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SAND TEXTURE AND COMPOSITION IN SMALL, SOUTHERN APPALACHIAN STREAMS: INDICATIONS OF SEDIMENT ORIGIN AND TRANSPORT PROCESSES

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ABSTRACT

Sand grains associated with intense chemical weathering during residence in pedogenic and alluvial storage environments have been described in clastic fluvial sediment loads. These phases are labile, but their behavior in stream sediments has not been systematically studied. The purpose of this study was to determine the abundance of weathered particles in stream sediments from two streams in Mountain Lake watershed, Paris Mountain, South Carolina. The distribution of weathered particles was then compared with stream profile, sand composition, and texture data in order to assess controls on weathered particle distribution in light of bulk downstream trends. An undifferentiated assemblage of schists and gneisses underlies the watershed. Sixty-five sample localities were established along Kaufman and Hartness Creeks, which are second order systems. All samples were analyzed for grain size distribution. Grain mounts of the medium sand fraction of 20 selected samples were prepared for petrographic analysis. The results indicate that sediments in Mountain Lake watershed are texturally and compositionally immature. Both streams show a slight downstream trend with respect to improved sorting. Kaufman Creek shows a slight downstream trend with respect to increasing grain sizes. There are no systematic downstream changes in weathered particle abundance or bulk composition, but sediment compositions in the two creeks are very distinct. The lack of alluvial storage, related to the steep slope, and rapid export of material minimize *in situ* alteration within the streams, even of the labile weathered particles. Individual site slope and mineralogic composition are not correlated, indicating that the influence of slope on sediment maturation is scale dependent. Disaggregation of weathering rims on coarser clasts and continued soil particle input along the streams may partially mask early attrition of weathered particles. When integrated with other studies, the results suggest that significant loss of weathering rims is detectable between 2.3 to 4.8 km of net downstream transport in the Southern Appalachians. Because the lack of alluvial storage limits *in situ* weathering of sediment, variations in sediment composition reflect variations in source rock distribution as modified by soil processes.

INTRODUCTION

Interpreting the mechanisms related to alteration of clastic fluvial sediments is of key importance in distinguishing source rock and environmental signals preserved in the sedimentary record. Accordingly, many studies have focused on petrographic examination of modern stream sands to assess different sediment populations reflecting different sources, environmental conditions, transport histories, and weathering mechanisms (Cameron and Blatt, 1971; Mann and Caravoc, 1973; Basu, 1976; Mack, 1981; Franzinelli and Potter, 1983; McBride and Picard, 1987; Girty and others, 1988; Grantham and Velbel, 1988; Johnsson and others, 1988; Johnsson, 1990b, a; Johnsson and Meade, 1990; Girty, 1991; Johnsson and others, 1991; Savage and Potter, 1991; Heins, 1993; Johnsson, 1993; Robinson and Johnsson, 1997). A relatively separate body of literature has focused on the controls on downstream textural changes in modern rivers, particularly sediments in the gravel size range (Jones and Humphrey, 1997; Hoey and Bluck, 1999; Rice, 1999; Jones, 2000; Heller and others, 2001; Rice and Church, 2001; Surian, 2002; Brummer and Montgomery, 2003; Constantine and others, 2003).

The net effects of alteration are related to both the intensity and duration of exposure to physio-chemical environments that are not in equilibrium with a given sedimentary particle (Johnsson, 1993). Distinguishing the effects of intensity versus duration of exposure can be difficult in an absolute, quantitative sense, especially in the rock record. However, qualitative data concerning the relative influences of these rates along given transport distances under specific environmental conditions are more easily estimated and are of value when interpreting the sedimentary record (Savage and Potter, 1991). Along a link, defined as a channel segment between tributaries, if bank failure, hill slope failure, and runoff are minimized, then changes in bulk sediment composition will be due primarily to *in situ* alteration. If the net rate of alteration is greater than the average rate of grain transport through the link (i.e. the time spent in the bedload plus the time spent in temporary storage in alluvial deposits), then strong differences should be noted over very small distances. If the average rate of grain transport through the link is greater than the rate of alteration, however, no significant compositional trends should be detected.

A number of studies of clastic fluvial sediments have also noted that bedload sediments often contain intensely weathered particles associated with residence time in colluvial (saprolite, regolith, and soil) and/or alluvial (stream bar and floodplain) depositional environments (Grantham and Velbel, 1988; Johnsson, 1990a; Johnsson and Meade, 1990; Pope, 1995). Johnsson (1990b) suggests that weathered particles, including soil grain types and grains with weathering rims, are likely susceptible to mechanical abrasion and rapid mass loss during transport. This may be a primary control on coupling of chemical/mechanical processes influencing grain size and grain size normalized compositional changes in fluvial sediments. A simple, theoretical box model helps conceptualize how these changes and processes are related (Figure 1). Although downstream loss of weathering rims on larger size fractions, including cobbles, has been shown to be an important control on the expression of downstream fining trends in mountainous streams (Heller and others, 2001), there have been few systematic attempts to assess the controls on the production, transport, and fate of weathered particles in the sand fraction. In one of the few examples of weathered particle studies, Grantham and Velbel (1988) note that the relative abundance of garnet grains with weathering rims begins to decline after about 4.8 km of transport in the southern Appalachians, but these numbers are only loosely constrained. Further study of such weathered particles, however, may provide very sensitive proxies for interpretation of weathering and transport processes influencing bedload materials in modern systems (Grantham and Velbel, 1988; Johnsson, 1993; Heller et al., 2001).

The purpose of this paper is to assess the controls on the distribution and behavior of weathered particles in stream sediments from a small, steep, weathering-limited watershed in a low-

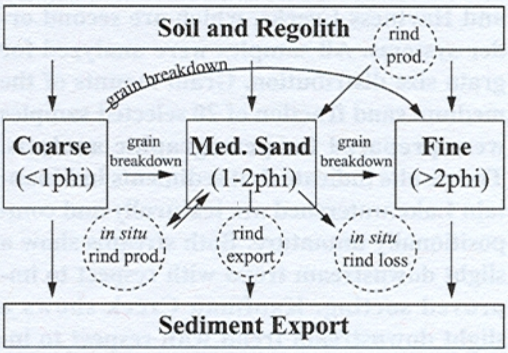

Figure 1. Theoretical box model for potential sources, fates, and processes related to the abundance of medium grains with weathering rims.

order, subtropical basin. Mountain Lake watershed, located on Paris Mountain, in Greenville, South Carolina, provides two small streams that have been sampled at a high resolution to examine the bulk texture and composition in addition to the weathered particle abundance. The dataset provides a thoroughly documented reference point for comparison with similar studies of headwater stream sediments and serves as a springboard for further research in the local area.

REGIONAL SETTING

The 295 ha Mountain Lake watershed (Figure 2) is located on the northeast flank of Paris Mountain (34° 56’N, 82° 22’W) in Greenville, South Carolina, USA. Paris Mountain is a monadnock that lies in the Inner Piedmont Terrain about 20 km southeast of the Blue Ridge escarpment. Tectonically, the area is part of the Paris Mountain thrust sheet, which is one of four regional thrust sheets that form a composite stack known as the Inner Piedmont province (Horton and McConnell, 1991). The lithologies underlying the watershed include a complex assemblage of biotite schist, muscovite schist, quartz muscovite schist, and biotite gneiss with varying amounts of sillimanite and kyanite (Niewendorp, 1997). Structurally, the watershed is characterized by a complex array of imbricate thrusts resulting in a complex metamorphic stratigraphy of different types of schists and gniesses, with deeper metamorphic units exposed to the east and south.

The study area is in the east central portion of the Paris Mountain USGS 7.5-minute quadrangle. The highest elevation in the watershed is the peak of Paris Mountain, at approximately 690 m above sea level. The lowest point at Mountain Lake lies at an elevation of 342 m. The total relief is 348 m.

Hartness and Kaufman Creeks dominate the surface hydrologic system of the study area. Analysis of channels marked on the Paris Mountain USGS 7.5-minute quadrangle indicate that both creeks are second-order systems (Strahler, 1952). In the northern portion of the watershed, the 2.3 km-long Kaufman Creek drains 1.40 km^2 and descends 154 m along its course for an average slope of 0.067. Kaufman Creek cuts across regional structural trends for most of its lower course. In the southern portion of the watershed, the 1.9 km-long Hartness Creek drains 1.55 km^2 and descends 118 m for an average slope of 0.062.

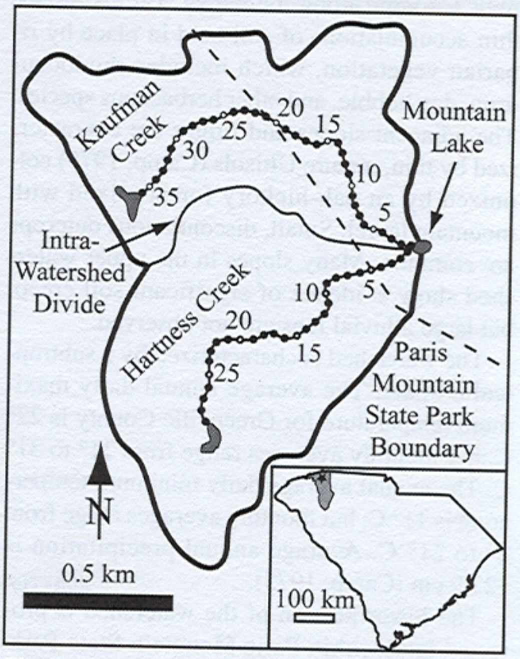

Figure 2. Map of Mountain Lake watershed, located on Paris Mountain in northern Greenville Co., South Carolina. Dots represent sampling localities at 50 m intervals along Kaufman Creek (north, n= 36) and Hartness Creek (south, n=29); numbering begins at the confluence and counts upstream.

Outcrops occur in the channels as either metamorphic lithologies with steeply dipping foliation that directs water along strike or as gently convex-up exposures of biotite gneiss. Both stream channels are characterized by a series of step pools connected by waterfalls and segments of straight channel. Niewendorp (1997) traced several faults that coincide with or extend directly under relatively straight reaches of Hartness Creek between sites 1-10, 14-22, and 22-29, suggesting some structural control of the drainage.

Lateral spread of high water is clearly confined by the steep topography and abundant rock outcrops along the banks. The banks are thin accumulations of soil held in place by riparian vegetation, which includes rhododendron, dog hobble, and other herbaceous species. The adjacent slopes and ridges are characterized by thin, mature Ultisols (Camp, 1975) colonized by an oak-hickory forest mixed with mountain laurel. Small, discontinuous outcrops are common. Many slopes in the upper watershed show evidence of significant soil creep, but large alluvial fans are not observed.

The watershed is characterized by a subtropical climate. The average annual daily maximum temperature for Greenville County is 22° C, but monthly averages range from 11° to 31° C. The annual average daily minimum temperature is 11° C, but monthly averages range from 2° to 21° C. Average annual precipitation is 122.9 cm (Camp, 1975).

The lower portion of the watershed is protected land within Paris Mountain State Park. The upper portions are private property. A few high-value housing developments exist around the margin of the watershed, but the area is still largely undeveloped. The creeks are each currently sourced from small impoundments. Observation of the watershed indicates no significant differences between the drainages for Kaufman and Hartness Creeks, no significant, localized anthropogenic disturbances, and no significant point sources of sandy sediment.

METHODS

Sampling

A total of 65 sampling sites were established at approximately 50 m intervals along the creeks (Figure 2, Hartness, n = 29; Kaufman, n = 36). Elevations of sites were taken from the Paris Mountain USGS 7.5-minute quadrangle map. To test for scale dependency of slope-texture and slope-composition relations, an enlarged copy of the Paris Mountain USGS 7.5-minute quadrangle was used to determine the instantaneous slope for each locality by dividing by the distance between the closest 6 m contour intervals. Representative samples of bedload sediment were collected at each locality with a 1-quart scoop and dried in an oven at 80°C. Although grain size analysis focused on the sand and granule size fractions, observations suggest that the population may be bimodal, with one mode in the sand range and another in the cobble to pebble range. Samples were not collected downstream from Mountain Lake to avoid complications related to sediment storage in the lake.

Grain Size Analysis

Samples were sieved through screens at half-ϕ intervals between -2.0 ϕ and 4.0 ϕ in a Ro-Tap machine for 12 minutes. Particles larger than -2.0 ϕ were omitted due to sampling biases. The grains smaller than 4.0 ϕ comprise only a very small percentage of the total sediment load and were not further separated. Mean and sorting were calculated according to the method of moments (Krumbein and Pettijohn, 1938):

Mean (1st moment): $X_f = (S(f^*m))/n$ (eq.1)

Sorting (2nd moment, standard deviation): $s_f = ((S(f^*(m-X_f)^2))/100)^{0.5}$ (eq. 2)

In these calculations, f equals the weight percent of each grain size, m equals the midpoint of each grain size range in ϕ, and n equals the total number of samples. The <63 μm fraction was qualitatively observed to be dominated by silt, and, for moment calculations, the midpoint of the range was placed at 6.5 ϕ.

Petrographic Analysis

A riffle split of the medium sand fraction (1.0 to 2.0 ϕ) was selected from twenty localities, embedded in epoxy, and thin sectioned for petrographic analysis. This fraction was chosen both for ease of optical analysis and to facilitate comparison with other studies. All thin sections were stained for potassium feldspar and plagioclase. The classification scheme (Table 1) was modeled after Robinson and Johnsson (1997) but was modified to focus on the limited range of source rocks, to incorporate observed subpopulations, to characterize the lithic composition, and to distinguish between degrees and

Table 1 – Classification scheme for petrographic analysis of the medium sand fraction in Mountain Lake Watershed

- **Qt** = total quartz = Qm+Qs+Qp
- **Qtm** = total moncrystalline quartz = Qm+Qs
  - **Qm** = quartz, monocrystalline
    - **Qms** = straight extinction
    - **Qmu** = undulatory extinction
  - **Qp** = quartz, polycrystalline
    - **Qp2-3** = 2-3 grains per crystal
    - **Qp>3** = >3 grains per crystal
  - **Qs** = quartz, subgrained
- **Ft** = total feldspar = Fp+Fk
  - **Fp** = plagioclase
  - **Fk** = potassium feldspar
- **Mt** = total mica = Mb+Mm+Ml
  - **Mm** = muscovite
  - **Mb** = biotite
- **At** = total accessories = Ao+Ai+Ak+As+Ab+Ap+Au1+Au2
  - **Ao** = opaque
  - **Ai** = inosilicates (hornblende)
  - **As** = sillimanite
  - **Ak** = kyanite
  - **Ab** = brown garnets
  - **Ap** = pink garnets
  - **Au1** = unknown: gray to brown, B(-), textured, ~-relief, possibly zeolite from fault/fracture
  - **Au2** = unknown: clear, 1^0 gray, hi (-) relief, possibly zeolite from fault/fracture
- **Ot** = total other grains = Ya+Pf+Ou+Bi
- **Ya** = alterites
- **Pf** = pedogenic/ferruginous
- **Ou** = other
- **Bi** = biogenic debris
- **Rt** = total rock fragments = Qp+As+Lq+Lf+Lm+La+Ly+Lp
- **Rtp** = total poly-phase rock fragments = Lq+Lf+Lm+La+Ly+Lp
  - **Rq** = rock fragments with quartz under the cross hairs
  - **Rf** = rock fragments with feldspar under the cross hairs
  - **Rm** = rock fragments with micas under the cross hairs = Lmm+Lmb
  - **Ra** = rock fragments with accessories under the cross hairs
  - **Ry** = rock fragments with alterites under the cross hairs
  - **Rp** = rock fragments with pedogenic ferrunginous materials under the cross hairs
- **Zx** = grains with FeO rims
  - **Z1** = minimal rinds (0-25%)
  - **Z2** = partial rinds (25-50%)
  - **Z3** = complete rinds (>75%)

Table 2 - Summary of slope and texture data for Mountain Lake Watershed.

	Kaufman Creek, distance downstream																			
	1.75	**1.70**	**1.65**	**1.60**	**1.55**	**1.50**	**1.45**	**1.40**	**1.35**	**1.30**	**1.25**	**1.20**	**1.15**	**1.10**	**1.05**	**1.00**	**0.95**	**0.90**	**0.85**	**0.80**
Mean (ϕ)	0.64	0.15	0.25	-0.13	-0.09	-0.13	-0.04	0.04	0.08	-0.30	0.17	0.08	-0.28	-0.30	0.46	0.07	0.33	0.67	0.11	0.49
Sorting	1.58	1.19	1.36	1.06	1.06	1.20	1.16	1.08	1.16	1.10	1.13	1.29	1.06	1.16	1.24	1.05	1.22	1.37	1.26	1.35
Fine (>2.0 ϕ)	1.21	0.57	0.75	0.21	0.22	0.49	0.41	0.32	0.37	0.34	0.48	0.65	0.32	0.43	0.69	0.33	0.58	0.77	0.59	0.77
Medium (1.0 to 2.0 ϕ)	0.17	0.22	0.29	0.29	0.28	0.29	0.28	0.23	0.30	0.27	0.20	0.29	0.21	0.32	0.20	0.20	0.23	0.20	0.29	0.22
Coarse (> 1.0 ϕ)	1.12	0.64	0.81	0.63	0.63	0.66	0.66	0.61	0.68	0.60	0.59	0.73	0.59	0.61	0.66	0.57	0.68	0.91	0.71	0.82
Fines/Medium	7.02	2.54	2.62	0.73	0.77	1.68	1.50	1.37	1.23	1.27	2.36	2.25	1.52	1.36	3.48	1.59	2.58	3.89	1.99	3.46
Medium/Coarse	0.15	0.35	0.35	0.46	0.45	0.44	0.42	0.38	0.44	0.44	0.34	0.40	0.36	0.52	0.30	0.36	0.33	0.22	0.41	0.27
Elevation	504	498	498	498	498	498	498	492	486	486	480	480	480	480	480	468	462	450	438	426
Site Slope	0.250	0.011	0.011	0.011	0.011	0.011	0.031	0.036	0.036	0.015	0.015	0.015	0.015	0.015	0.050	0.083	0.071	0.125	0.083	0.083

	Kaufman Creek, distance downstream															
	0.75	**0.70**	**0.65**	**0.60**	**0.55**	**0.50**	**0.45**	**0.40**	**0.35**	**0.30**	**0.25**	**0.20**	**0.15**	**0.10**	**0.05**	**0.00**
Mean (ϕ)	0.43	0.77	0.25	0.07	0.31	0.45	0.58	0.17	0.30	0.31	0.86	1.06	0.89	1.12	0.94	0.80
Sorting	1.37	1.41	1.20	1.32	1.50	1.30	1.23	1.31	1.24	1.34	1.10	1.47	1.09	1.22	1.37	1.64
Fine (>2.0 ϕ)	0.78	0.97	0.44	0.73	1.04	0.64	0.55	0.71	0.53	0.68	0.47	1.05	0.56	0.69	0.84	1.48
Medium (1.0 to 2.0 ϕ)	0.25	0.13	0.29	0.28	0.28	0.25	0.22	0.27	0.27	0.29	0.14	0.07	0.11	0.07	0.11	0.12
Coarse (> 1.0 ϕ)	0.86	0.88	0.71	0.73	0.93	0.80	0.74	0.74	0.73	0.82	0.60	1.05	0.51	0.73	0.93	1.08
Fines/Medium	3.19	7.60	1.50	2.62	3.67	2.53	2.52	2.61	1.97	2.32	3.46	14.72	4.91	10.08	7.47	12.09
Medium/Coarse	0.29	0.14	0.41	0.38	0.30	0.32	0.29	0.37	0.37	0.36	0.22	0.07	0.22	0.09	0.12	0.11
Elevation	414	408	396	390	384	378	378	372	372	372	366	366	366	366	360	354
Site Slope	0.125	0.036	0.036	0.050	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.029	0.029	0.031

Table 2 (continued) - Summary of slope and texture data for Mountain Lake Watershed.

	Downstream distance (Hartness)																			
	1.40	1.35	1.30	1.25	1.20	1.15	1.10	1.05	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45
Mean (ϕ)	0.61	0.85	-0.16	0.42	0.21	0.13	-0.20	0.35	0.04	0.01	0.30	0.24	0.67	0.36	0.13	0.50	0.16	0.49	0.51	0.26
Sorting	1.52	1.61	1.29	1.30	1.33	0.95	1.14	1.42	1.25	1.16	1.47	1.35	1.34	1.46	1.41	1.34	1.23	1.31	1.49	1.31
Fine (>2.0 ϕ)	1.15	1.31	0.82	0.68	0.82	0.18	0.51	0.89	0.55	0.39	1.03	0.84	0.78	1.03	0.93	0.89	0.50	0.75	1.08	0.72
Medium (1.0 to 2.0 ϕ)	0.17	0.11	0.21	0.25	0.23	0.19	0.21	0.26	0.30	0.30	0.25	0.23	0.19	0.23	0.28	0.17	0.30	0.20	0.21	0.25
Coarse (> 1.0 ϕ)	0.99	1.17	0.63	0.75	0.71	0.54	0.58	0.87	0.70	0.66	0.87	0.76	0.84	0.88	0.79	0.73	0.70	0.76	0.94	0.74
Fines/Medium	6.57	11.89	3.91	2.76	3.61	0.92	2.48	3.43	1.81	1.29	4.13	3.65	4.06	4.54	3.31	5.33	1.69	3.76	5.15	2.81
Medium/Coarse	0.18	0.09	0.33	0.33	0.32	0.36	0.35	0.30	0.43	0.45	0.28	0.30	0.23	0.26	0.35	0.23	0.42	0.26	0.22	0.34
Elevation	474	468	462	456	450	438	432	426	426	420	414	414	408	402	396	396	390	390	384	384
Site Slope	0.250	0.031	0.042	0.042	0.071	0.083	0.125	0.036	0.016	0.016	0.016	0.028	0.050	0.036	0.042	0.025	0.025	0.017	0.017	0.017

	Downstream distance (Hartness, continued)									Averages					
										Kaufman		Hartness		Watershed	
	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05	0.00	Avg	SD	Avg	SD	Avg	SD
Mean (ϕ)	0.22	0.44	0.05	0.06	0.19	0.26	0.48	0.37	0.08	0.31	0.29	0.28	0.27	0.20	0.29
Sorting	1.53	1.49	1.24	1.33	1.47	1.36	1.59	1.65	1.59	1.25	0.14	1.38	0.15	1.27	0.16
Fine (>2.0 ϕ)	1.16	1.07	0.61	0.74	0.98	0.77	1.41	1.59	1.43	0.61	0.24	0.88	0.27	0.66	0.29
Medium (1.0 to 2.0 ϕ)	0.26	0.22	0.25	0.29	0.30	0.27	0.16	0.19	0.26	0.23	0.04	0.23	0.05	0.24	0.05
Coarse (> 1.0 ϕ)	0.91	0.93	0.68	0.73	0.88	0.80	0.97	0.94	0.84	0.73	0.13	0.80	0.15	0.74	0.14
Fines/Medium	4.44	4.86	2.41	2.56	3.28	2.82	8.85	8.58	5.59	3.32	1.43	4.16	2.35	3.06	2.08
Medium/Coarse	0.29	0.24	0.37	0.40	0.34	0.34	0.16	0.20	0.30	0.33	0.09	0.30	0.09	0.34	0.09
Elevation	384	378	378	372	366	366	360	360	354	480	21.50	422	28.80	451	38.82
Site Slope	0.028	0.028	0.036	0.036	0.042	0.018	0.018	0.018	0.028	0.049	0.058	0.049	0.055	0.049	0.056

types of alteration. Most of the grain populations are standard minerals commonly identified under the microscope. Two types of "weathered particle" grain types were recognized. Alterite (Ya) grains are defined as those grains that have been altered to the point where the original mineralogy can no longer be confidently identified but have not been leached of all mobile elements (Johnsson, 1990b). In Mountain Lake watershed, alterites commonly consist of chlorite and sericite, and many have picked up a light pink stain. This could be due to the presence of remnant K-feldspars, clays that react with the stain, and/or leaching and filling of micropores by the stain solution. Pedogenic ferruginous (Pf) particles are secondary concretions of precipitated iron oxide or residual weathering products of alterites that have been further leached of all mobile phases (Johnsson, 1990b). In Mountain Lake watershed, pedogenic ferruginous particles, characterized by chaotic, thick, reddish-to-opaque oxide minerals, lack good crystal faces and often appear irregular in shape. Many types of otherwise recognizable grains from proximal pedogenic sources have weathering rims produced during residence in colluvial (regolith, sapprolite, soil) and alluvial (bar and floodplain) deposits.

Thin sections were point counted (n = >300; grid spacing of 0.66 mm) using the traditional method in which the entire sedimentary grain is used in the classification rather than the Gazzi-Dickinson method (Ingersoll and others, 1984). In the traditional method, if a single mineral species makes up more than 95% of the visible surface area of a grain, then the grain is classified as monomineralic. If no single mineral species makes up more than 95% of the visible surface area of a grain, then the grain is classified as a polymineralic rock fragment. Quartz is the only phase to be further subdivided into monocrystaline and polycrystaline aggregates. Rock fragments were sub-classified based on the composition of the grain under the cross-hairs. Statistical maximum and minimum limits for each grain type counted were calculated using the method of Howarth (1998).

Weathering Rims

The abundance of weathering rims, recognized as reddish-brown material similar to Pf grains, but concentrated in thin convexo-concavo zones along the boundaries of grains that are otherwise identifiable, was also recorded. Grains are considered to have a class one (Z1) rim if reddish alteration covers 1-25% of the total visible circumference and fracture length combined. Class two (Z2) rims cover 25-75% of the total visible circumference and fracture length combined. Class three (Z3) rims cover 75-100% of the total visible circumference and fracture length combined.

RESULTS

The sediments in Mountain Lake watershed are texturally and compositionally immature, but stream profiles, bulk composition, and textural trends reveal significant differences between the two creeks. Data tables have been abbreviated and summarized due to the sheer quantity of data, but a complete dataset of all textural and compositional parameters for each site is available from the authors.

Stream Profiles

The two creeks are characterized by distinctly different profiles (Table 2 and Figure 3). A single, large slope break dominates the Kaufman Creek profile, whereas Hartness Creek is characterized by a much more even slope along its entire length. These same differences are reflected in a plot of the instantaneous slopes, calculated using the nearest 6 m contour intervals, for each site (Figure 4).

Grain Size Data

Sediment samples from Mountain Lake watershed show considerable variability with respect to grain size distributions along a downstream profile (Table 2, Figures 5 and 6). Mean grain sizes from sediment samples in Mountain Lake watershed fall within a range of -0.28 to 1.12 ϕ. The mean grain size in Kaufman

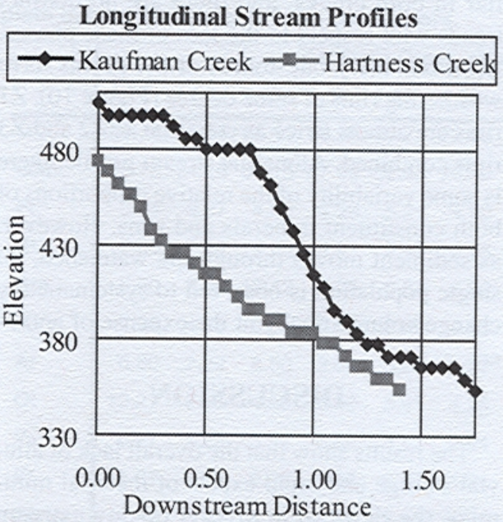

Figure 3. Longitudinal profiles for A) Kaufman Creek and B) Hartness Creek. Profiles are based on the elevations of the sampling sites.

Creek is 0.32 φ, while the mean grain size in Hartness Creek is 0.28 φ. Sorting coefficients fall within a range of 0.94 to 1.65. On average, the sediments are poorly sorted in both creeks, with only one sample falling into the extreme low end of the moderately sorted category (Folk, 1974). In Kaufman Creek, the mean grain size increases downstream, and sorting improves slightly downstream. In Hartness Creek, mean grain size does not change downstream, but there is a slight trend toward improved sorting.

Textural trends illustrated in Figures 5 and 6 indicate that the most downstream sites seem to behave anomalously. The relative percentages of the coarse and medium sand fractions in both creeks change sharply, as do the sorting in both creeks and the mean grain size in Kaufman Creek. These sites are located near the junction of the streams with Mountain Lake, where the systems essentially form a small delta/estuary system. Anthropogenically induced complications from reduced flow velocity are assumed to be influencing these sites and, accordingly, textural data from the three closest sites to the lake have been discarded for statistical purposes in each creek.

Compositional Data

Compositional analyses indicate significant amounts of alterites, feldspars, micas, and lithic fragments in addition to quartz (Table 3, Figure

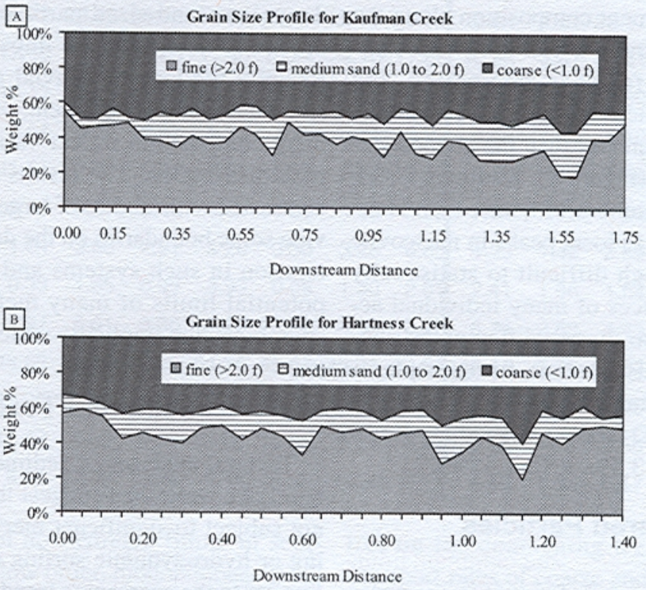

Figure 5. Textural profiles for A) Kaufman Creek and B) Hartness Creek. The choice of "coarse" (< 1.0 φ), medium sand (1.0 to 2.0 φ), and "fine" (>2.0 φ) fractions is based on the box model presented in Figure 1.

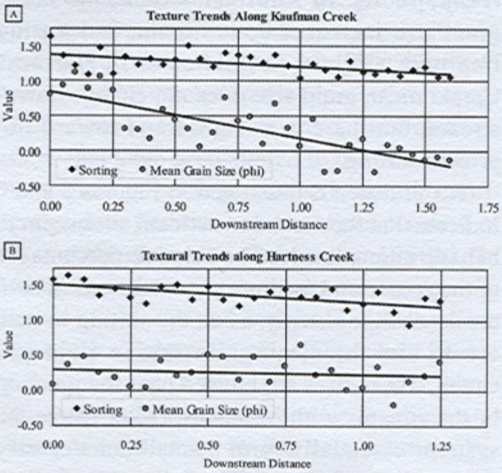

Figure 6. Grain size and sorting trends for A) Kaufman Creek and B) Hartness Creek. The three lowest sites (i.e. lower 0.15 km) are not considered for statistical purposes due to the interference of Mountain Lake. Kaufman Creek shows a trend toward coarser grain sizes (R^2 = 0.6347, y = -0.6595x + 0.8472), but only a very weak trend toward improved sorting (R^2 = 0.3274). Hartness Creek shows a very weak trend toward improved sorting (R^2 = 0.3800), but no trend with respect to grain size (R^2 = 0.0172).

7). Although there are no significant, systematic changes in the sediment composition along the stream profile, Hartness Creek sands are characterized by total feldspar, microcline, and hornblende abundances that are more than one standard deviation greater than the abundances in Kaufman Creek (Figure 8). Kaufman Creek contains a greater amount of quartz than Hartness Creek, as well as local peaks in muscovite abundance. Although difficult to statistically determine, abundances of many individual accessory minerals also suggest different distributions. Sillimanite distribution, for example, is much more consistent along Hartness Creek (11.7 +/- 7.5%, RSD 0.65%), than along Kaufman Creek (2.7 +/- 3.5%, RSD 1.32%).

Weathered Particles

Alterites and pedogenic ferruginous particles are present in low abundances throughout the watershed (Figure 9). Rind abundances are similar in both creeks, and there are no distinct trends with respect to the loss of these phases. Approximately one-fourth of the grains have weathering rims of some degree (Figure 10). Z1 rims are almost twice as common as Z2 and Z3 rims combined. Along the stream profile, there is some variability of the relative proportions of both constituent minerals and rims. However, as sediment moves through the watershed, no single population is observed to systematically change volumetrically at the expense of another.

DISCUSSION

The results show that the overall lack of alluvial storage and rapid export of material minimize the detectable effects of downstream alteration of sedimentary particles at this scale, even those associated with pedogenic sources. The dominant weathering mechanism influencing the stream sediment is the extended residence time in the soil horizons on the adjacent slopes; in situ chemical alteration is minimized by the rapid export. No net influence of mechanical weathering is detected in the sand fraction, although this could be masked partially by the breakdown of larger cobbles, which move more slowly through the system and may break down into sand-sized particles. More work is needed to determine the impact of this effect. Because the lack of alluvial storage limits in situ weathering of sediment, variations in sediment composition reflect variations in source rock distribution. The results of this study are contrasted with studies of larger systems to provide some boundaries on the detectability of alteration in such systems and insight into the potential limits of many methodological assumptions that implicitly underlie similar studies.

Sediment Texture

Textural analyses of sediments from Mountain Lake watershed suggest that sediments are not subject to significant mechanical weathering or hydrodynamic sorting during transport. Similar to the coarsening trends here documented in Kaufman Creek, Brummer and Montgomery (2003) noted downstream coarsening, rather

Table 3 – Summary of medium sand composition (wt%) for Mountain Lake Watershed. A complete dataset is available from the authors.

	Kaufman Creek, downstream distance												Hartness	
	1.75	**1.60**	**1.45**	**1.30**	**1.15**	**1.00**	**0.85**	**0.75**	**0.55**	**0.25**	**0.10**	**0.00**	**1.35**	**1.20**
Qt	59.74	76.14	61.11	68.98	69.71	72.55	63.82	71.19	67.21	71.43	62.58	57.19	46.89	40.85
Qtm	58.75	74.18	59.15	67.99	67.43	70.59	62.50	70.53	64.61	71.10	61.92	56.21	45.25	38.89
Ft	5.94	3.27	4.25	4.29	5.21	4.90	2.30	4.30	3.90	2.33	2.32	0.65	21.97	22.22
Rt	7.59	7.84	14.38	8.91	9.12	10.78	14.14	7.28	12.99	6.98	10.26	17.65	14.75	15.03
Rtp	6.60	5.88	12.42	7.92	6.84	8.82	12.83	6.62	10.39	6.64	9.60	16.67	13.11	13.07
Mt	7.92	4.25	6.86	6.60	8.79	4.25	7.89	6.29	3.90	7.97	7.62	7.84	3.28	3.92
At	6.60	2.29	8.50	2.64	3.26	3.27	7.57	3.64	4.87	5.98	7.62	5.88	8.52	12.09
Ot	12.21	6.21	4.90	8.58	3.91	4.25	4.28	7.28	7.14	5.32	9.60	10.78	4.59	5.88
Ya	6.27	5.23	3.59	6.60	3.91	2.94	1.32	5.30	3.57	3.99	4.97	4.25	2.62	2.29
Pf	5.61	0.98	0.65	1.98	0.00	1.31	2.96	1.99	3.25	0.66	4.64	4.90	1.64	0.65
Pf+Ya	11.88	6.21	4.25	8.58	3.91	4.25	4.28	7.28	6.82	4.65	9.60	9.15	4.26	2.94
Zt	41.91	43.79	51.31	44.22	40.39	42.48	49.34	50.33	51.30	46.18	39.07	56.54	52.79	33.01
Z1	29.37	34.97	30.39	35.64	30.62	30.72	31.25	38.74	37.34	33.55	24.17	28.76	29.51	26.80
Z2	8.58	5.88	15.03	6.93	6.84	7.19	11.18	6.95	9.74	7.97	11.26	20.59	16.72	4.90
Z3	3.96	2.94	5.88	1.65	2.93	4.58	6.91	4.64	4.22	4.65	3.64	7.19	6.56	1.31

	Hartness Creek, downstream distance								Averages					
	1.05	**0.90**	**0.75**	**0.60**	**0.45**	**0.30**	**0.15**	**0.00**	Kaufman		Hartness		Average	
									Avg	SD	Avg	SD	Avg	SD
Qt	45.60	46.05	45.54	47.85	47.21	43.89	35.50	41.50	66.80	5.84	44.09	3.81	55.45	4.83
Qtm	43.32	44.74	44.55	46.86	45.57	42.90	33.22	39.54	65.41	5.74	42.49	4.14	53.95	4.94
Ft	24.43	20.72	23.43	24.75	19.34	21.12	23.78	19.93	3.64	1.51	22.17	1.89	12.90	1.70
Rt	11.40	17.43	11.22	14.85	11.80	15.84	24.10	17.65	10.66	3.41	15.41	3.84	13.04	3.62
Rtp	9.12	16.12	10.23	13.86	10.16	14.85	21.82	15.69	9.27	3.29	13.80	3.70	11.54	3.50
Mt	3.58	1.64	5.61	2.97	5.25	7.26	5.21	5.23	6.68	1.68	4.40	1.62	5.54	1.65
At	8.14	11.51	7.92	5.61	7.21	6.93	6.51	12.42	5.18	2.14	8.69	2.45	6.93	2.29
Ot	6.84	2.63	6.27	3.96	9.18	4.95	4.89	3.27	7.04	2.75	5.25	1.90	6.14	2.33
Ya	4.56	1.64	3.96	2.31	4.26	3.30	3.26	0.65	4.33	1.46	2.89	1.22	3.61	1.34
Pf	1.63	0.33	1.65	0.99	3.93	0.66	1.30	2.61	2.41	1.86	1.54	1.07	1.98	1.46
Pf+Ya	6.19	1.97	5.61	3.30	8.20	3.96	4.56	3.27	6.74	2.62	4.43	1.82	5.58	2.22
Zt	49.51	48.68	51.49	46.20	64.26	48.84	49.84	62.09	46.41	5.32	50.67	8.57	48.54	6.95
Z1	31.92	28.95	33.66	31.02	43.28	30.03	27.36	36.93	32.13	4.09	31.95	4.98	32.04	4.53
Z2	12.38	12.83	9.90	9.24	11.80	13.86	16.94	16.99	9.85	4.26	12.56	3.88	11.20	4.07
Z3	5.21	6.91	7.92	5.94	9.18	4.95	5.54	8.17	4.43	1.63	6.17	2.19	5.30	1.91

than conventional downstream fining of sediments in another low order, mountainous, headwater system. Detailed geomorphic analysis in the latter case suggested that the primary control on the coarsening trends is differential transport rates of coarse and fine material, with addition of coarse sediment as a secondary control. The downstream coarsening trend in Kauf-

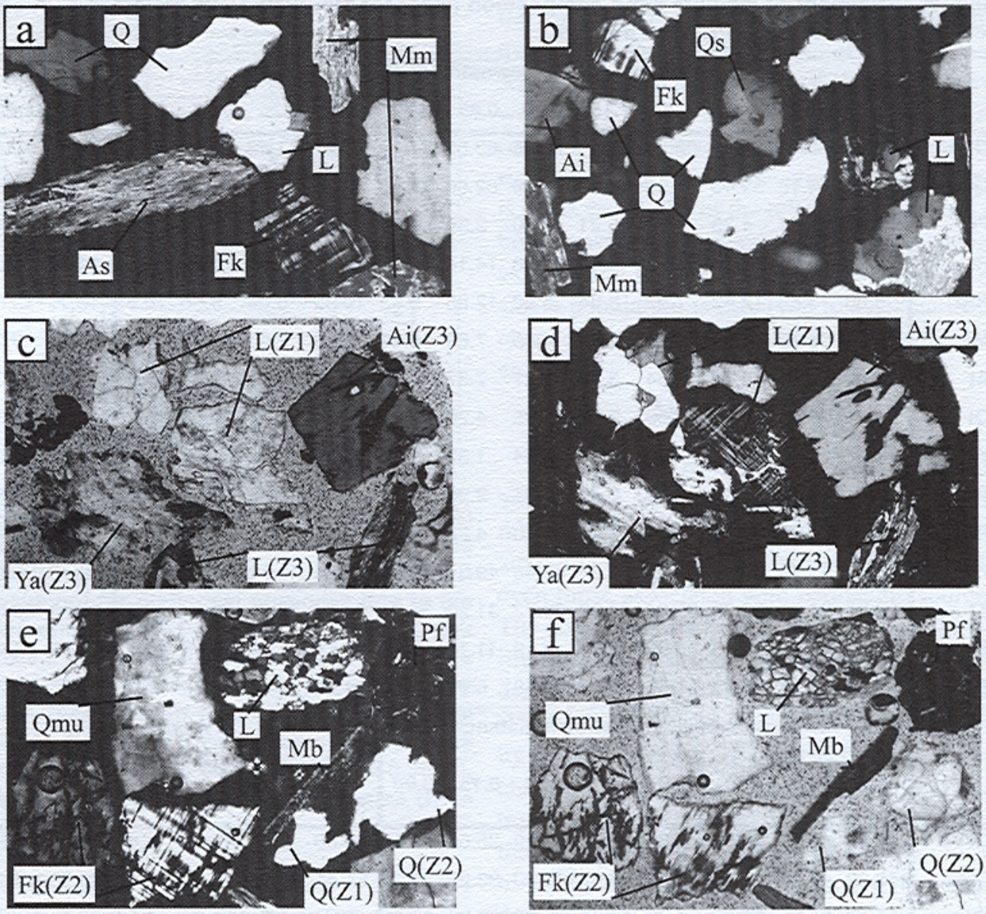

Figure 7. Selected photomicrographs of major phase classifications (Table 1; rim data in parentheses). All fields of view of approximately 4mm. a) and b) are different views under crossed polars. The lithic (L) in a) is composed of quartz (Q) and biotite (Mb). The top right lithic in b) is composed of quartz (Q), biotite (Mb), and pedogenic ferruginous material (Pf); the lower lithic is composed of quartz (Q), muscovite (Mm), and pedogenic ferruginous material (Pf). c) and) are the same view with polars uncrossed and crossed respectively. The upper left lithic is composed of quartz (Q) and biotite (Mb); the middle lithic is composed of potassium feldspar (Fk), alterite (Ya), and biotite (Mb). The bottom lithic is composed of quartz (Q), biotite (Mb), and pedogenic ferruginous material (Pf). e) and f) are the same view with polars crossed and uncrossed respectively. The lithic is composed of quartz (Q), biotite (Mb), and opaque oxides (Ao).

man Creek (Figure 6), with its large, steep slope break, and observed lack of large colluvial deposits in the stream channel, are here interpreted to reflect a similar process at work in Kaufman Creek drainage basin. The more variable slopes in Hartness Creek are associated with a weaker textural signal, suggesting that there are other factors complicating the grain size distribution (Figure 3, Figure 6). The discrepancies between grain size trends in the two creeks are likely related to the fact that Kaufman Creek drainage basin has significantly greater relief (348 m) than Hartness Creek drainage basin (202 m) (Figure 3). These data, combined with the evidence for abundant outcrops and thin soils on the adjacent slopes, support the interpretation of Mountain Lake watershed as a weathering-limited system. Consistent sorting coefficients along both creeks (Figure 6) suggest that the sampling of the me-

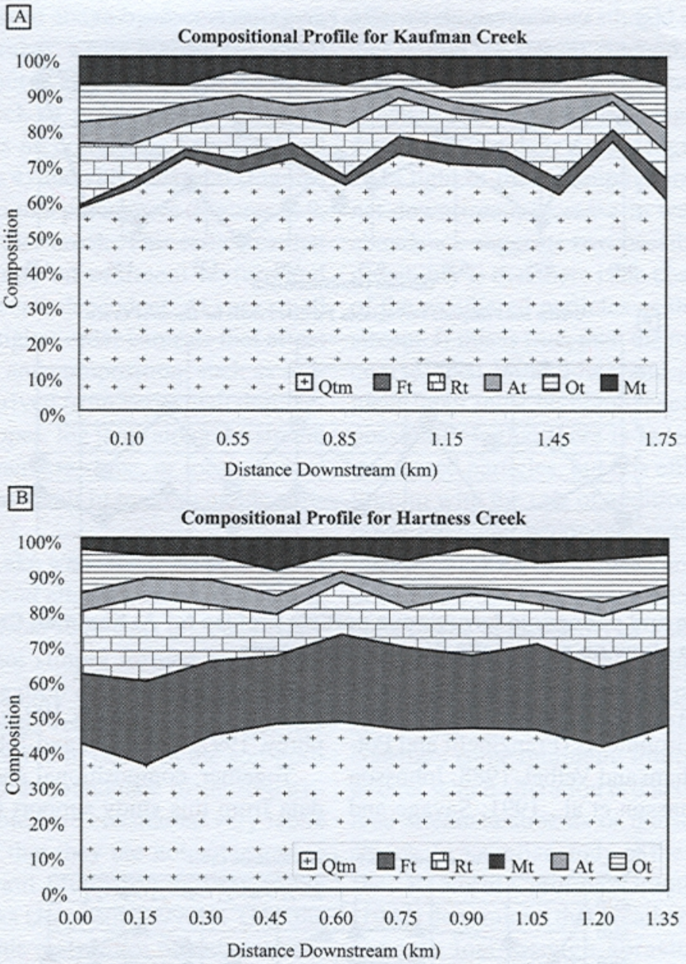

Figure 8. Bulk compositional variation for A) Kaufman Creek and B) Harntess Creek. Neither stream shows significant systematic changes in the relative percentage of any species relative to another.

dium sand fraction for compositional analysis has not been obviously biased by hydrodynamic sorting processes.

Downstream Compositional Trends

The compositional profiles indicate that there are no significant changes in the bulk composition or weathered particle abundance in the medium sand fraction as sediments are transported down the creeks. Several recent studies of modern environments have hypothesized that alluvial storage, related to slope, acts as a dominant control on compositional maturation trends by extending the duration of exposure of sediments to chemical weathering (Schumm, 1968; Franzinelli and Potter, 1983; Grantham and Velbel, 1988; Johnsson and others, 1988; Johnsson and others, 1991; Savage and Potter, 1991; Johnsson, 1993; Jones and Humphrey, 1997; Robinson and Johnsson, 1997). In these systems, sediment is temporarily stored in deposits such as levees, bars, and floodplains. While in storage, sediments are leached of mobile phases due to an extended fluid-sediment contact time. During channel migration, this stored sediment is reincorporated into the system and the overall compositional maturity of the sediment is increased. This relationship between alluvial storage and sedi-

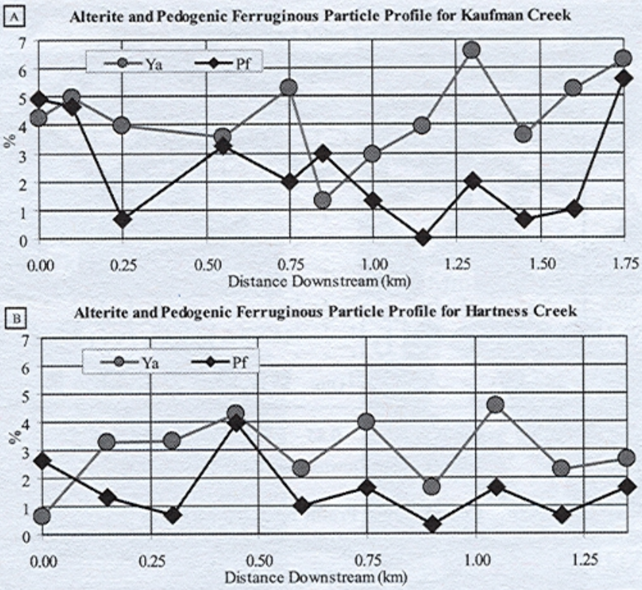

Figure 9. Alterite and pedogenic ferruginous particle profiles for A) Kaufman Creek and B) Harntess Creek. Data show no systematic downstream trends.

ment maturation has been documented in arctic and tropical environments (Franzinelli and Potter, 1983; Grantham and Velbel, 1988; Johnsson et al., 1988; Johnsson et al., 1991; Savage and Potter, 1991; Johnsson, 1993; Jones and Humphrey, 1997; Robinson and Johnsson, 1997).

Together, compositional and weathering rim data from this study support the slope/storage

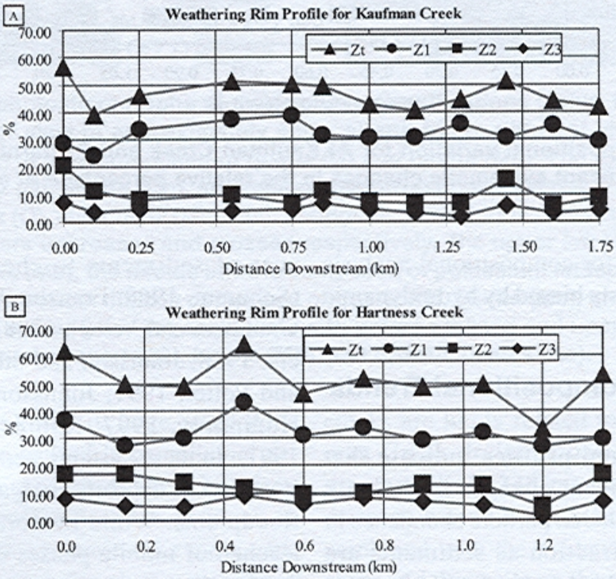

Figure 10. Distribution of weathering rims in A) Kaufman Creek and B) Hartness Creek. Z1 rims cover 1-25% of the combined rim and fracture length of the grain, Z2 rims 25-75%, and Z3 rims 75-100%. There are no systematic downstream changes associated with the bulk profiles, suggesting that the bulk rim population is not affected by mechanical weathering at this scale of observation

hypothesis discussed above by documenting an opposite end-member, where high slopes, rapid transport, and limited alluvial storage are associated with a lack of petrographic changes. However, there is no correlation between local site slope (Figure 4) and either textural (Figures 5, 6) or compositional parameters (Figures 8, 9, and 10) along either creek. This indicates that the effects of slope on sediment texture and composition are scale dependent. At very small scales there are higher order controls that affect sediment texture and composition, such as sediments locally derived from very small drainages on adjacent slopes, log jams along the stream that artificially increase slope, or local channel morphologies that result in hydrodynamic sorting.

In Mountain Lake watershed, the presence of weathering rims and alterites shows that during early evolution these sediments are chemically weathered and not simply formed by the mechanical disagregation of source rocks. Based on the lack of observed alluvial storage, this weathering is inferred to occur in the soil horizon. The consistent abundance of these particles and rims, which are considered very labile phases, suggests that they are not subjected to further significant alteration as they move through the creeks (Johnsson, 1990b). Thus the composition at this early stage of sediment development reflects the mineral composition of the source rocks as modified by soil processes. Although the importance of soil processes has been demonstrated before in tropical environments (e.g., Franzinelli and Potter, 1983; Johnsson, 1990b), these data clearly show that this is true in more temperate environments as well.

The lack of storage in Mountain Lake watershed precludes significant *in situ* chemical weathering in longitudinal bars, but the detection of any particle attrition is potentially complicated by two additional factors (Figure 1). First, the relative increase in coarse clast abundance suggests, but does not prove, that mechanical breakdown of coarse grains is not a significant source for sand-sized particles with weathering rims. Abrasion of highly weathered rims associated with these relatively slow-moving, increasingly abundant clasts may, however, effectively produce weathered sand-sized particles within the stream. Second, the steep banks that lie adjacent to the streams also provide a constant source of fresh, pedogenically derived material along their entire length.

In light of these complications, the lack of a net downstream increase in weathered particle abundance suggests two possibilities. The first possibility is that there is no change at all in any of the weathered particles as they move downstream. If this is true, then the material added by coarse clast breakdown and pedogenic sediment input must be homogeneous. The second possibility is that there is indeed some loss of weathered particles, but it is effectively in equilibrium with the rate of addition by coarse clast breakdown and pedogenic sediment input, and thereby masked. Further research is required to understand the relative importance of these effects on the detectability of alteration trends.

Although no significant compositional alteration has been detected in the present study, results can be integrated with other data to constrain some minimum limits on the distances over which alteration is detectable in the bulk load stream sediments of the southern Appalachians. In a similar study of the Coweeta watershed in North Carolina, Grantham and Velbel (1988) determined that weathering rims on garnets are lost through abrasion in mountain streams somewhere between 0.8 and 4.8 km. Somewhere within this interval, the rate of rim loss due to abrasion in the streambed becomes greater than the rate of rim addition because the rate of attrition of rims surpasses the rate of creation/addition of fresh rims. This distance is likely related to stream network patterns and the tendency for steep headwater streams merge into higher order systems with flatter alluvial valleys over just a few kilometers. In the higher order systems, the rate of input of fresh material from the adjacent slopes is limited by increased distance to the channel and a decrease in slope; simultaneously, the channel slope decreases, thereby increasing the duration of exposure to chemical weathering per unit downstream distance.

These results support previous conclusions that weathered particles are useful tracers of weathering and transport processes (Grantham and Velbel, 1988; Johnsson, 1993; Heller et al., 2001). Although not necessarily preserved in ancient deposits, careful monitoring of these particles in modern systems should provide a method for relating processes to subtle changes in the bedload that are not evident through analysis of changes in bulk composition alone. As tracers, weathered particles provide a useful tool that should be relatively insensitive to compositional differences between source areas. Thus, results from different basins may provide comparable, parallel proxies that can be used to more confidently assess the impacts of various processes on fluvial sediments.

Compositional Differences Between the Creeks

The lack of downstream changes in bulk sediment mineralogy along Hartness and Kaufman Creeks is consistent with rapid transport of material through the system and suggests that the compositional differences between the streams are not merely sampling artifacts. There are three hypotheses related to this difference. The first scenario involves differences in the bedrock beneath each watershed. Although the geology of Mountain Lake watershed has not been mapped in sufficient detail to distinguish such differences, studies of other small basins have also encountered similar complexities when working with such high-resolution datasets (Mann and Caravoc, 1973; Mack, 1981; Grantham and Velbel, 1988; Heins, 1993; Yuretich and others, 1996). The second potential influence on bulk compositional differences between the streams involves differences in degree or depth of excavation of the weathering horizons on the adjacent slopes. The homogeneous climate and evidence for extremely rapid denudation of the slopes, however, suggests that these differences are minimal. A third possible influence would be the anthropogenic input of sand into the system. Field observations of the watershed and contacts with local residents, however, suggest that the watersheds are virtually identical with respect to degree of development and lack any significant, potential point source(s) for such consistent sand input.

After considering these three hypotheses, the first hypothesis is preferred. Although the complex geology of Mountain Lake watershed has not yet been mapped in detail, the current data suggests that the deeper metamorphic units exposed to the south and the east under the source area for Hartness Creek, produce more feldspar, more hornblende, and less quartz in the medium sand fraction than the shallower units underlying the source area for Kaufman Creek. Grantham and Velbel (1988) note that the Coweeta watershed, which is also in the southern Appalachians, is too complex to map at a high-resolution scale but use petrographic parameters of stream sediments to actually try and distinguish source rock differences. This is likely a function of bulk differences in source rock mineralogy and composition but could also reflect textural differences that selectively include or exclude medium sand-sized crystals of certain phases. Although the structure is likely a significant influence on the physiography of Mountain Lake watershed, lithologic differences between the sub-drainage basins may also be related to the different stream profiles. Kaufman Creek produces high abundances of quartz, which is highly resistant to chemical weathering, and is characterized by 348 m of total relief; Hartness Creek, on the other hand, produces higher abundances of more labile minerals and has only 202 m of total relief.

These results suggest that immature sediments containing abundant unstable phases may prove to be hypersensitive indicators of provenance by preserving a distinct local source rock signature that is of limited value in drawing regional conclusions regarding geology (Butler, 1979; Mack, 1984; Girty and others, 1988; Heins, 1993). Ternary diagrams of quartz/feldspar/rock fragments, for example, can be used to infer two very distinct proximal populations derived from the same source (Figure 11). The error polygons, formed by the 95% confidence intervals calculated according to Howarth (1998), for the Kaufman Creek, Hartness Creek, and watershed averages are mutually exclusive. Because this difference is primarily in the feldspars, the same magnitude

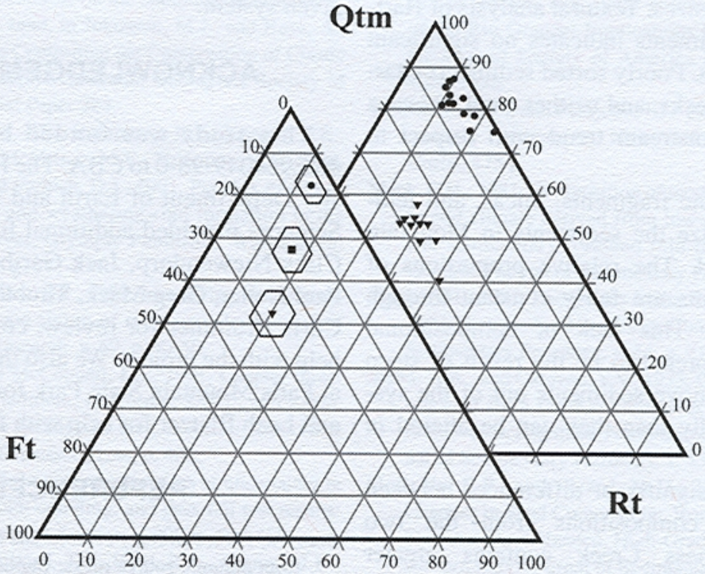

Figure 11. Quartz-Feldspar-Rock Fragment (QFR) ternary diagrams: A) Total samples from Kaufman Creek (closed circles) and Hartness Creek (open triangles). B) Suite averages for Kaufman Creek (closed circles), Hartness Creek (open triangles), and the entire watershed (closed squares). Error polygons for each group represent the 95% confidence levels of the suite means with respect to each species (e.g. Robinson and Johnsson, 1997) were calculated using methods of Howarth (1998). The mutual exclusion of all fields suggests caution when making regional provenance interpretations from immature sediments.

of differences should show up even if these point counts were done according to the Gazzi-Dickinson method, which would reclassify the "rock fragments" recognized in the current study based only on the crystal (or microcrystalline aggregate) directly beneath the cross-hairs (Ingersoll et al., 1984). These data support the conclusions of other studies that ternary diagrams by themselves should be interpreted cautiously (Butler, 1979; Mack, 1984; Girty et al., 1988; Heins and Ingersoll, 2000).

Future Work

These results propose several hypotheses for future studies. Further work on the character of medium sand grains in the soil horizons should document the range of phases present and how alteration of grains proceeds. Further work on the age and depth of soil profiles, the transport rate of material from the slopes to the streambed, the rim distribution in deposits of Mountain Lake, and rim distributions associated with longer stream reaches should offer quantitative constraints on the rates and distances associated with these processes. Further work on the distribution of these rims with respect to the parent phase may yield quantitative predictions of compositional changes associated with textural maturation.

CONCLUSIONS

1. Mountain Lake watershed, located on Paris Mountain in Greenville, South Carolina, is a subtropical system drained by Kaufman and Hartness Creeks, which are both second-order, headwater streams. A complex, undifferentiated assemblage of high-grade metamorphic and granitic source rocks underlies the watershed. Bulk samples of bedload sediments, including gravel-, sand-, and clay-sized detritus, were collected from 65 sites along the creeks for textural and petrographic analysis.
2. Textural analysis of Kaufman Creek sediments indicates a downstream trend toward

increased grain sizes. Textural analysis of Hartness Creek sediments indicates no significant grain size trends. Poorly sorted sediments characterize both creeks, and neither creek shows a significant downstream trend with respect to sorting.

3. Quartz, lithic fragments, micas, and feldspars characterize the sediments in Mountain Lake watershed. The relative proportions of these constituents are fairly constant through the watershed. This lack of compositional change is interpreted to be the result of steep slopes, which move sediments out of the system more rapidly than they can be altered *in situ*.

4. There are significant differences between the sediment compositions from the two streams. Hartness Creek contains greater amounts of potassium feldspar than Kaufman Creek, and Kaufman Creek contains significantly more quartz than Hartness Creek. These differences are interpreted to reflect the source rock distribution undetectable by normal surface mapping. Results suggest that immature sediment containing abundant labile phases preserves a very strong, distinct source rock signature but is of limited value in drawing regional generalizations concerning provenance.

5. Roughly 25% of all grains show evidence of iron oxide weathering rims. These rims, along with the presence of alterites and pedogenic ferruginous grains, indicate that sand-sized grains are chemically weathered in Mountain Lake watershed. A complete lack of trends with respect to weathering rims or weathered particle abundance indicates that this weathering is restricted to the soil horizons prior to introduction into the stream. Integration of the current data with the findings of Grantham and Velbel (1988) suggests that these rims may be lost due to mechanical abrasion between 2.0 and 4.8 kilometers of transport.

6. Careful monitoring of labile grain types, including accessory minerals and weathered particles, in different size fractions may help quantitatively constrain subtle parameters related to physical and chemical processes in a given system.

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REFERENCES

Basu, A., 1976, Petrology of Holocene fluvial sand derived from plutonic source rocks: Implications to paleoclimactic interpretation: Journal of Sedimentary Petrology, v. 46, p. 694-709.

Brummer, C.J., and Montgomery, D.R., 2003, Downstream coarsening in headwater channels: Water Resources Research, v. 39.

Butler, J.C., 1979, Trends in ternary petrologic variation diagrams - fact or fantasy: American Mineralogist, v. 64, p. 1115-1121.

Cameron, K.L., and Blatt, H., 1971, Durabilities of sand size schist and "volcanic" rock fragments during fluvial transport, Elk Creek, Black Hills, South Dakota: Journal of Sedimentary Petrology, v. 41, p. 565-576.

Camp, W.J., 1975, Soil Survey of Greenville County, South Carolina: Washington, D.C., United States Department of Agriculture Soil and Conservation Service, p. 71.

Constantine, C.R., Mount, M.F., and Florsheim, J.L., 2003, The effects of longitudinal differences in gravel mobility on the downstream fining pattern in the Cosumnes River, California: Journal of Geology, v. 111, p. 233-241.

Franzinelli, E., and Potter, P.E., 1983, Petrology, Chemistry, and Texture of Modern River Sands, Amazon River System: Journal of Geology, v. 91, p. 23-39.

Girty, G.H., 1991, A Note on the Composition of Plutoniclastic Sand Produced in Different Climatic Belts: Journal of Sedimentary Petrology, v. 61, p. 428-433.

Girty, G.H., Mossman, B.J., and Pincus, S.D., 1988, Petrology of Holocene Sand, Peninsular Ranges, California and Baja Norte, Mexico - Implications for Provenance-Discrimination Models: Journal of Sedimentary Petrology, v. 58, p. 881-887.

Grantham, J.H., and Velbel, M.A., 1988, The Influence of Climate and Topography on Rock-Fragment Abundance in Modern Fluvial Sands of the Southern Blue Ridge Mountains, North Carolina: Journal of Sedimentary Petrology, v. 58, p. 219-227.

Heins, W.A., 1993, Source rock texture versus climate and topography as controls on the composition of modern, plutonoclastic sand, in Johnsson, M.J., and Basu, A., eds., Processes Controlling the Composition of Clastic Sediments: Boulder Colorado, Geological Society of America Special Paper 284.

Heller, P.L., Beland, P.E., Humphrey, N.F., Konrad, S.K., Lynds, R.M., McMillan, M.E., Valentine, K.E., Widman, Y.A., and Furbish, D.J., 2001, Paradox of downstream fining and weathering-rind formation in the lower Hoh River, Olympic Peninsula, Washington: Geology, v. 29, p. 971-974.

Hoey, T.B., and Bluck, B.J., 1999, Identifying the controls over downstream fining of river gravels: Journal of Sedimentary Research, v. 69, p. 40-50.

Horton, J.W.J., and McConnell, K.I., 1991, Chapter three: the Western Piedmont, in Horton, J.W.J., and Zullo, V.A., eds., The geology of the Carolinas: Knoxville, University of Tennessee Press, p. 405.

Howarth, R.J., 1998, Improved estimators of uncertainty in proportions, point-counting, and pass-fail test results: American Journal of Science, v. 298, p. 594-607.

Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.B., Pickle, J.D., and Sares, S.W., 1984, The effect of grain size on detrital modes: a test of the Gazzi-Dickinson point-counting method: Journal of Sedimentary Petrology, v. 54, p. 103-116.

Johnsson, M.J., 1990a, Overlooked Sedimentary Particles from Tropical Weathering Environments: Geology, v. 18, p. 107-110.

Johnsson, M.J., 1990b, Tectonic Versus Chemical-Weathering Controls on the Composition of Fluvial Sands in Tropical Environments: Sedimentology, v. 37, p. 713-726.

Johnsson, M.J., 1993, The system controlling the composition of clastic sediments, in Johnsson, M.J., and Basu, A., eds., Processes controlling the Composition of Clastic Sediments: Geological Society of America Special Paper, no. 284.

Johnsson, M.J., and Meade, R.H., 1990, Chemical-Weathering of Fluvial Sediments During Alluvial Storage - the Macuapanim Island Point-Bar, Solimoes River, Brazil: Journal of Sedimentary Petrology, v. 60, p. 827-842.

Johnsson, M.J., Stallard, R.F., and Lundberg, N., 1991, Controls on the Composition of Fluvial Sands from a Tropical Weathering Environment - Sands of the Orinoco River Drainage-Basin, Venezuela and Colombia: Geological Society of America Bulletin, v. 103, p. 1622-1647.

Johnsson, M.J., Stallard, R.F., and Meade, R.H., 1988, 1st-Cycle Quartz Arenites in the Orinoco River Basin, Venezuela and Colombia: Journal of Geology, v. 96, p. 263-2771.

Jones, A.P., 2000, Late quaternary sediment sources, storage and transfers within mountain basins using clast lithological analysis: Pineta Basin, central Pyrenees, Spain: Geomorphology, v. 34, p. 145-161.

Jones, L.S., and Humphrey, N.F., 1997, Weathering-controlled abrasion in a coarse-grained, meandering reach of the Rio Grande: Implications for the rock record: Geological Society of America Bulletin, v. 109, p. 1080-1088.

Krumbein, W.C., and Pettijohn, F.J., 1938, Manual of Sedimentary Petrography: New York, Appleton-Century Crofts, 475 p.

Mack, G.H., 1981, Composition of modern stream sand in a humid climate derived from low-grade metamorphic and sedimentary foreland fold-thrust belt of North Georgia: Journal of Sedimentary Petrology, v. 51.

Mack, G.H., 1984, Exceptions to the Relationship between Plate-Tectonics and Sandstone Composition: Journal of Sedimentary Petrology, v. 54, p. 212-220.

Mann, W.R., and Caravoc, V.V., 1973, Composition of sand released from three source areas under humid, low relief weathering in the North Carolina Piedmont: Journal of Sedimentary Petrology, v. 43, p. 870-881.

McBride, E.F., and Picard, M.D., 1987, Downstream Changes in Sand Composition, Roundness, and Gravel Size in a Short-Headed, High-Gradient Stream, Northwestern Italy: Journal of Sedimentary Petrology, v. 57, p. 1018-1026.

Niewendorp, C., 1997, Geologic map of Paris Mountain, 7.5 minute quadrangle, Greenville County, South Carolina, South Carolina Department of Natural Resources, Geological Survey Open-File Report 99.

Pope, G.A., 1995, Internal Weathering in Quartz Grains: Physical Geography, v. 16, p. 315-338.

Rice, S., 1999, The nature and controls on downstream fining within sedimentary links: Journal of Sedimentary Research, v. 69, p. 32-39.

Rice, S.P., and Church, M., 2001, Longitudinal profiles in simple alluvial systems: Water Resources Research, v. 37, p. 417-426.

Robinson, R.S., and Johnsson, M.J., 1997, Chemical and physical weathering of fluvial sands in an arctic environment: Sands of the Sagavanirktok River, North Slope, Alaska: Journal of Sedimentary Research, v. 67, p. 560-570.

Savage, K.M., and Potter, P.E., 1991, Petrology of Modern Sands of the Rios Guaviare and Inirida, Southern Colombia - Tropical Climate and Sand Composition: Journal of Geology, v. 99, p. 289-298.

Schumm, S.A., 1968, Speculations concerning paleohydrologic controls of terrestrial sedimentation: Geological Society of America Bulletin, v. 79, p. 1573-1588.

Strahler, A.N., 1952, Hypsometric (area-altitude) analysis of erosional topography: Geological Society of America Bulletin, v. 63, p. 1117-1142.

Surian, N., 2002, Downstream variation in grain size along an Alpine river: analysis of controls and processes: Geomorphology, v. 43, p. 137-149.

Yuretich, R., Knapp, E., Irvine, V., Batchelder, G., McManamon, A., and Schantz, S.P., 1996, Influences upon the rates and mechanisms of chemical weathering and denudation as determined from watershed studies in Massachusetts: Geological Society of America Bulletin, v. 108, p. 1314-1327.