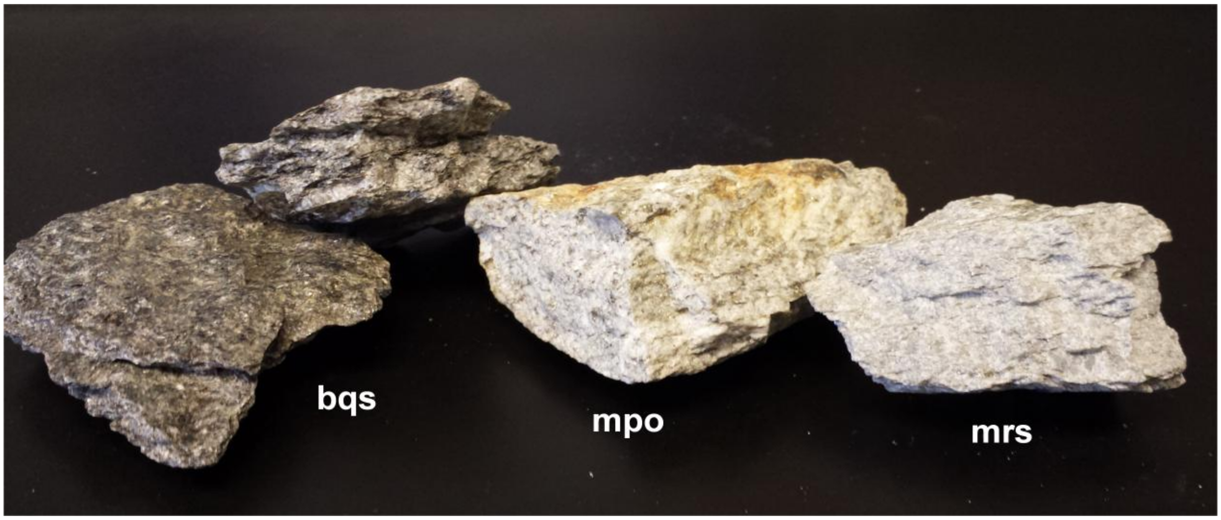
The rock is a granofels.
Prefix the appropriate minerals, e.g. ***diopside-olivine granofels***

Figure 6: Metamorphic rock identification flow-chart.
From: Schmid et al. 2007

All samples were identified three times. The first round of identification was very broad, identifying rocks as “Orthogneiss,” “Paragneiss,” “Amphibolite,” or “Other.” The second round of identification was very detailed subdividing rocks on the basis of details of their mineralogy, mineral abundances, and individual structures. The third round was intermediate in detail, identifying 15 rock subtypes. These 15 subtypes subsequently were clustered into 6 main groups: “Orthogneiss,” “Paragneiss,” “Ortho- or Paragneiss,” “Jointed Gneiss,” “Amphibolite,” and “Other.” Although time-consuming, this process of repeated classification provided detailed compositional information and a broad overview of the lithologies present. This range of information is important because metamorphic bedrock can show many variations over distances as short as 0.5 km. This method of detailed identification and subsequent clustering is common among these types of studies and was also used in Lindsey et al. (2007) and Plumley (1948).

The 15 rock subtypes were clustered into six major groups based on similarities in mineral assemblages, lineations and weathering pattern. “Orthogneiss” consisted of muscovite-plagioclase orthogneiss (mpo) and muscovite-rich schist (mrs). “Paragneiss” consisted of biotite-rich schist (brs), greenschist (gs), and kyanite-and/or garnet-bearing schist or biotite schist (k&). “Ortho- or Paragneiss” consisted of biotite-quartz schist (bqs) and biotite-quartz granofels (bqg). “Jointed Gneiss” consisted of biotite-quartz gneiss (bqgn) and greengneiss (ggn). “Amphibolite” consisted of hornblende amphibolite and actinolite amphibolites (A). “Other” consisted of kyanite-bearing granofels (kg), porphyrblastic rock (pbr), quartzite and quartz veins (q), ecoglite-bearing granofels (ebg), and muscovite-rich granofels (mg). The detailed rock types and resulting major groups are illustrated in Figure 7, and are listed in Appendix A. Compositional data are available in Appendix B.

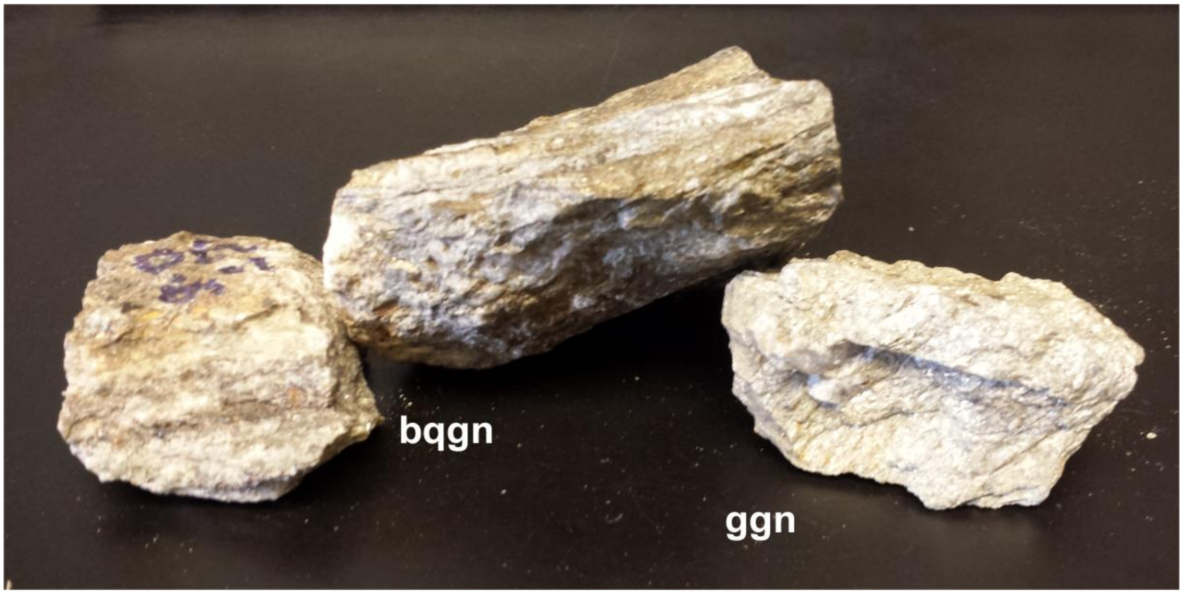
Orthogneiss



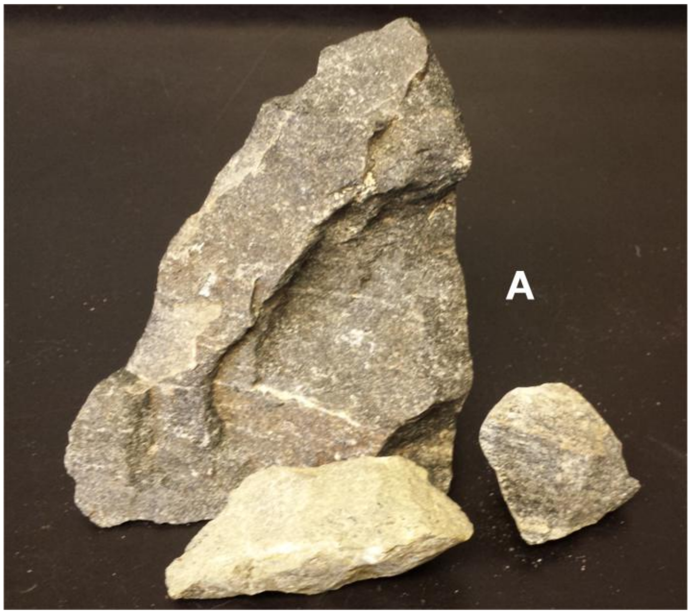
Paragneiss

Ortho- or Paragneiss

Jointed Gneiss



Amphibolite



Other

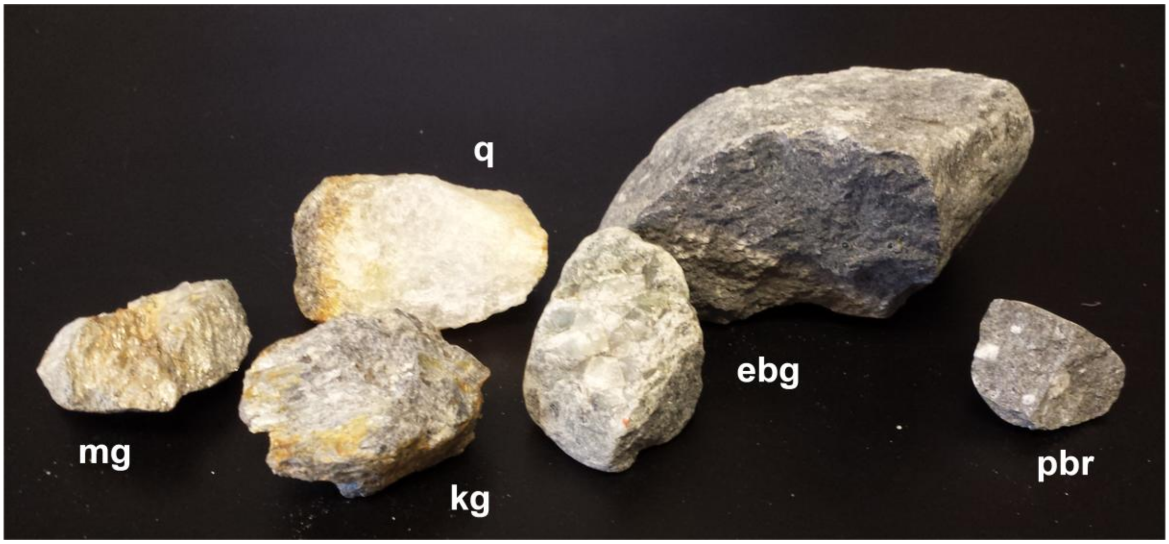
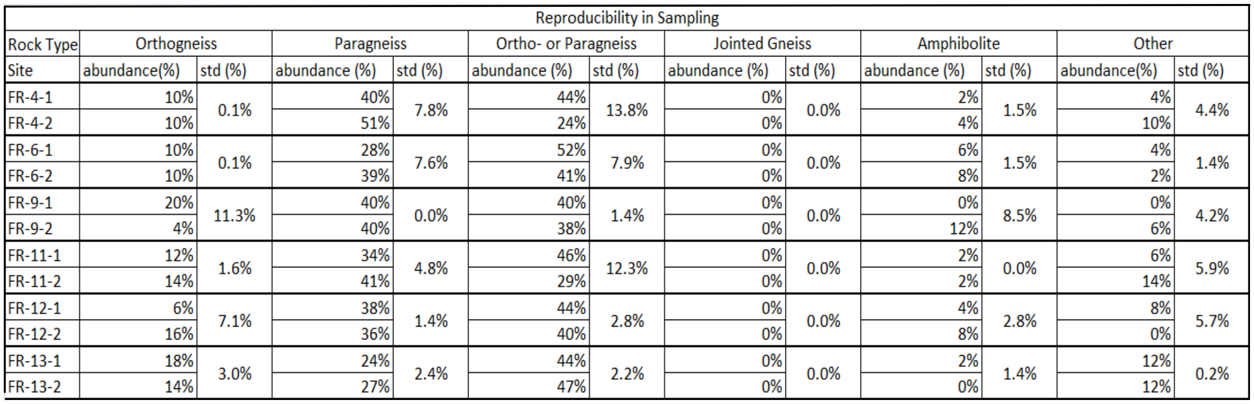


Figure 7: Metamorphic rock identifications – the 15 subtypes clumped into their “parent” bedrock.

Data were input into the R statistical analysis and plotting software and into Excel. Various bar graphs were constructed to examine the distribution of gravel composition. The plots of Paragneiss, Orthogneiss, Both, and Amphibolite were of particular interest. The abundance of each of these components was plotted across all sample sites which is useful for showing changes in gravel composition along the river.

Results

Fifty grains were taken from each sample site along the Fagge River. Six of these sites had an additional 50 grains taken in order to test the reproducibility of sampling. Table 1 lists the abundances of the gravel compositions at each of the six sites sampled twice.



Reproducibility in Sampling

Rock Type	Orthogneiss		Paragneiss		Ortho- or Paragneiss		Jointed Gneiss		Amphibolite		Other	
Site	abundance(%)	std (%)	abundance (%)	std (%)	abundance (%)	std (%)	abundance (%)	std (%)	abundance (%)	std (%)	abundance(%)	std (%)
FR-4-1	10%	0.1%	40%	7.8%	44%	13.8%	0%	0.0%	2%	1.5%	4%	4.4%
FR-4-2	10%		51%		24%		0%		4%		10%	
FR-6-1	10%	0.1%	28%	7.6%	52%	7.9%	0%	0.0%	6%	1.5%	4%	1.4%
FR-6-2	10%		39%		41%		0%		8%		2%	
FR-9-1	20%	11.3%	40%	0.0%	40%	1.4%	0%	0.0%	0%	8.5%	0%	4.2%
FR-9-2	4%		40%		38%		0%		12%		6%	
FR-11-1	12%	1.6%	34%	4.8%	46%	12.3%	0%	0.0%	2%	0.0%	6%	5.9%
FR-11-2	14%		41%		29%		0%		2%		14%	
FR-12-1	6%	7.1%	38%	1.4%	44%	2.8%	0%	0.0%	4%	2.8%	8%	5.7%
FR-12-2	16%		36%		40%		0%		8%		0%	
FR-13-1	18%	3.0%	24%	2.4%	44%	2.2%	0%	0.0%	2%	1.4%	12%	0.2%
FR-13-2	14%		27%		47%		0%		0%		12%	

Table 1: The 6 samples sites that were sampled twice to test reproducibility.

In order to test the reproducibility for each of these sites, an F-test (two-sample for variance) was performed in Excel to determine the appropriate t-test to follow (Table C1). Assuming the null hypothesis (H_0) is true, that the difference in variance between samples at a given site is statistically insignificant, the F value should be greater than the $F_{\text{critical (one-tail)}}$ value. All sites but FR-13 rejected this null hypothesis, prompting the use of a T-test (two samples assuming unequal variance). FR-13 accepted the null hypotheses, encouraging a T-test (two sample assuming equal variance). All sites accepted the null hypothesis (H_0) of no significant difference in the means of the two samples because the $t_{statistical}$ value was less than the $t_{critical\ (two\text{-}tail)}$ value.

Overall Summary (out of 28 samples)				
Lithology	average abundance (%)	standard deviation (%)	max abundance (%) (# of occurances)	min abundance (%) (# of occurances)
Orthogneiss	12%	7%	27% (1)	0% (1)
Paragneiss	34%	11%	51% (1)	9% (1)
Ortho- or Paragneiss	41%	13%	66% (1)	10% (1)
Jointing Gneiss	1%	3%	10% (1)	0% (20)
Amphibolite	6%	5%	20% (1)	0% (5)
Other	6%	4%	14% (1)	0% (3)

Table 2: The table above summarizes abundance data for each rock type for the entire study area.

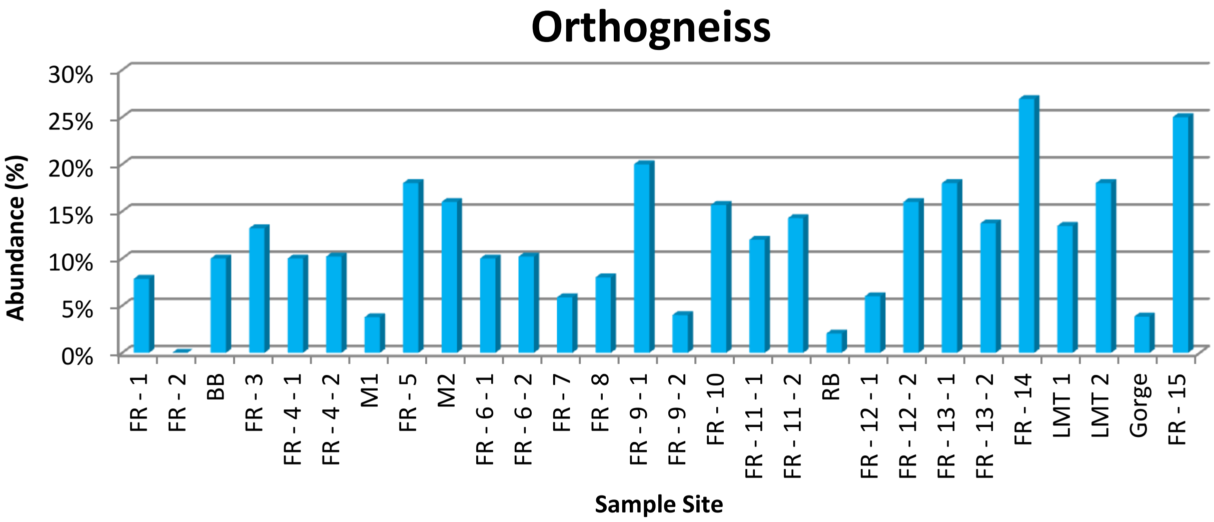
Interval Summary				
FR - 1 through M1 (out of 7 samples)				
Lithology	average abundance (%)	standard deviation (%)	max abundance (%) (# of occurances)	min abundance (%) (# of occurances)
Orthogneiss	8%	5%	13% (1)	0% (1)
Paragneiss	33%	15%	51% (1)	9% (1)
Ortho- or Paragneiss	46%	15%	66% (1)	24% (1)
Jointing Gneiss	2%	3%	7% (1)	0% (4)
Amphibolite	5%	3%	10% (1)	0% (1)
Other	6%	3%	10% (1)	1% (1)
FR - 5 through FR - 11 (out of 11 samples)				
Orthogneiss	12%	5%	20% (1)	4% (1)
Paragneiss	38%	8%	50% (1)	24% (1)
Ortho- or Paragneiss	38%	9%	52% (1)	18% (1)
Jointing Gneiss	1%	1%	4% (1)	0% (8)
Amphibolite	5%	4%	12% (1)	0% (1)
Other	6%	4%	14% (1)	0% (1)
RB through FR - 15 (out of 10 samples)				
Orthogneiss	14%	8%	27% (1)	2% (1)
Paragneiss	31%	10%	46% (1)	13% (1)
Ortho- or Paragneiss	40%	14%	58% (1)	10% (1)
Jointing Gneiss	1%	3%	10% (1)	0% (8)
Amphibolite	7%	7%	20% (1)	0% (3)
Other	6%	5%	12% (2)	0% (2)

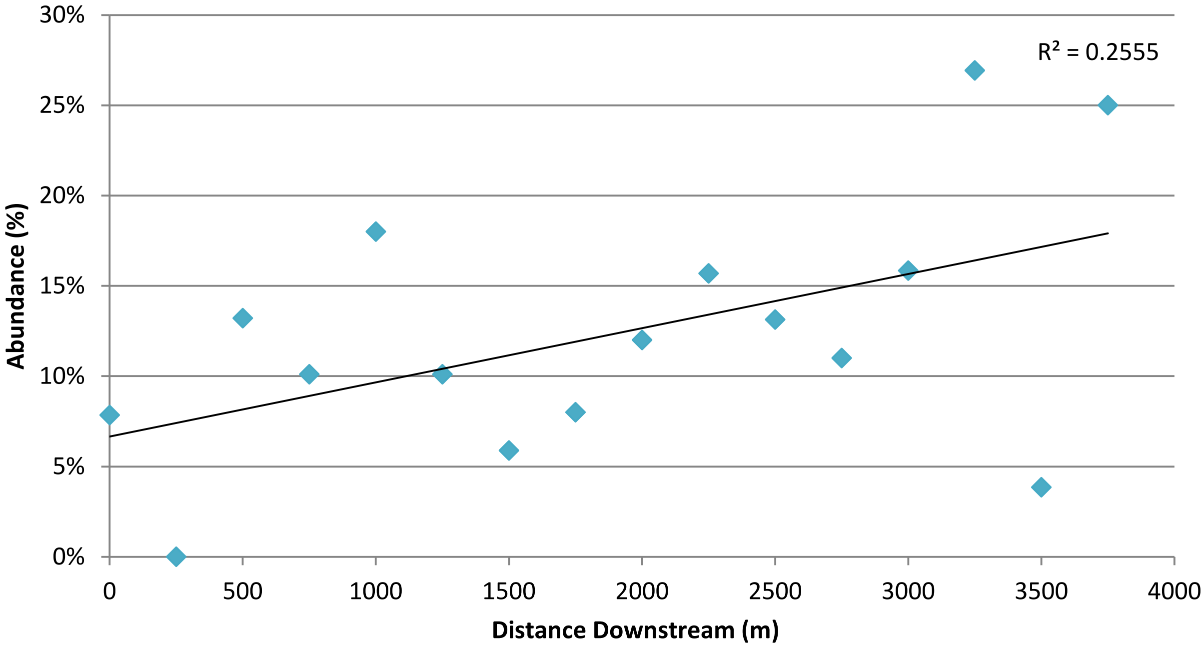
Table 3: The table above summarizes abundance data for each rock type for three portions of the study area: FR-1 though M1, FR-5 through FR-11, and RB through FR-15.

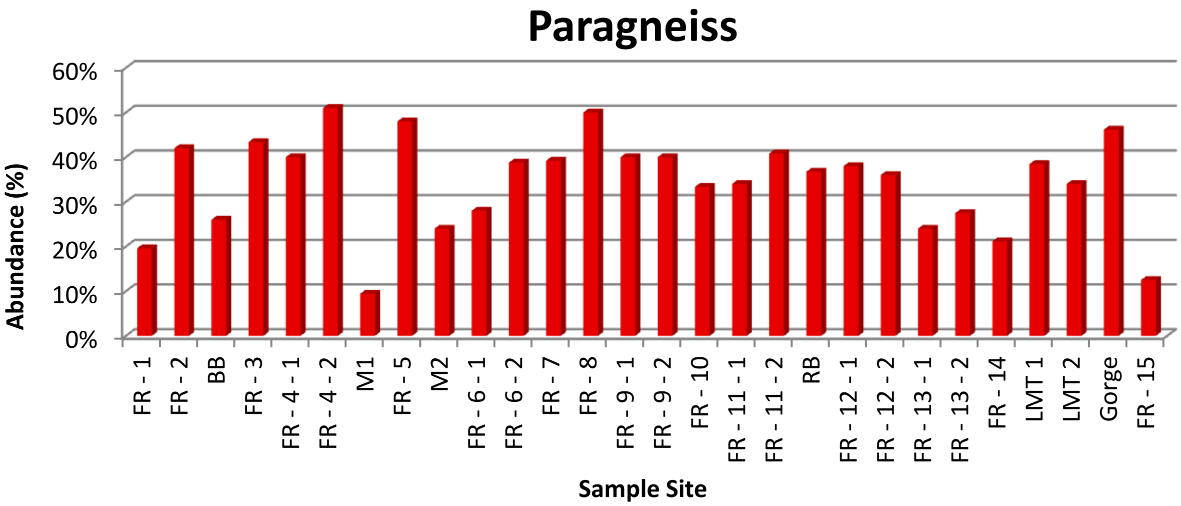
Tables 2 and 3 clearly indicate the gravel composition is dominated by gneiss, “Ortho- or Paragneiss” in particular, which is consistent with the dominance of gneiss in the bedrock of the study site. However, it is impossible to tell whether orthogneiss or paragneiss is more abundant in the gravels within “Ortho- or Paragneiss.” The abundance of “Ortho- or Paragneiss” appears to decrease from the upper portion to the middle portion of the stream, and to increase from the middle portion to the lower portion. In general, as seen in Table 3, the other abundant rock types are “Orthogneiss” and “Paragneiss.” “Paragneiss” appears to decrease from the upper to middle portion, and increase from the middle to lower portion. “Orthogneiss” appears to increase consistently downstream, “Amphibolote” shows no change from the upper to middle portion, “Other” stays relatively constant, and “Jointed Gneiss” is present irregularly.

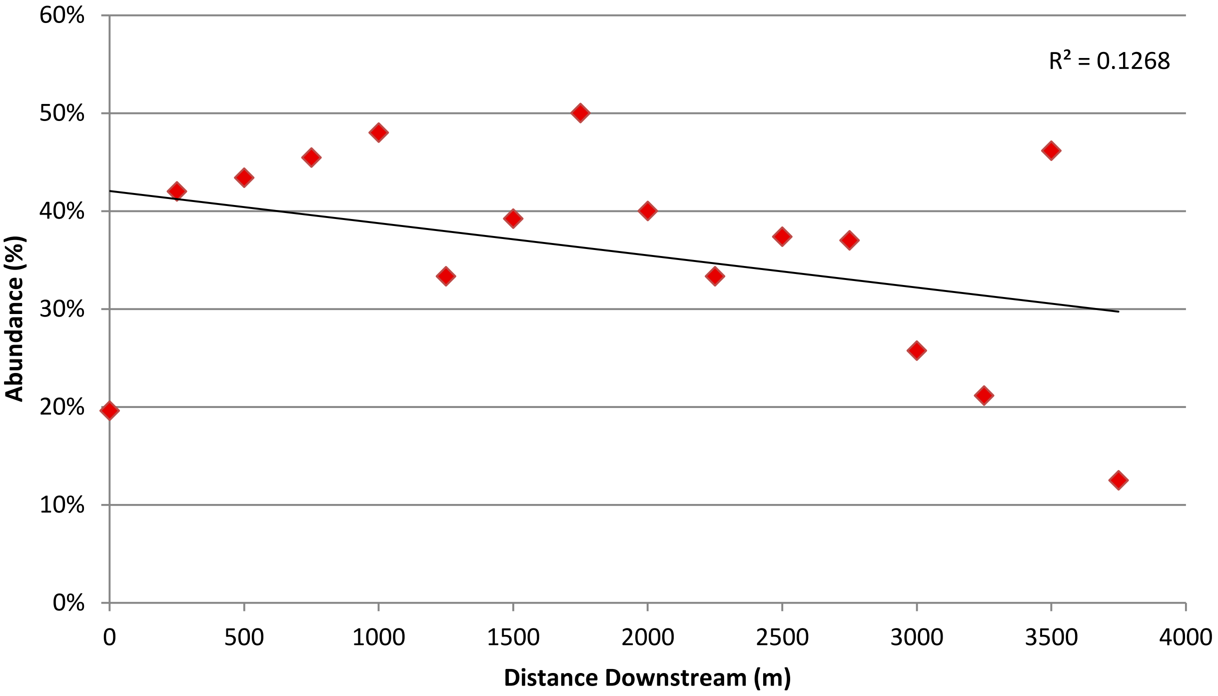
In order to examine the spatial distribution of sediment composition, the abundances of each rock type present at each site are plotted as bar graphs and as scatter plots in Figures 8 and 9. These plots illustrate spatial patterns, such as where a particular rock type is present along the Fagge River, and where the abundances of a rock type change. Figure 9 clearly shows gravel compositions are dominated by gneisses including: “Orthogneiss,” “Paragneiss,” “Ortho- or Paragneiss,” as shown in Tables 2 and 3. “Paragneiss” abundances seem to decrease slightly downstream, but this rock type is certainly important along the entire length of the Fagge River. There is a large supply of Paragneiss from the major tributaries, but not the moraines. “Orthogneiss” appears to show a very gradual increase in abundance downstream with a large supply from M2 and both LMT1 and LMT2. In general, downstream variations in the abundances of “Orthogneiss” and “Paragneiss” suggest compositional breaks at sites M1/FR-5 and FR-11/RB. “Ortho- or Paragneiss” appears to show a very gradual decrease in abundance downstream, similar to what is seen in “Paragneiss.” “Jointed Gneiss” was identified in only 8 locations along the Fagge River, most of which are before the outcrop correlating with this rock type. “Amphibolite” abundances appear to show a general increase downstream with a major contribution from LMT 2, which is located near an outcrop of Amphibolite. The “Other” category also appear to show a general increase downstream, with a very high abundance at FR-11.

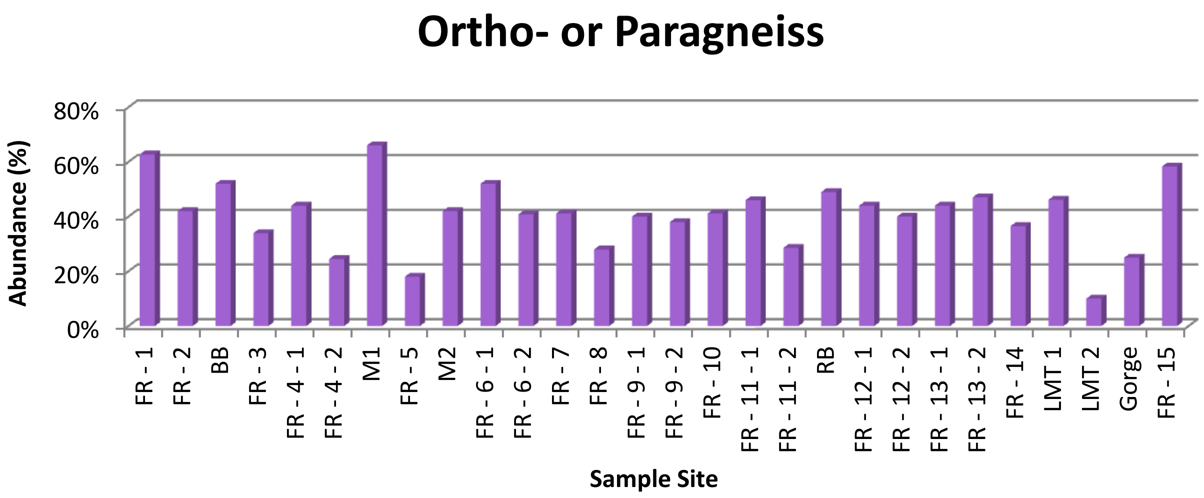
A statistical analysis was done on the “Orthogneiss” and “Paragneiss” scatter plots, which include only the samples from the Fagge River itself, in order to test if the apparent changes discussed above are statistically significant. A T-test was executed assuming the null hypothesis (H_0), that there is no significant trend, is true. If H_0 were to be rejected, where $t_{observation}$ is less than $t_{critical}$, then a T-test would be done on the other rock types. If H_0 were to be accepted, where $t_{observation}$ is greater than $t_{critical}$, then all other trends would be insignificant as these are the two most abundant, and therefore important, rock types and have the steepest slopes. For 15 observations of "Orthogneiss", the null hypothesis was accepted ($t_{observation} = 3.480 > t_{critical} = 2.145$), meaning there is no significant trend. For 15 observations of "Paragneiss", the null hypothesis was accepted ($t_{observation} = 3.097 > t_{critical} = 2.145$), meaning there is no significant trend. No other testing was done to confirm that all other rock types show no significant trends. See Appendix C for statistical summaries.

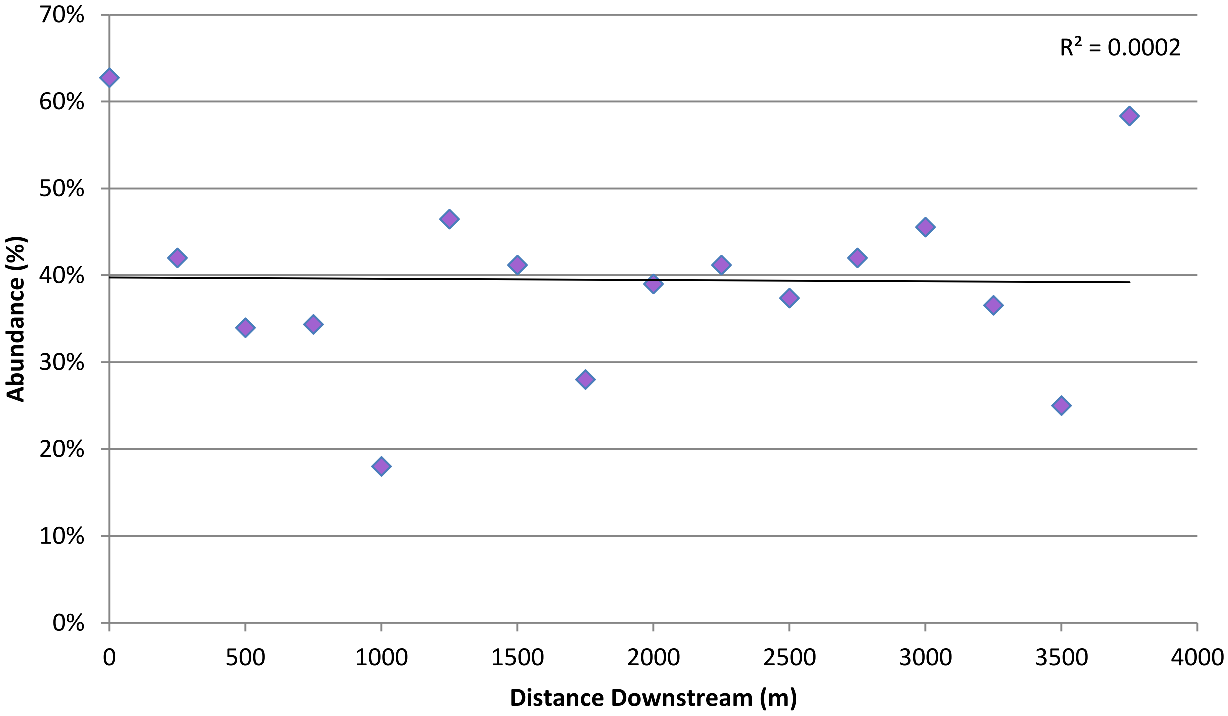

Orthogneiss
Abundance (%)
30%
25%
20%
15%
10%
5%
0%
FR - 1
FR - 2
BB
FR - 3
FR - 4 - 1
FR - 4 - 2
M1
FR - 5
M2
FR - 6 - 1
FR - 6 - 2
FR - 7
FR - 8
FR - 9 - 1
FR - 9 - 2
FR - 10
FR - 11 - 1
FR - 11 - 2
RB
FR - 12 - 1
FR - 12 - 2
FR - 13 - 1
FR - 13 - 2
FR - 14
LMT 1
LMT 2
Gorge
FR - 15
Sample Site

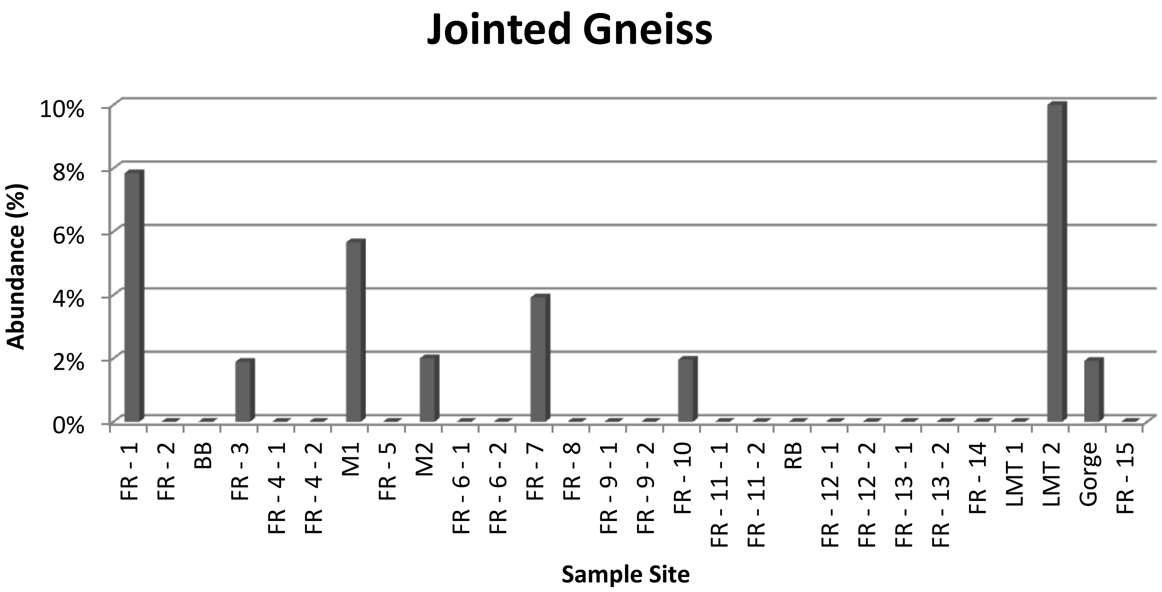

30%
25%
20%
15%
10%
5%
0%
Abundance (%)
R² = 0.2555
0
500
1000
1500
2000
2500
3000
3500
4000
Distance Downstream (m)

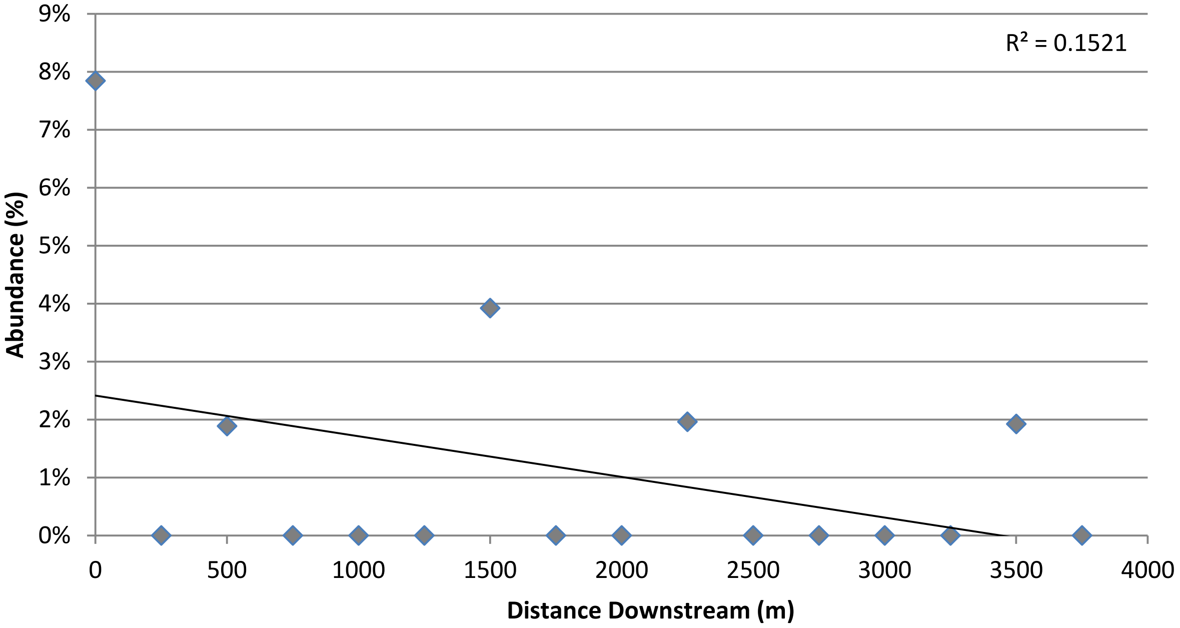

Paragneiss
60%
50%
40%
30%
20%
10%
0%
Abundance (%)
FR - 1
FR - 2
BB
FR - 3
FR - 4 - 1
FR - 4 - 2
M1
FR - 5
M2
FR - 6 - 1
FR - 6 - 2
FR - 7
FR - 8
FR - 9 - 1
FR - 9 - 2
FR - 10
FR - 11 - 1
FR - 11 - 2
RB
FR - 12 - 1
FR - 12 - 2
FR - 13 - 1
FR - 13 - 2
FR - 14
LMT 1
LMT 2
Gorge
FR - 15
Sample Site

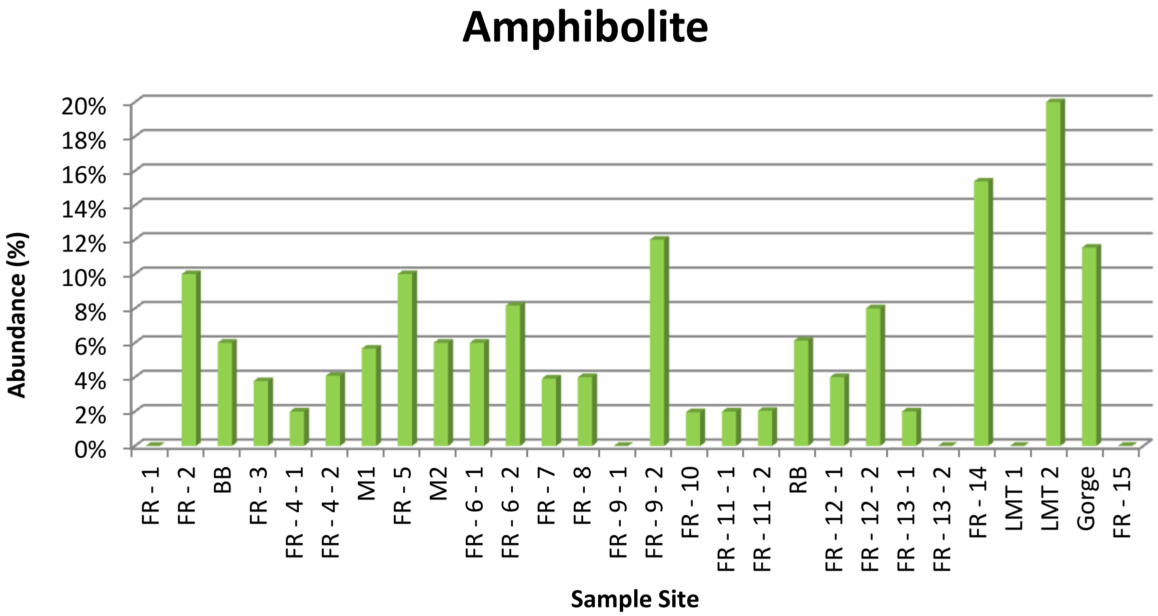

60%
50%
40%
30%
20%
10%
0%
Abundance (%)
R² = 0.1268
0
500
1000
1500
2000
2500
3000
3500
4000
Distance Downstream (m)

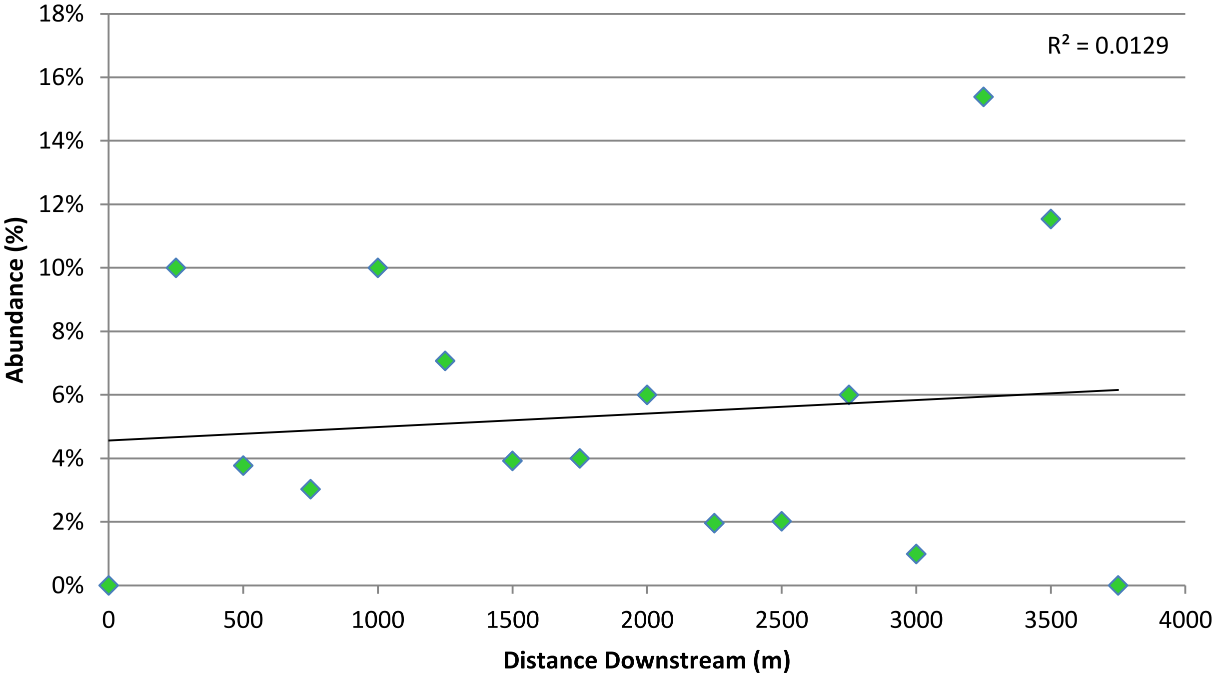

Ortho- or Paragneiss
Abundance (%)
80%
60%
40%
20%
0%
FR - 1
FR - 2
BB
FR - 3
FR - 4 - 1
FR - 4 - 2
M1
FR - 5
M2
FR - 6 - 1
FR - 6 - 2
FR - 7
FR - 8
FR - 9 - 1
FR - 9 - 2
FR - 10
FR - 11 - 1
FR - 11 - 2
RB
FR - 12 - 1
FR - 12 - 2
FR - 13 - 1
FR - 13 - 2
FR - 14
LMT 1
LMT 2
Gorge
FR - 15
Sample Site

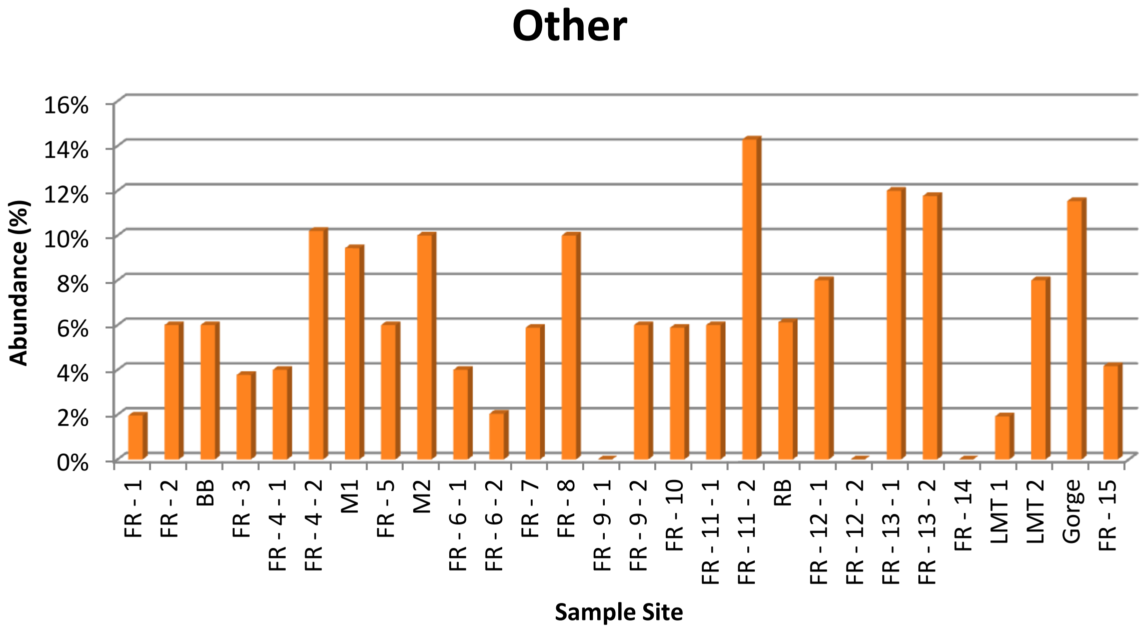

70%
60%
50%
40%
30%
20%
10%
0%
Abundance (%)
R² = 0.0002
0
500
1000
1500
2000
2500
3000
3500
4000
Distance Downstream (m)


Jointed Gneiss
Abundance (%)
10%
8%
6%
4%
2%
0%
FR - 1
FR - 2
BB
FR - 3
FR - 4 - 1
FR - 4 - 2
M1
FR - 5
M2
FR - 6 - 1
FR - 6 - 2
FR - 7
FR - 8
FR - 9 - 1
FR - 9 - 2
FR - 10
FR - 11 - 1
FR - 11 - 2
RB
FR - 12 - 1
FR - 12 - 2
FR - 13 - 1
FR - 13 - 2
FR - 14
LMT 1
LMT 2
Gorge
FR - 15
Sample Site


R² = 0.1521
Abundance (%)
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
0
500
1000
1500
2000
2500
3000
3500
4000
Distance Downstream (m)


Amphibolite
Abundance (%)
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
FR - 1
FR - 2
BB
FR - 3
FR - 4 - 1
FR - 4 - 2
M1
FR - 5
M2
FR - 6 - 1
FR - 6 - 2
FR - 7
FR - 8
FR - 9 - 1
FR - 9 - 2
FR - 10
FR - 11 - 1
FR - 11 - 2
RB
FR - 12 - 1
FR - 12 - 2
FR - 13 - 1
FR - 13 - 2
FR - 14
LMT 1
LMT 2
Gorge
FR - 15
Sample Site


R² = 0.0129
Abundance (%)
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
0
500
1000
1500
2000
2500
3000
3500
4000
Distance Downstream (m)



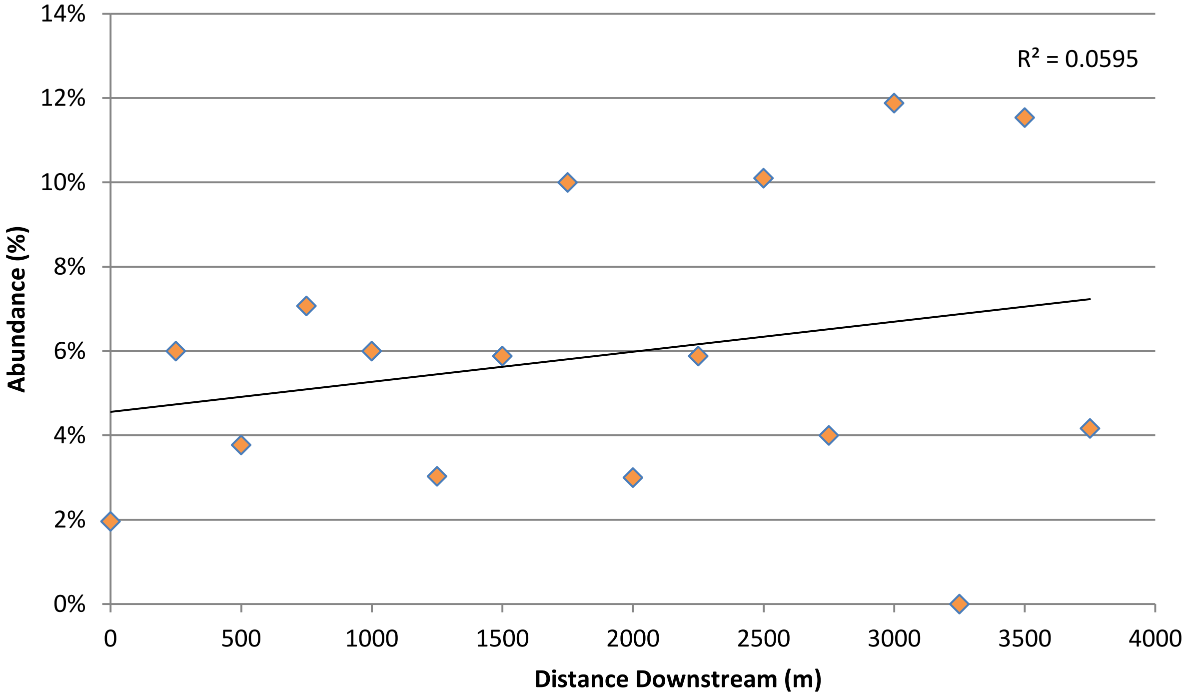


Figure 8: The percentage of each rock type at each site. There are 28 sample sites represented in the x-axis of the bar plots (in geographical order, with sample FR-1 being at the upstream end of the study area and sample FR-15 at the downstream end). These include the samples taken from moraines and major tributaries. The x-axis of the scatter plots describe distance in meters downstream assuming each study site is 250m apart from each other. The scatter plot only includes samples taken along the Fagge River (samples FR-1 through FR-15, plus the Gorge sample).

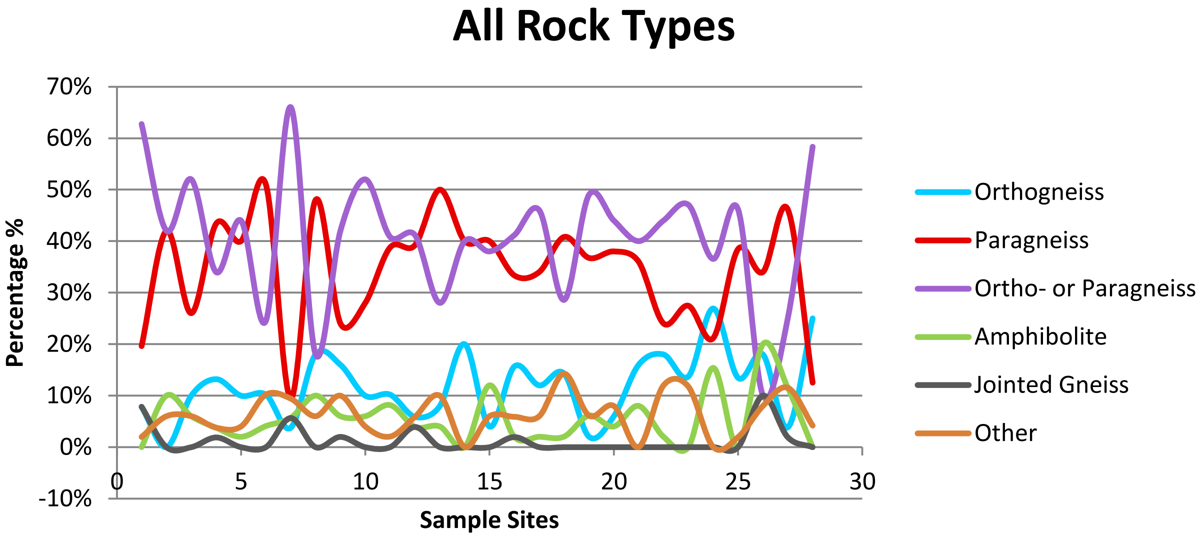


Figure 9: The above diagram show the percentage of each rock type present in a site for all rock types.

Discussion

The geologic map for this region shows that the bedrock in the study site is dominated by gneiss, and by paragneiss in particular (Figure 3). Analysis of the gravel samples shows that the gravel for this region is also dominated by gneiss, which is consistent with the bedrock geology and local derivation of the gravels. There is also a dominance of "Ortho- or Paragneiss" in the gravel composition. This was the group in which it was not possible to determine whether the grains originally were orthogneiss or paragneiss. This type of uncertainty is a common problem in this type of study. Lindsey et al. (2007) and Plumley (1948) both described difficulties differentiating similar rock types and clumped their rock classifications. I would predict that the grains identified to be "Ortho- or Paragneiss" are mostly "Paragneiss" because identifiable paragneiss is much more abundant than identifiable orthogneiss. The alternative would be that orthogneiss weathers more quickly than paragneiss, so that the unidentifiable gneisses would have originally been orthogneiss. It is difficult to say which of these explanations is correct.

As seen in Figure 8, “Orthogneiss,” “Amphibolite,” and “Other” became somewhat more abundant downstream, while “Paragneiss,” “Ortho- or Paragneiss” and “Jointed Gneiss” are still present. This confirms that the gravel population becomes more diverse downstream.

I found that there were no significant trends in the abundances of any gravel lithology along the ~4 km long Fagge River. This matches the findings of Lindsey et al. (2007) and Plumley (1948), who demonstrated that transport distances of 10 km or more were needed to develop significant changes in lithologic abundances. This could be for reasons described below.

One reason could be the size of the drainage basin. Lindsey et al. (2007) collected gravel samples from tributary fans and terraces of the Santa Cruz River in Arizona as well as from terraces of the Wind River in Wyoming, of which were formed in response to climate change. Fan and terrace deposits from the Santa Cruz River extended approximately 5-10 km, and pebble lithologies remained uniform downstream. The Wind River terraces extend approximately 120 km downstream, but differences in lithologic proportions downstream are minor. Plumley (1948) collected terrace gravels from three creeks in the Black Hills, and found that hard lithologies show little change in abundance ~16 km downstream or farther. These projects found that changes in the abundances of hard lithologies were not observed until at least 15 km downstream, suggesting that the Fagge River is too short to see effects of transport.

Another reason could be the bedrock diversity and the bedrock distribution within the basin. After creating an overall summary table (Tables 2 and 3), I was able to compare the average abundance, maximum and minimum abundance, and standard deviations of each group. I found there were two groups: 3 important lithologies (“Parageniss,” “Orthogneiss” and “Ortho- or Paragneiss”) and 3 less important lithologies (“Amphibolite,” “Jointed Gneiss” and “Other”). The 3 most important lithologies are the most important bedrock lithologies, which are gneisses. This demonstrates that the bedrock has low lithologic diversity. The absence of abundance trends may be influenced by the distribution of relatively similar bedrock across the basin since the initial abundance of a lithology within the gravel is directly related to the location of its source (Plumley, 1948). The various lithologies continue to appear downvalley in the bedrock, thus feeding the Fagge River a relatively consistent composition of gravels along its length.

Not only is the bedrock diversity low, but the range of bedrock hardness is limited. Lindsey et al. (2007) and Plumley (1948) worked in areas containing both hard and soft lithologies, for example gneiss vs. sandstone. They both found that soft rocks showed a quicker response to downstream abrasion thus decreasing in abundance downstream at a faster rate than hard rocks. Plumley (1948) clumped his metamorphic rocks together suggesting they had similar hardness values and thus had similar responses to downstream transport. The study area for this project contained only metamorphic rocks, all of which have similar hardness, which could limit the effects of differential abrasion on lithologic abundances downstream.

Lastly, the identification methods used in this study could potentially limit the ability to recognize subtle compositional changes. All samples were identified megascopically with the use of a hand lens, which made it difficult to differentiate gneisses. This difficulty motivated use of the clumped "Ortho- or Paragneiss" group. It is also possible that "Jointed Gneiss" and "Orthogneiss" should have been clumped together. "Jointed Gneiss" was identified in only 8 locations along the Fagge River, most of which are above the outcrop of "Jointed Gneiss." This positioning may indicate that the outcrop of "Jointed Gneiss" was actually another outcrop of orthogneiss that was not glacially polished. Grouping lithologies is one way to approach this issue, and is common among similar studies. Another more accurate method would be to use a petrographic microscope when identifying and differentiating between rock types. Both methods were used by Plumley (1948) who found that sometimes it was necessary to use a petrographic microscope for identification as some grains were impossible to identify with only a hand lens. Microscope petrography would have been useful for distinguishing the gneisses, but the limitations of this study did not allow me to use this method.

Despite these difficulties, gravel composition became more diverse downstream which is consistent with the exposure of new bedrock types downstream and a transport distance that is too short for any grain selection by differential abrasion. The dominance of paragneiss in the gravel compositions is consistent with the dominance of paragneiss in the surrounding bedrock. This study confirms the results and limitations found by Lindsey et al. (2007) and Plumley (1948) when working in a small drainage basin.

Conclusions

- In the study, both the surrounding bedrock and gravels within the Fagge River are dominated by gneisses. After extensive examination of all samples collected, 15 rock subtypes were identified that were subsequently clumped into 6 main groups: “Orthogneiss,” “Paragneiss,” “Ortho- or Paragneiss,” “Jointed Gneiss,” “Amphibolite,” and “Other”.

- The Kaunertal valley is 62.54 km^2 and the drainage basin is only ~4 km in length with a very low bedrock diversity, making this study site too small and the sediment supply is too compositionally uniform to see well-defined changes in gravel composition downstream.

- Results showed that the most abundant gravel compositions are “Orthogneiss,” “Paragneiss” and “Ortho- or Paragneiss.” Any compositional changes observed are poorly defined downstream and there are no statistically significant trends.

- “Orthogneiss,” “Amphibolite,” and “Other” became somewhat more abundant downstream, while “Paragneiss,” “Ortho- or Paragneiss” and “Jointed Gneiss” are still present. This means that the gravel population becomes more diverse downstream.

Suggestions for future work

Overall, this project was very helpful in developing me as a research assistant. I was given the chance to form my own research project and determine how to collect and analyze my own data. I was made aware of all things that need to be considered when forming a project. For example, for this project it was pertinent that I knew the physical and or logistical constraints on the work I can do and the data I can collect, how large of a drainage basin I was working in, the variety in the surrounding bedrock and how well the bedrock was mapped in the study site.

Physical constraints could be frequent changes in weather and how that may affect the discharge of the stream which affects the accessibility of the stream or the hiking path itself. Logistical constraints could be the amount of people helping in the field, the size of our backpacks, and the amount of weight one can carry, or how rocks are identified. For this project, the composition of each grain was determined by visual examination with a hand lens, using a standard rock identification chart from Schmid et al (2007). The size of the drainage basin is needed to be known in order to figure out how many and how frequently samples should be taken. The bedrock diversity is important to know to get an idea of what you should expect in your samples, how much variation you should expect in your data, and how too much or too little diversity can affect your data. Study sites that are well mapped are very helpful when thinking of the geologic background of the area, locations of lithology changes in the bedrock, locations of major moraines or tributaries to the drainage basin, and so on.

Before this project, I was unaware of the steps needed to be taken to form a project as in my previous research experiences, data was already collected and handed to me to analyze. I learned a lot from this project from of taking good field notes to help you with interpretations later in the lab to thinking of all the things you must know before approaching your project in the field or the lab.

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Appendices

Appendix A: Rock Identifications

Rock Types	
Abbrev.	Name
A	Amphibolite
bqg	biotite-quartz granofels
bqgn	biotite-quartz gneiss
bqs	biotite-quartz schist
brs	biotite-rich schist
ebg	ecoglite?-biotite granofels
ggn	green gneiss
gs	green schist
k&	kyanite-bearing-biotite, garnet-bearing-biotite or biotite schist
kg	kyanite-bearing granofels
mg	muscovite-rich granofels
mpo	muscovite-plagioclase orthogneiss
mrs	muscovite-rich schist
pbr	porphyroblastic rock
q	quartzite or quartz veins

Table A1: The table above lists the 15 subtypes of rocks in the field site.

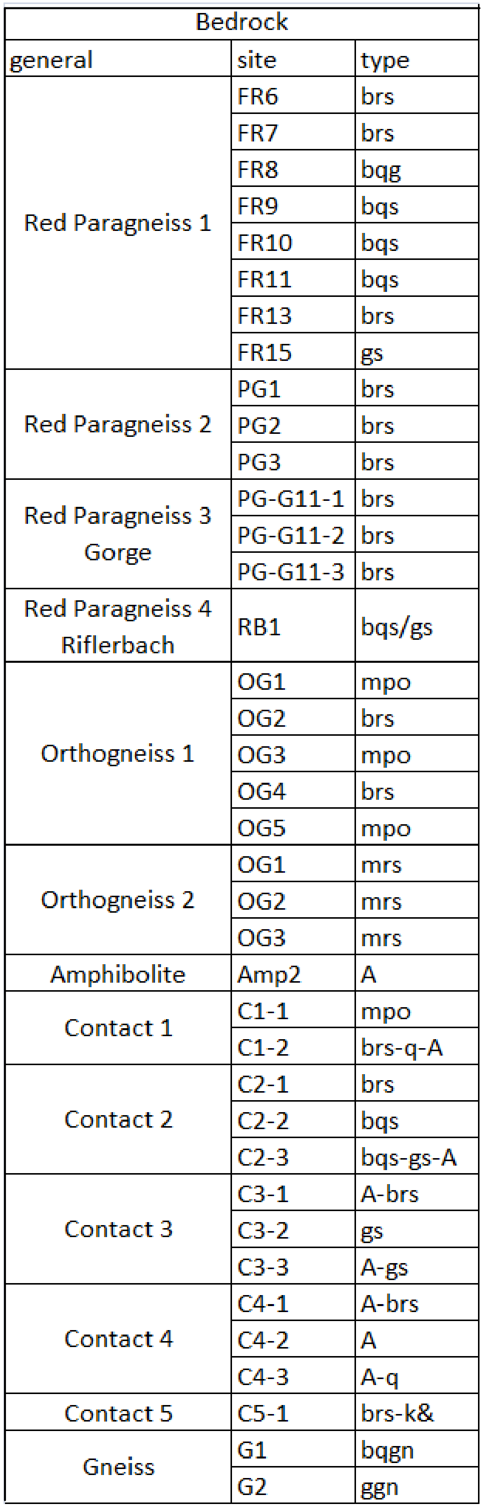
Rock Groups:

Orthogneiss	Paragneiss	Ortho- or Paragneiss	Jointed Gneiss	Amphibolite	Other
mpo	brs	bqs	bqgn	A	kg
mrs	gs	bqg	ggn	-	pbr
-	k&	-	-	-	q
-	-	-	-	-	ebg
-	-	-	-	-	mg

Table A2: The table above shows how the 15 subtypes were subdivided into their “parent” rock type.

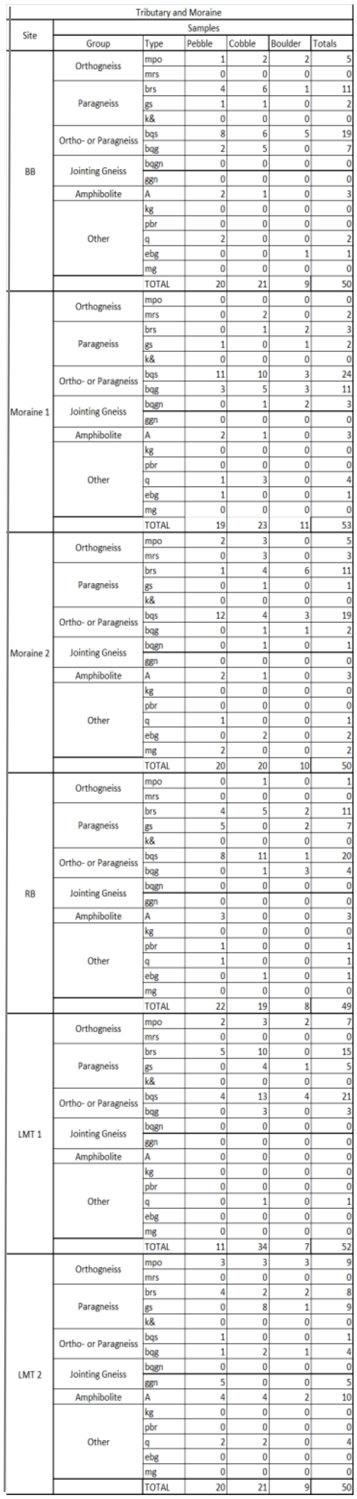
Appendix B: Bedrock, Fagge River, Major Tributary and Moraine Sample Site Data Collection

Bedrock Samples:



Bedrock		
general	site	type
Red Paragneiss 1	FR6	brs
	FR7	brs
	FR8	bqg
	FR9	bqs
	FR10	bqs
	FR11	bqs
	FR13	brs
	FR15	gs
Red Paragneiss 2	PG1	brs
	PG2	brs
	PG3	brs
Red Paragneiss 3 Gorge	PG-G11-1	brs
	PG-G11-2	brs
	PG-G11-3	brs
Red Paragneiss 4 Riflerbach	RB1	bqs/gs
Orthogneiss 1	OG1	mpo
	OG2	brs
	OG3	mpo
	OG4	brs
	OG5	mpo
Orthogneiss 2	OG1	mrs
	OG2	mrs
	OG3	mrs
Amphibolite	Amp2	A
Contact 1	C1-1	mpo
	C1-2	brs-q-A
Contact 2	C2-1	brs
	C2-2	bqs
	C2-3	bqs-gs-A
Contact 3	C3-1	A-brs
	C3-2	gs
	C3-3	A-gs
Contact 4	C4-1	A-brs
	C4-2	A
	C4-3	A-q
Contact 5	C5-1	brs-k&
Gneiss	G1	bqgn
	G2	ggn

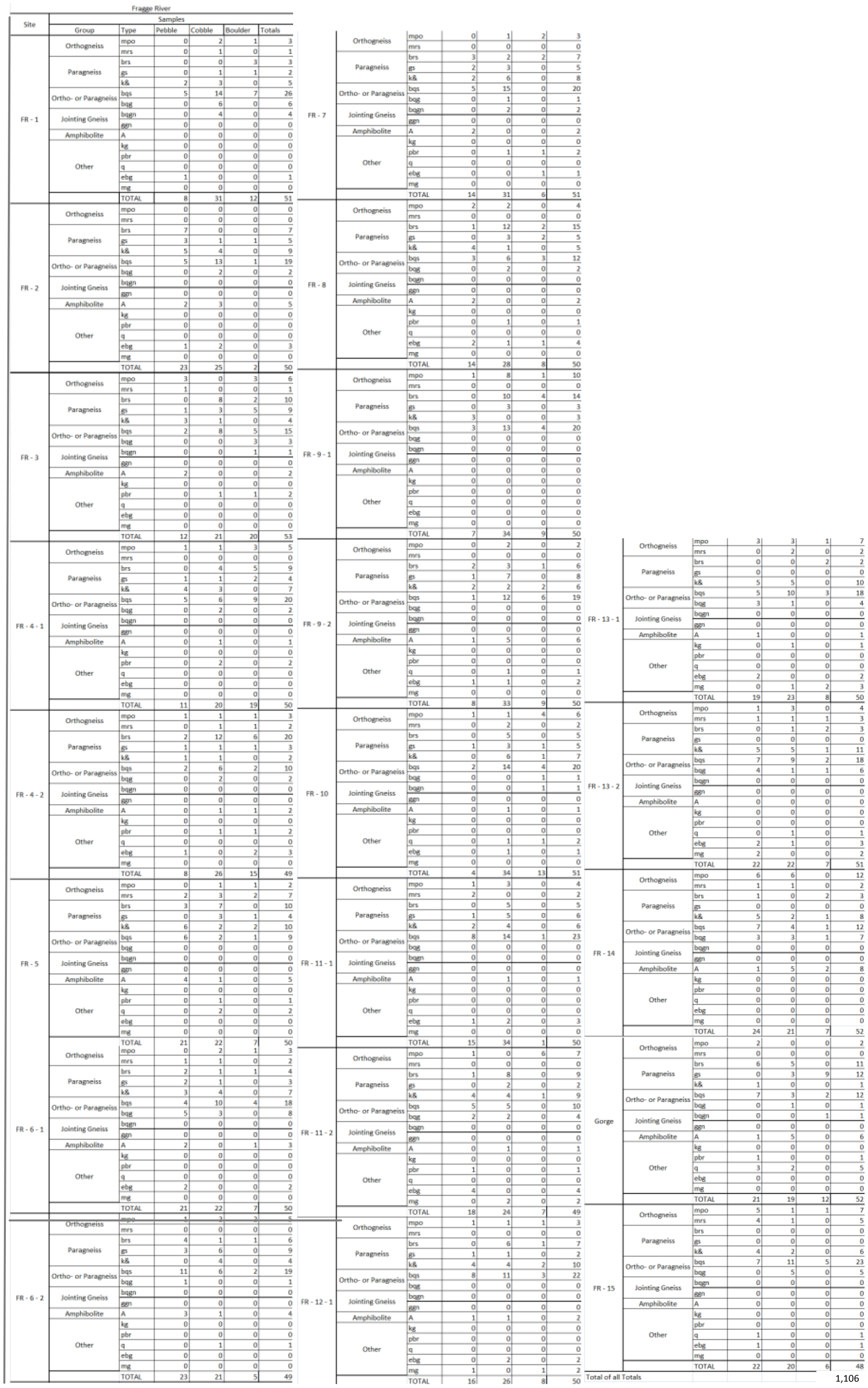
Tributary and Moraine Samples:



Tributary and Moraine						
Site	Samples					
	Group	Type	Pebble	Cobble	Boulder	Totals
BB	Orthogneiss	mpo	1	2	2	5
		mrs	0	0	0	0
	Paragneiss	brs	4	6	1	11
		gs	1	1	0	2
		k&	0	0	0	0
	Ortho- or Paragneiss	bqs	8	6	5	19
		bqg	2	5	0	7
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	2	1	0	3
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	2	0	0	2
		ebg	0	0	1	1
		mg	0	0	0	0
		TOTAL	20	21	9	50
Moraine 1	Orthogneiss	mpo	0	0	0	0
		mrs	0	2	0	2
	Paragneiss	brs	0	1	2	3
		gs	1	0	1	2
		k&	0	0	0	0
	Ortho- or Paragneiss	bqs	11	10	3	24
		bqg	3	5	3	11
	Jointing Gneiss	bqgn	0	1	2	3
		ggn	0	0	0	0
	Amphibolite	A	2	1	0	3
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	1	3	0	4
		ebg	1	0	0	1
		mg	0	0	0	0
		TOTAL	19	23	11	53
Moraine 2	Orthogneiss	mpo	2	3	0	5
		mrs	0	3	0	3
	Paragneiss	brs	1	4	6	11
		gs	0	1	0	1
		k&	0	0	0	0
	Ortho- or Paragneiss	bqs	12	4	3	19
		bqg	0	1	1	2
	Jointing Gneiss	bqgn	0	1	0	1
		ggn	0	0	0	0
	Amphibolite	A	2	1	0	3
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	1	0	0	1
		ebg	0	2	0	2
		mg	2	0	0	2
		TOTAL	20	20	10	50
RB	Orthogneiss	mpo	0	1	0	1
		mrs	0	0	0	0
	Paragneiss	brs	4	5	2	11
		gs	5	0	2	7
		k&	0	0	0	0
	Ortho- or Paragneiss	bqs	8	11	1	20
		bqg	0	1	3	4
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	3	0	0	3
	Other	kg	0	0	0	0
		pbr	1	0	0	1
		q	1	0	0	1
		ebg	0	1	0	1
		mg	0	0	0	0
		TOTAL	22	19	8	49
LMT 1	Orthogneiss	mpo	2	3	2	7
		mrs	0	0	0	0
	Paragneiss	brs	5	10	0	15
		gs	0	4	1	5
		k&	0	0	0	0
	Ortho- or Paragneiss	bqs	4	13	4	21
		bqg	0	3	0	3
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	0	0	0	0
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	1	0	1
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	11	34	7	52
LMT 2	Orthogneiss	mpo	3	3	3	9
		mrs	0	0	0	0
	Paragneiss	brs	4	2	2	8
		gs	0	8	1	9
		k&	0	0	0	0
	Ortho- or Paragneiss	bqs	1	0	0	1
		bqg	1	2	1	4
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	5	0	0	5
	Amphibolite	A	4	4	2	10
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	2	2	0	4
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	20	21	9	50

Tables B1 and B2: The tables above list the bedrock, major tributary and moraine sample sites and rock classifications.

Fagge River Samples:

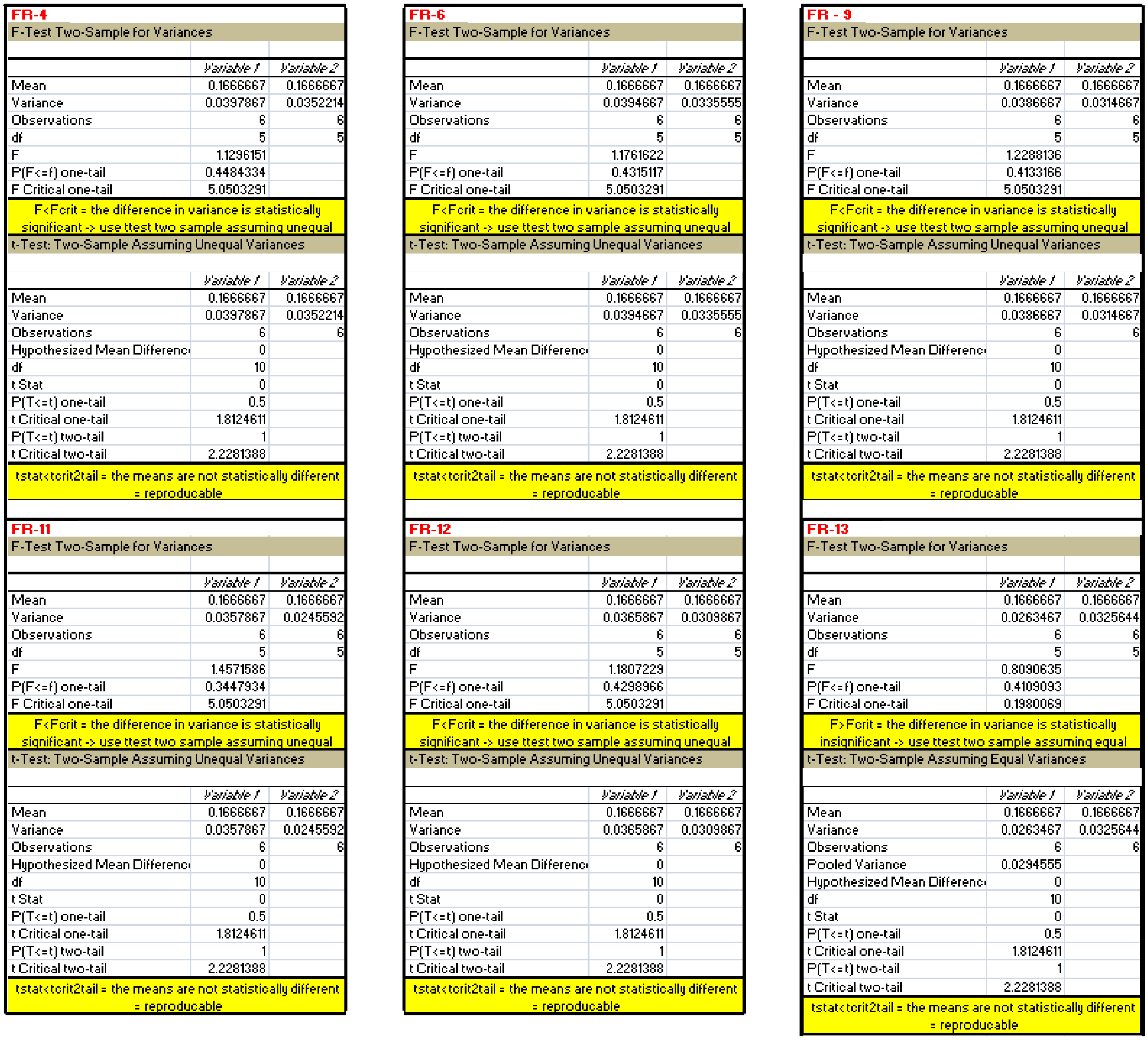


Fragge River

Site	Samples					
	Group	Type	Pebble	Cobble	Boulder	Totals
FR - 1	Orthogneiss	mpo	0	2	1	3
		mrs	0	1	0	1
	Paragneiss	brs	0	0	3	3
		gs	0	1	1	2
		k&	2	3	0	5
	Ortho- or Paragneiss	bqs	5	14	7	26
		bqg	0	6	0	6
	Jointing Gneiss	bqgn	0	4	0	4
		ggn	0	0	0	0
	Amphibolite	A	0	0	0	0
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	0	0	0
		ebg	1	0	0	1
		mg	0	0	0	0
		TOTAL	8	31	12	51
FR - 2	Orthogneiss	mpo	0	0	0	0
		mrs	0	0	0	0
	Paragneiss	brs	7	0	0	7
		gs	3	1	1	5
		k&	5	4	0	9
	Ortho- or Paragneiss	bqs	5	13	1	19
		bqg	0	2	0	2
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	2	3	0	5
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	0	0	0
		ebg	1	2	0	3
		mg	0	0	0	0
		TOTAL	23	25	2	50
FR - 3	Orthogneiss	mpo	3	0	3	6
		mrs	1	0	0	1
	Paragneiss	brs	0	8	2	10
		gs	1	3	5	9
		k&	3	1	0	4
	Ortho- or Paragneiss	bqs	2	8	5	15
		bqg	0	0	3	3
	Jointing Gneiss	bqgn	0	0	1	1
		ggn	0	0	0	0
	Amphibolite	A	2	0	0	2
	Other	kg	0	0	0	0
		pbr	0	1	1	2
		q	0	0	0	0
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	12	21	20	53
FR - 4 - 1	Orthogneiss	mpo	1	1	3	5
		mrs	0	0	0	0
	Paragneiss	brs	0	4	5	9
		gs	1	1	2	4
		k&	4	3	0	7
	Ortho- or Paragneiss	bqs	5	6	9	20
		bqg	0	2	0	2
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	0	1	0	1
	Other	kg	0	0	0	0
		pbr	0	2	0	2
		q	0	0	0	0
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	11	20	19	50
FR - 4 - 2	Orthogneiss	mpo	1	1	1	3
		mrs	0	1	1	2
	Paragneiss	brs	2	12	6	20
		gs	1	1	1	3
		k&	1	1	0	2
	Ortho- or Paragneiss	bqs	2	6	2	10
		bqg	0	2	0	2
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	0	1	1	2
	Other	kg	0	0	0	0
		pbr	0	1	1	2
		q	0	0	0	0
		ebg	1	0	2	3
		mg	0	0	0	0
		TOTAL	8	26	15	49
FR - 5	Orthogneiss	mpo	0	1	1	2
		mrs	2	3	2	7
	Paragneiss	brs	3	7	0	10
		gs	0	3	1	4
		k&	6	2	2	10
	Ortho- or Paragneiss	bqs	6	2	1	9
		bqg	0	0	0	0
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	4	1	0	5
	Other	kg	0	0	0	0
		pbr	0	1	0	1
		q	0	2	0	2
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	21	22	7	50
FR - 6 - 1	Orthogneiss	mpo	0	2	1	3
		mrs	1	1	0	2
	Paragneiss	brs	2	1	1	4
		gs	2	1	0	3
		k&	3	4	0	7
	Ortho- or Paragneiss	bqs	4	10	4	18
		bqg	5	3	0	8
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	2	0	1	3
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	0	0	0
		ebg	2	0	0	2
		mg	0	0	0	0
		TOTAL	21	22	7	50
FR - 6 - 2	Orthogneiss	mpo	1	2	2	5
		mrs	0	0	0	0
	Paragneiss	brs	4	1	1	6
		gs	3	6	0	9
		k&	0	4	0	4
	Ortho- or Paragneiss	bqs	11	6	2	19
		bqg	1	0	0	1
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	3	1	0	4
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	1	0	1
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	23	21	5	49
FR - 7	Orthogneiss	mpo	0	1	2	3
		mrs	0	0	0	0
	Paragneiss	brs	3	2	2	7
		gs	2	3	0	5
		k&	2	6	0	8
	Ortho- or Paragneiss	bqs	5	15	0	20
		bqg	0	1	0	1
	Jointing Gneiss	bqgn	0	2	0	2
		ggn	0	0	0	0
	Amphibolite	A	2	0	0	2
	Other	kg	0	0	0	0
		pbr	0	1	1	2
		q	0	0	0	0
		ebg	0	0	1	1
		mg	0	0	0	0
		TOTAL	14	31	6	51
FR - 8	Orthogneiss	mpo	2	2	0	4
		mrs	0	0	0	0
	Paragneiss	brs	1	12	2	15
		gs	0	3	2	5
		k&	4	1	0	5
	Ortho- or Paragneiss	bqs	3	6	3	12
		bqg	0	2	0	2
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	2	0	0	2
	Other	kg	0	0	0	0
		pbr	0	1	0	1
		q	0	0	0	0
		ebg	2	1	1	4
		mg	0	0	0	0
		TOTAL	14	28	8	50
FR - 9 - 1	Orthogneiss	mpo	1	8	1	10
		mrs	0	0	0	0
	Paragneiss	brs	0	10	4	14
		gs	0	3	0	3
		k&	3	0	0	3
	Ortho- or Paragneiss	bqs	3	13	4	20
		bqg	0	0	0	0
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	0	0	0	0
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	0	0	0
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	7	34	9	50
FR - 9 - 2	Orthogneiss	mpo	0	2	0	2
		mrs	0	0	0	0
	Paragneiss	brs	2	3	1	6
		gs	1	7	0	8
		k&	2	2	2	6
	Ortho- or Paragneiss	bqs	1	12	6	19
		bqg	0	0	0	0
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	1	5	0	6
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	1	0	1
		ebg	1	1	0	2
		mg	0	0	0	0
		TOTAL	8	33	9	50
FR - 10	Orthogneiss	mpo	1	1	4	6
		mrs	0	2	0	2
	Paragneiss	brs	0	5	0	5
		gs	1	3	1	5
		k&	0	6	1	7
	Ortho- or Paragneiss	bqs	2	14	4	20
		bqg	0	0	1	1
	Jointing Gneiss	bqgn	0	0	1	1
		ggn	0	0	0	0
	Amphibolite	A	0	1	0	1
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	1	1	2
		ebg	0	1	0	1
		mg	0	0	0	0
		TOTAL	4	34	13	51
FR - 11 - 1	Orthogneiss	mpo	1	3	0	4
		mrs	2	0	0	2
	Paragneiss	brs	0	5	0	5
		gs	1	5	0	6
		k&	2	4	0	6
	Ortho- or Paragneiss	bqs	8	14	1	23
		bqg	0	0	0	0
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	0	1	0	1
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	0	0	0
		ebg	1	2	0	3
		mg	0	0	0	0
		TOTAL	15	34	1	50
FR - 11 - 2	Orthogneiss	mpo	1	0	6	7
		mrs	0	0	0	0
	Paragneiss	brs	1	8	0	9
		gs	0	2	0	2
		k&	4	4	1	9
	Ortho- or Paragneiss	bqs	5	5	0	10
		bqg	2	2	0	4
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	0	1	0	1
	Other	kg	0	0	0	0
		pbr	1	0	0	1
		q	0	0	0	0
		ebg	4	0	0	4
		mg	0	2	0	2
		TOTAL	18	24	7	49
FR - 12 - 1	Orthogneiss	mpo	1	1	1	3
		mrs	0	0	0	0
	Paragneiss	brs	0	6	1	7
		gs	1	1	0	2
		k&	4	4	2	10
	Ortho- or Paragneiss	bqs	8	11	3	22
		bqg	0	0	0	0
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	1	1	0	2
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	0	0	0
		ebg	0	2	0	2
		mg	1	0	1	2
		TOTAL	16	26	8	50
FR - 13 - 1	Orthogneiss	mpo	3	3	1	7
		mrs	0	2	0	2
	Paragneiss	brs	0	0	2	2
		gs	0	0	0	0
		k&	5	5	0	10
	Ortho- or Paragneiss	bqs	5	10	3	18
		bqg	3	1	0	4
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	1	0	0	1
	Other	kg	0	1	0	1
		pbr	0	0	0	0
		q	0	0	0	0
		ebg	2	0	0	2
		mg	0	1	2	3
		TOTAL	19	23	8	50
FR - 13 - 2	Orthogneiss	mpo	1	3	0	4
		mrs	1	1	1	3
	Paragneiss	brs	0	1	2	3
		gs	0	0	0	0
		k&	5	5	1	11
	Ortho- or Paragneiss	bqs	7	9	2	18
		bqg	4	1	1	6
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	0	0	0	0
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	1	0	1
		ebg	2	1	0	3
		mg	2	0	0	2
		TOTAL	22	22	7	51
FR - 14	Orthogneiss	mpo	6	6	0	12
		mrs	1	1	0	2
	Paragneiss	brs	1	0	2	3
		gs	0	0	0	0
		k&	5	2	1	8
	Ortho- or Paragneiss	bqs	7	4	1	12
		bqg	3	3	1	7
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	1	5	2	8
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	0	0	0	0
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	24	21	7	52
Gorge	Orthogneiss	mpo	2	0	0	2
		mrs	0	0	0	0
	Paragneiss	brs	6	5	0	11
		gs	0	3	9	12
		k&	1	0	0	1
	Ortho- or Paragneiss	bqs	7	3	2	12
		bqg	0	1	0	1
	Jointing Gneiss	bqgn	0	0	1	1
		ggn	0	0	0	0
	Amphibolite	A	1	5	0	6
	Other	kg	0	0	0	0
		pbr	1	0	0	1
		q	3	2	0	5
		ebg	0	0	0	0
		mg	0	0	0	0
		TOTAL	21	19	12	52
FR - 15	Orthogneiss	mpo	5	1	1	7
		mrs	4	1	0	5
	Paragneiss	brs	0	0	0	0
		gs	0	0	0	0
		k&	4	2	0	6
	Ortho- or Paragneiss	bqs	7	11	5	23
		bqg	0	5	0	5
	Jointing Gneiss	bqgn	0	0	0	0
		ggn	0	0	0	0
	Amphibolite	A	0	0	0	0
	Other	kg	0	0	0	0
		pbr	0	0	0	0
		q	1	0	0	1
		ebg	1	0	0	1
		mg	0	0	0	0
		TOTAL	22	20	6	48
Total of all Totals						1,106

Table B3: The table above lists the Fagge River sample sites, and the grain sizes and rock classifications of the grains collected.

Appendix C: Statistical Analysis



FR-4

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0397867	0.0352214
Observations	6	6
df	5	5
F	1.1296151	
P(F<=f) one-tail	0.4484334	
F Critical one-tail	5.0503291	

F<Fcrit = the difference in variance is statistically significant -> use ttest two sample assuming unequal

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0397867	0.0352214
Observations	6	6
Hypothesized Mean Differenc	0	
df	10	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.8124611	
P(T<=t) two-tail	1	
t Critical two-tail	2.2281388	

tstat<tcrit2tail = the means are not statistically different = reproducable

FR-6

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0394667	0.0335555
Observations	6	6
df	5	5
F	1.1761622	
P(F<=f) one-tail	0.4315117	
F Critical one-tail	5.0503291	

F<Fcrit = the difference in variance is statistically significant -> use ttest two sample assuming unequal

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0394667	0.0335555
Observations	6	6
Hypothesized Mean Differenc	0	
df	10	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.8124611	
P(T<=t) two-tail	1	
t Critical two-tail	2.2281388	

tstat<tcrit2tail = the means are not statistically different = reproducable

FR - 9

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0386667	0.0314667
Observations	6	6
df	5	5
F	1.2288136	
P(F<=f) one-tail	0.4133166	
F Critical one-tail	5.0503291	

F<Fcrit = the difference in variance is statistically significant -> use ttest two sample assuming unequal

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0386667	0.0314667
Observations	6	6
Hypothesized Mean Differenc	0	
df	10	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.8124611	
P(T<=t) two-tail	1	
t Critical two-tail	2.2281388	

tstat<tcrit2tail = the means are not statistically different = reproducable

FR-11

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0357867	0.0245592
Observations	6	6
df	5	5
F	1.4571586	
P(F<=f) one-tail	0.3447934	
F Critical one-tail	5.0503291	

F<Fcrit = the difference in variance is statistically significant -> use ttest two sample assuming unequal

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0357867	0.0245592
Observations	6	6
Hypothesized Mean Differenc	0	
df	10	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.8124611	
P(T<=t) two-tail	1	
t Critical two-tail	2.2281388	

tstat<tcrit2tail = the means are not statistically different = reproducable

FR-12

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0365867	0.0309867
Observations	6	6
df	5	5
F	1.1807229	
P(F<=f) one-tail	0.4298966	
F Critical one-tail	5.0503291	

F<Fcrit = the difference in variance is statistically significant -> use ttest two sample assuming unequal

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0365867	0.0309867
Observations	6	6
Hypothesized Mean Differenc	0	
df	10	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.8124611	
P(T<=t) two-tail	1	
t Critical two-tail	2.2281388	

tstat<tcrit2tail = the means are not statistically different = reproducable

FR-13

F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0263467	0.0325644
Observations	6	6
df	5	5
F	0.8090635	
P(F<=f) one-tail	0.4109093	
F Critical one-tail	0.1980069	

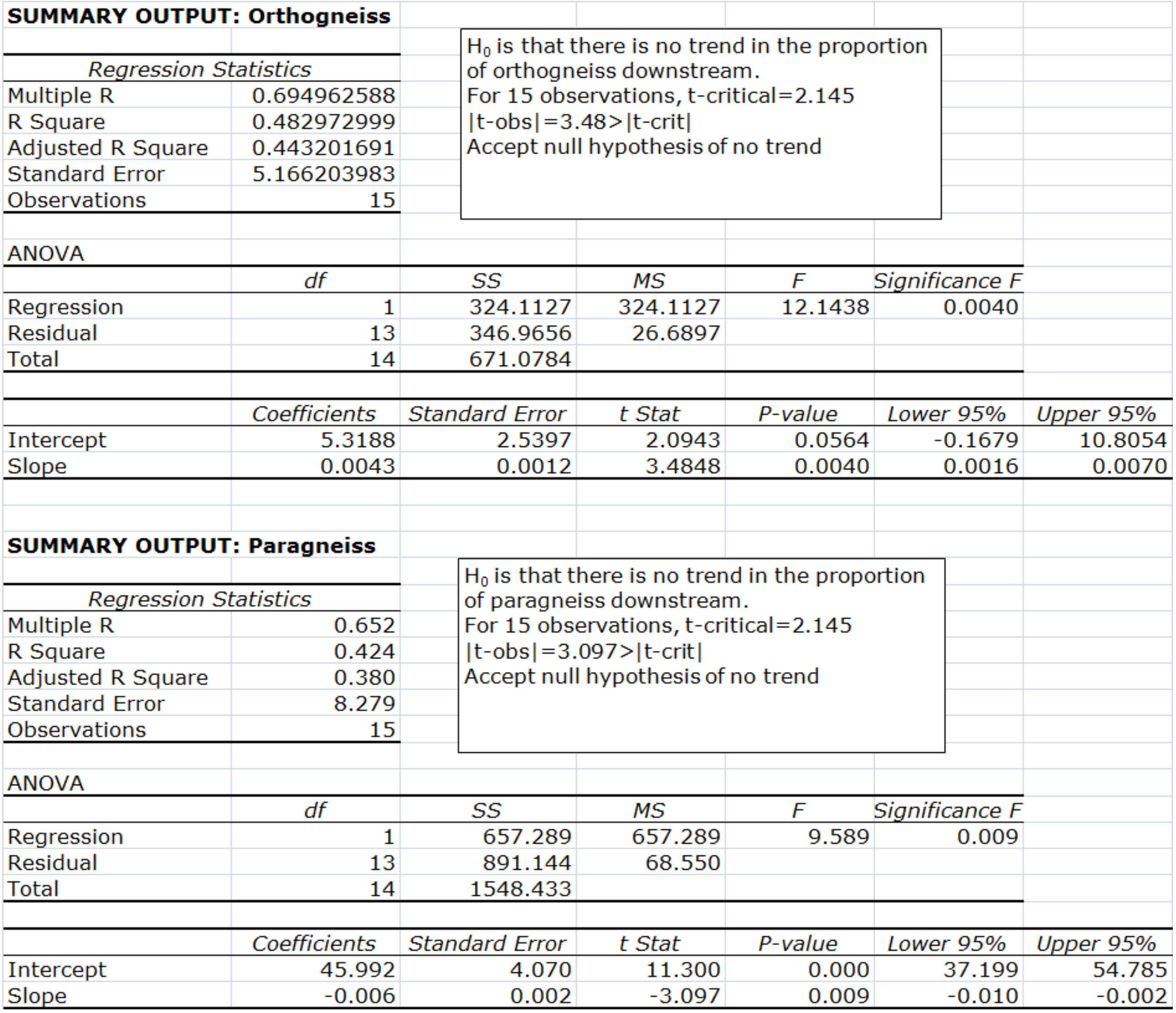
F>Fcrit = the difference in variance is statistically insignificant -> use ttest two sample assuming equal

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	0.1666667	0.1666667
Variance	0.0263467	0.0325644
Observations	6	6
Pooled Variance	0.0294555	
Hypothesized Mean Differenc	0	
df	10	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.8124611	
P(T<=t) two-tail	1	
t Critical two-tail	2.2281388	

tstat<tcrit2tail = the means are not statistically different = reproducable

Table C1: The F-test and T-test output and steps for testing table 1 reproducibility.



SUMMARY OUTPUT: Orthogneiss

Regression Statistics	
Multiple R	0.694962588
R Square	0.482972999
Adjusted R Square	0.443201691
Standard Error	5.166203983
Observations	15

H_0 is that there is no trend in the proportion of orthogneiss downstream.
For 15 observations, t-critical=2.145
|t-obs|=3.48>|t-crit|
Accept null hypothesis of no trend

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	324.1127	324.1127	12.1438	0.0040
Residual	13	346.9656	26.6897		
Total	14	671.0784			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	5.3188	2.5397	2.0943	0.0564	-0.1679	10.8054
Slope	0.0043	0.0012	3.4848	0.0040	0.0016	0.0070

SUMMARY OUTPUT: Paragneiss

Regression Statistics	
Multiple R	0.652
R Square	0.424
Adjusted R Square	0.380
Standard Error	8.279
Observations	15

H_0 is that there is no trend in the proportion of paragneiss downstream.
For 15 observations, t-critical=2.145
|t-obs|=3.097>|t-crit|
Accept null hypothesis of no trend

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	657.289	657.289	9.589	0.009
Residual	13	891.144	68.550		
Total	14	1548.433			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	45.992	4.070	11.300	0.000	37.199	54.785
Slope	-0.006	0.002	-3.097	0.009	-0.010	-0.002

Table C2: The T-test output for orthogneiss and paragneiss (scatter plots in Figure 8).