THE INFLUENCE OF CLIMATE AND TOPOGRAPHY ON ROCK-FRAGMENT ABUNDANCE IN MODERN FLUVIAL SANDS OF THE SOUTHERN BLUE RIDGE MOUNTAINS, NORTH CAROLINA[1]

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ABSTRACT: Chemical weathering influences the detrital composition of sand-size sediment derived from source areas subject to different amounts of precipitation in the Coweeta Basin, North Carolina. Of the grain types studied, rock fragments are most sensitive to chemical degradation; therefore, their abundance is the best indicator of cumulative weathering effects. Destruction of sand-size rock fragments by chemical weathering is a function of both the intensity and duration of chemical weathering experienced by grains in regoliths of the source area. In the Coweeta Basin, the intensity of chemical weathering is directly related to the climate via effective precipitation in individual subbasins, whereas the duration of chemical weathering is inversely related to the relief ratio of the watershed. Therefore, soils in watersheds with low-relief ratios and high discharge per unit area experience the most extensive chemical weathering, and sediments derived from these watersheds contain the lowest percentage of rock fragments. The effects of climate alone cannot explain the systematic variation of rock fragment abundance in sediments from the Coweeta Basin. The compositional imprint left on these sediments by chemical weathering is a function of both climate and topographic slope in the sediment source area.

INTRODUCTION

Over the last decade, numerous studies have investigated the effect of climate on the petrology of Holocene sands (Mann and Cavaroc 1973; Young et al. 1975; Basu 1976; Mack and Suttner 1977; Suttner et al. 1981; and Basu 1985). Young et al. (1975) and Suttner et al. (1981) suggested that more intense chemical weathering in the soils of humid source areas accounts for the lesser abundance of rock fragments in sediments derived from these source areas relative to sediments derived from arid sources.

This study is designed to examine the relationship between rock-fragment abundance in Holocene stream sediments and chemical weathering within a source area. It differs from previous studies (Young et al. 1975; Basu 1976; Mack and Suttner 1977) in three fundamental ways. First, this study is confined to one small, topographic basin with considerable climatic variability across its length. This provides better control on factors such as the effects of sediment transport and source-rock variability which otherwise might influence the results.

Second, this study examines the effect of chemical weathering on sand-size sediments within a variable humid climate. Unlike previous studies (e.g., Young et al. 1975), which have compared only the extreme climatic conditions of arid versus humid, this study will focus on a range of humid rainfall conditions (170–240 cm/yr) to determine whether the effects of chemical weathering on sediment composition can be differentiated at this more refined level.

Third, this study specifically investigates the effect of chemical weathering on rock-fragment abundance in the sand-size fraction of the sediments, since these are thought to be the most sensitive indicators of climatic variability in the source area (Basu 1976).

STUDY AREA

The study area for this project is the Coweeta Hydrologic Laboratory, located in the Blue Ridge Mountains of southwestern North Carolina (Fig. 1). The laboratory is a 1,625-hectare basin managed by the U.S. Department of Agriculture Forest Service and is used primarily to investigate the effect of varying practices of forest management on the hydrology and nutrient flow in the basin (Douglass and Swank 1975; Swank and Douglass 1977). However, no watersheds used in this study were disturbed or altered within the past twenty years, so the effects of varied biota in the source area are minimal.

The area was chosen for this study principally because of the large variability of precipitation across the basin. More important than rainfall, however, stream discharge from the areas of high precipitation is more than double that from areas of low precipitation. Discharge represents the effective precipitation, the amount of water which has percolated through the weathering profile and been involved in the chemical weathering of the source rock.

The Coweeta Hydrologic Laboratory is also very well suited to this study because of the large amount of background information and data that are available. These include stream discharge and precipitation data for most of the individual watersheds (USDA Forest Service, unpubl. data); detailed geochemistry of the watersheds, including mineral weathering data (Velbel 1984a); a complete geologic map (Hatcher 1980); and detailed descriptions of geologic units present in the Coweeta Basin (Hatcher 1971, 1974, 1976, 1979). Table 1 lists precipitation, stream discharge, relief ratio, Cumulative Chemical Weathering Index (CCWI), and bedrock type for each of the watersheds used in this study. The CCWI will be discussed later in the paper.

Topography

The relief in the Coweeta Basin is quite rugged, with elevations ranging from 1,592 m at Albert Mountain on

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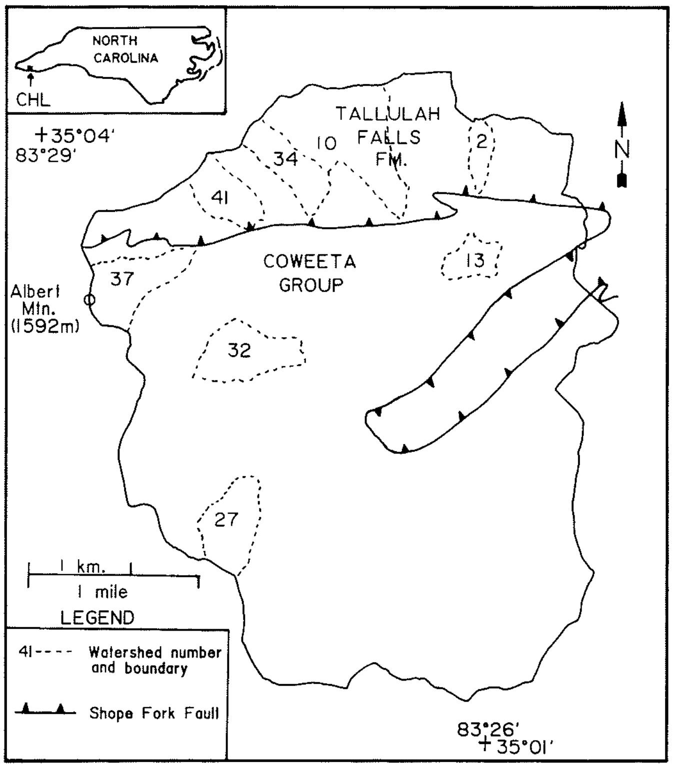

FIG. 1.—Map of the Coweeta Hydrologic Laboratory (CHL) showing relationship of bedrock geology to watersheds used in this study.

TABLE 1.—*Data for watersheds used in study*

Watershed	Precipitation[1] (cm)	Discharge[2] (cm)	Relief[3] Ratio	CCWI[4]	Bedrock Type
2	173	81	0.81	100	Tallulah Falls
10	—	107	0.53	202	Tallulah Falls
34	196	119	0.60	198	Tallulah Falls
41	206	135	0.90	150	Tallulah Falls
13	188	107	0.56	191	Coweeta Group
27	239	173	0.82	211	Coweeta Group
32	216	140	0.51	274	Coweeta Group
37	224	163	1.00	163	Coweeta Group

[1] Average annual precipitation (cm/unit area) calculated from unpublished USDA Forest Servica data.

[2] Average annual discharge (cm/unit area) calculated from unpublished USDA Forest Servica data.

[3] Relief ratio calculated from the maximum relief divided by the maximum length of each watershed.

[4] CCWI (Cumulative Chemical Weathering Index) calculated from the average discharge divided by the relief ratio for each watershed.

the western border to 670 m in the valley of Coweeta Creek in the east. The relief ratio (Carson and Kirkby 1972) across this part of the whole basin is 0.36; however, relief ratios in the individual watersheds are much higher, ranging from 0.51 to 1.00.

Watershed aspect causes minimal variability upon chemical weathering among watersheds underlain by one bedrock group because the four watersheds underlain by the Tallulah Falls Formation all have a southerly exposure, whereas the four watersheds underlain by the Coweeta Group bedrock all have a northerly exposure.

Climate and Hydrology

Average annual precipitation at the Coweeta Hydrologic Laboratory is among the highest in the eastern United States, with precipitation ranging from 170 cm at the lower elevations to 250 cm at the higher elevations (Swank and Douglass 1975). The precipitation is distributed fairly evenly throughout the year with only a minor amount falling as snow. The mean annual temperature for the area is 12.8°C, with average maxima and minima of 33°C and −17°C, respectively (Douglass and Swank 1975).

Stream flow in the basin is perennial. Values for individual watersheds range from 81 to 173 cm per unit area per year and are a function of precipitation and evapotranspiration within each watershed. In this study, climatic variability is measured as stream discharge per unit area per year (effective precipitation). This more accurately represents the water which is involved in the chemical weathering of the source rock than does precipitation per unit area (Duchaufour 1982).

Base flow is sustained by extended drainage of unsaturated soil and saprolite (Hewlett 1961) so that by late summer flows tend to be lowest and most stable. Direct runoff occurs primarily in disturbed watersheds and is usually less than 10 percent of total runoff (Swank and Douglass 1977).

Bedrock Geology

The bedrock consists of two Upper Precambrian, metamorphosed, lithostratigraphic units, the Tallulah Falls Formation and the Coweeta Group, which are juxtaposed along the synclinally folded Shope Fork Thrust Fault (Fig. 1). The Tallulah Falls Formation, the older of the two units, consists predominantly of metagraywackes, muscovite and biotite schists, and amphibolites (Hatcher 1971, 1976).

Hatcher (1979) divides the Coweeta Group into three formations. The oldest of these is the Persimmon Creek Gneiss, a massive oligoclase-quartz-biotite gneiss with minor amounts of metasandstone and schist near the top of the unit. The Coleman River Formation overlies the Persimmon Creek Gneiss and is composed predominantly of meta-arkose and quartz-feldspar gneiss with interlayers of pelitic schist. The Ridgepole Mountain Formation is the uppermost unit of the Coweeta Group and contains the greatest variety of lithologies, including pelitic and biotite schists, clean quartzites to muscovite-chlorite quartzites, and metasandstones (Hatcher 1979).

The major difference between the Tallulah Falls Formation and the Coweeta Group is that the sedimentary protoliths for the Tallulah Falls Formation were less mineralogically mature than for the Coweeta Group (Hatcher 1979).

Geochemistry

Velbel (1985) suggests that the dissolved load of the streams in the Coweeta Basin is affected by two variables, parent rock type and flushing rate. He states that the greater the maturity of the parent-rock protolith (as in the Coweeta Group rocks), the lower the abundance of weatherable minerals, and thus the lower the concentrations of dissolved weathering products in the stream water. In contrast, the Tallulah Falls protoliths were mineralogically less mature, so that streams draining this bedrock unit have higher dissolved concentrations relative to streams draining the Coweeta Group rocks for watersheds with comparable discharges.

The dissolved load in the streams in the Coweeta Basin is also affected by the flushing rate at which the water is percolating through the watersheds. Velbel (1985) suggests that with a high flushing rate, there is less opportunity for the water to acquire solutes, so that the limiting factor may be the rate at which cations are contributed to the percolating solution.

METHODS

Field Sampling

Sand-size stream sediments were collected across the Coweeta Basin in two transects, one sampling sediments derived from the Tallulah Falls Formation and the other for sediments derived from the Coweeta Group bedrock. This was done to minimize the effect of parent-rock variability among watersheds for each group and to provide two data sets to determine reproducibility of the results.

Sediment samples were taken 12 to 30 m above a weir at the base of each watershed. Three samples were taken 6 to 9 m apart to test for homogeneity of the sediments within each watershed. To minimize the effect of transportation, all samples were collected from streams which are first- or second-order, and less than 800 m in length.

Sample Preparation and Point Counting

The three samples from each watershed were individually wet-sieved into three fractions, coarse (-1 to 1 ϕ); medium (1 to 2 ϕ); and fine (2 to 4 ϕ). Portions of each fraction were vacuum-impregnated with epoxy and thin-sectioned. Each thin section was point-counted for monocrystalline quartz, polycrystalline quartz, rock fragments, mica, garnet, plagioclase, heavy minerals and others at about 300 points per thin section. Rock fragments are polymineralic grains, defined following Suttner et al. (1981). Modal percentages of monocrystalline quartz, polycrystalline quartz, rock fragments, and mica were then recalculated to 100 percent for the remaining analysis (Table 2).

OTHER TESTS

The following two tests were devised by the authors to determine whether other factors besides chemical weathering might be affecting the sediment composition in the Coweeta Basin. These tests are very simple and are intended to show any significant effects of transportation of parent-rock variability upon the sediments.

Test for the Effect of Transportation

Garnet grains have been shown to develop a gibbsite-goethite weathering rind in most saprolites from the Coweeta Basin (Velbel 1984b). These rinds are relatively fragile and can withstand little high-energy transportation. To determine the effect of transportation upon the sediments, garnets were categorized as having complete rinds, partial rinds, or no rinds in the coarse-sediment fraction from each watershed.

The results of this test (Table 3) show that a large number of all the garnets from the watersheds draining both Tallulah Falls Formation rocks (watersheds 2, 10, 34, 41) and Coweeta Group rocks (watersheds 13, 27, 32, 37) have either whole (unbroken) or partial gibbsite-goethite weathering rinds. The average relative percent of garnets with whole rinds in sediments derived from the Tallulah Falls Formation rocks is 46 percent, while 83 percent of the garnets have a whole or partial rind. For the sediments derived from the Coweeta Group rocks, the average relative percent of garnets with a whole weathering rind is 51 percent, while 83 percent of these garnets have at least a partial rind.

The occurrence of garnets with partial or no rinds does not necessarily imply that these were eroded during transportation since not all garnets in the weathering profile form gibbsite-goethite weathering rinds. These rinds form primarily in the saprolite horizon of the weathering profile but are often chemically removed once the garnets enter the soil horizon (Velbel 1984b).

The results of this study's test for the effect of transportation on sediments within the Coweeta Basin show that little mechanical breakdown or abrasion of garnet weathering rinds has occurred between the source area and the sampling stations, a distance of less than 800 m for each watershed. However, at distances of 4.8 km or greater downstream, weathering rinds are completely absent on any garnets (Velbel, unpubl. data). This suggests that mechanical breakdown by transportation within the study area is minimal but that continued transportation outside the study area is affecting the most labile grains, such as these gibbsite-goethite weathering rinds.

These results concur with most previous studies investigating the effect of limited distances of transportation upon sediment composition. Young et al. (1975) and Suttner et al. (1981) studied the effect of transportation upon sediments by comparing sand-size stream sediments to the sand-size fraction of the soil from both a gneissic and plutonic source area. They found that the sand fraction of the soil and fluvial sand from the same parent rock had very similar compositions and concluded that the effect of transportation over short distances is relatively minor in comparison to the importance of chemical weathering in the source area. Other studies (Mann and Cavaroc 1973; Basu 1976; Breyer and Bart 1978) have also concluded that the effect of short fluvial transportation on sediments is negligible.

Our test for grain modification by transportation suggests that even mechanically sensitive grain types have been largely unaffected by transportation from the source area to the sampling sites.

TABLE 2.—*Modal percentages of grain types by size fraction in three sediment samples (A, B, C) from each watershed used in this study*

	Coarse			Medium			Fine		
Sample	A	B	C	A	B	C	A	B	C
Watershed 2									
Total Pts	247	265	263	323	252	264	298	250	271
Mono Qtz	13.4	12.5	14.1	35.3	38.9	36.4	52.3	50.0	48.4
Poly Qtz	40.0	40.0	38.4	25.7	17.9	20.0	6.0	5.2	5.9
Rock Frg	43.7	44.1	43.0	27.7	31.0	33.4	25.2	26.0	28.0
Mica	2.8	3.4	4.6	11.5	12.3	10.3	16.4	18.8	17.7
Watershed 10									
Total Pts	273	259	290	265	239	265	255	228	262
Mono Qtz	17.2	20.8	16.5	40.7	38.1	40.0	62.7	64.4	55.0
Poly Qtz	37.0	35.1	40.3	26.4	26.4	24.5	5.5	7.9	6.1
Rock Frg	39.6	35.1	34.5	17.7	22.2	15.0	11.8	11.3	11.1
Mica	6.2	8.8	8.6	15.1	13.4	20.7	20.0	16.2	27.9
Watershed 34									
Total Pts	315	300	327	290	280	316	305	291	317
Mono Qtz	18.7	15.3	19.9	40.7	42.5	39.6	64.6	68.3	62.2
Poly Qtz	29.2	33.6	33.6	16.6	20.3	17.7	3.9	5.8	4.4
Rock Frg	35.3	38.6	35.1	17.4	19.3	17.7	10.8	11.0	11.7
Mica	16.8	12.3	11.3	25.2	17.7	24.7	20.6	14.7	21.7
Watershed 41									
Total Pts	220	264	298	270	278	272	276	277	201
Mono Qtz	19.7	28.8	18.8	45.2	45.0	47.4	52.9	48.3	53.2
Poly Qtz	25.9	20.8	28.5	9.6	13.7	9.6	4.7	4.7	7.4
Rock Frg	41.3	36.7	39.5	27.3	24.8	27.1	19.8	18.8	18.3
Mica	13.0	13.6	13.1	17.9	16.5	16.0	22.5	28.1	21.0
Watershed 13									
Total Pts	292	314	330	256	248	265	257	252	253
Mono Qtz	33.6	27.4	29.1	57.4	59.3	55.5	63.0	64.7	64.4
Poly Qtz	21.2	22.9	24.2	10.9	10.1	8.3	4.7	3.2	4.3
Rock Frg	44.5	49.0	45.8	19.9	21.4	21.1	12.5	11.9	10.7
Mica	0.7	0.7	0.9	11.7	9.3	15.1	19.8	20.2	20.5
Watershed 27									
Total Pts	264	286	230	272	289	257	257	242	247
Mono Qtz	24.6	20.3	18.7	50.7	47.4	51.3	65.0	66.0	64.8
Poly Qtz	34.5	28.0	39.1	10.3	15.2	10.5	2.7	1.7	2.8
Rock Frg	36.7	39.2	35.2	17.6	16.9	17.5	8.6	7.9	8.1
Mica	4.2	12.5	7.0	21.3	20.4	20.6	23.7	24.4	24.3
Watershed 32									
Total Pts	292	238	237	259	267	269	268	278	272
Mono Qtz	40.1	39.5	42.2	56.0	58.4	62.4	67.5	66.2	66.2
Poly Qtz	30.9	30.7	27.0	9.3	9.4	11.5	2.6	3.6	3.7
Rock Frg	26.0	26.5	23.6	16.6	16.9	13.4	6.3	6.5	6.3
Mica	3.1	3.3	7.1	18.1	15.4	12.0	23.5	23.7	23.9
Watershed 37									
Total Pts	362	307	315	288	282	295	278	289	268
Mono Qtz	17.1	14.0	13.7	45.1	44.0	40.7	55.4	54.7	58.2
Poly Qtz	23.2	18.9	28.6	9.0	13.4	12.9	4.0	5.9	4.1
Rock Frg	54.4	57.7	53.0	26.4	28.0	27.1	12.2	12.8	13.4
Mica	5.2	9.4	4.7	19.4	14.5	19.3	28.4	26.6	24.2

Test for Parent-Rock Heterogeneity

Mann and Cavaroc (1973) and Basu et al. (1975) have shown that parent-rock lithology has a significant effect upon the composition of sediments derived from a source area. To minimize this effect in the Coweeta Basin, watersheds were sampled in two groups, one draining the Tallulah Falls Formation and one draining the Coweeta Group bedrock. However, lithologic variability within one of these major lithostratigraphic units may still be a significant factor in affecting sediment compositions among watersheds.

The best way to determine the significance of lithologic variability of a bedrock unit would be to compile a detailed lithologic map of both the Coweeta Group and Tallulah Falls Formation in the Coweeta Basin. This is not feasible since a thick soil-saprolite weathering profile covers most of the bedrock, and intense structural deformation has caused numerous repeated sections so that estimating lithologic abundances and distributions is very

TABLE 3.—*Percentage of garnets with whole, partial, or no weathering rinds in the coarse-size fraction of sediments from each watershed*

Watersheds draining the Tallulah Falls Formation bedrock:			
Watershed	Whole Rind	Partial Rind	No Rind
WS#2	45%	33%	22%
WS#10	48%	43%	9%
WS#34	46%	42%	12%
WS#41	43%	31%	26%
Average	46%	37%	17%
Watersheds draining the Coweeta Group bedrock:			
Watershed	Whole Rind	Partial Rind	No Rind
WS#13	60%	29%	11%
WS#27	52%	32%	16%
WS#32	52%	33%	15%
WS#37	39%	34%	27%
Average	51%	32%	17%

TABLE 4.—*Percentage undulose quartz in the medium-size fraction of sediments from each watershed*

Watersheds draining the Tallulah Falls Formation bedrock:	
Watershed	Undulose
WS#2	49%
WS#10	47%
WS#34	46%
WS#41	46%
Average	47%
Watersheds draining the Coweeta Group bedrock:	
Watershed	Undulose
WS#13	28%
WS#27	27%
WS#32	24%
WS#37	28%
Average	27%

difficult. Therefore, an alternative method was applied which used the undulosity of monocrystalline quartz grains in the sediments as a crude indicator of parent-rock heterogeneity.

To determine roughly the degree of heterogeneity of the parent rock among watersheds underlain exclusively by the Tallulah Falls Formation or the Coweeta Group rocks, we devised a simple test following the work of Basu et al. (1975). They showed that crystalline source rock for a sediment can be distinguished on the petrographic characteristics of quartz, since sediments derived from a low-rank metamorphic source rock tend to have more undulatory monocrystalline quartz and more polycrystalline quartz with greater than three crystals per grain than sediments derived from a plutonic source. Sediments from a middle to high-rank metamorphic source have quartz compositions intermediate between low-rank metamorphic and plutonic.

In this study, approximately 300 monocrystalline quartz grains from the medium-size sand fraction of each watershed were point-counted on a flat stage and classified as either undulose (> 5° extinction) or nonundulose (< 5° extinction). These relative percentages are compared between sediments derived from different watersheds with the same parent rock, either Tallulah Falls Formation or Coweeta Group, in Table 4. These are presented as the percentage of undulose quartz to total monocrystalline quartz in the sediments from watersheds across the Coweeta Basin.

The average percent undulose quartz in the sediment from the four watersheds draining the Tallulah Falls Formation parent rocks is 47 percent, with only a 3 percent range. Among the four watersheds draining the Coweeta Group rocks, the average percent undulose quartz is 27 percent, with only a 4 percent range. However, the average percent undulose quartz varies by 20 percent between sediments derived from the Tallulah Falls Formation and Coweeta Group rocks, indicating that the lithologic difference between these two bedrock groups is reflected in the sediments.

Although the degree of undulosity in quartz is governed by the metamorphic grade and deformational history of the rock as well as the lithology, this test suggests that lithologic homogeneity exists within each of the two major geologic units, but not between these units. Therefore, interwatershed lithologic variability within either major lithostratigraphic unit is not very likely a significant influence on sand composition in the Coweeta Basin.

RESULTS

The average modal abundance of each grain type was calculated from the point counts of three samples taken from each watershed. These were plotted against grain size (coarse, medium, and fine) following the method of Young et al. (1975) for each group of sediments derived either from the Tallulah Falls Formation or Coweeta Group rocks. Of the four grain types plotted, the modal abundance of mica shows the most systematic relationship to the climatic variability (discharge per unit area) in the source area for both the Tallulah Falls and Coweeta Group sediments. As the discharge per unit area for watersheds underlain by Tallulah Falls Formation bedrock increases (from watersheds 2–10 to 34–41; see Table 1), the average modal abundance of mica in these sediments also increases (Fig. 2A), except in watershed 34. The same basic relationship holds between watershed discharge and mica abundance in the sediments derived from the Coweeta Group bedrock (Fig. 2B); with increased discharge per unit area among the four watersheds, there is a corresponding increase in the average abundance of mica in these sediments, except for the fine fraction in watershed 27.

There is no obvious relationship between the climatic variability and the modal abundance of monocrystalline quartz, polycrystalline quartz, or rock fragments from these plots.

DISCUSSION

Young et al. (1975) observed climatic imprinting from the source area in recent fluvial sediments derived from low-rank metamorphic, high-rank metamorphic, and plutonic source rocks. They found that major petrograph-

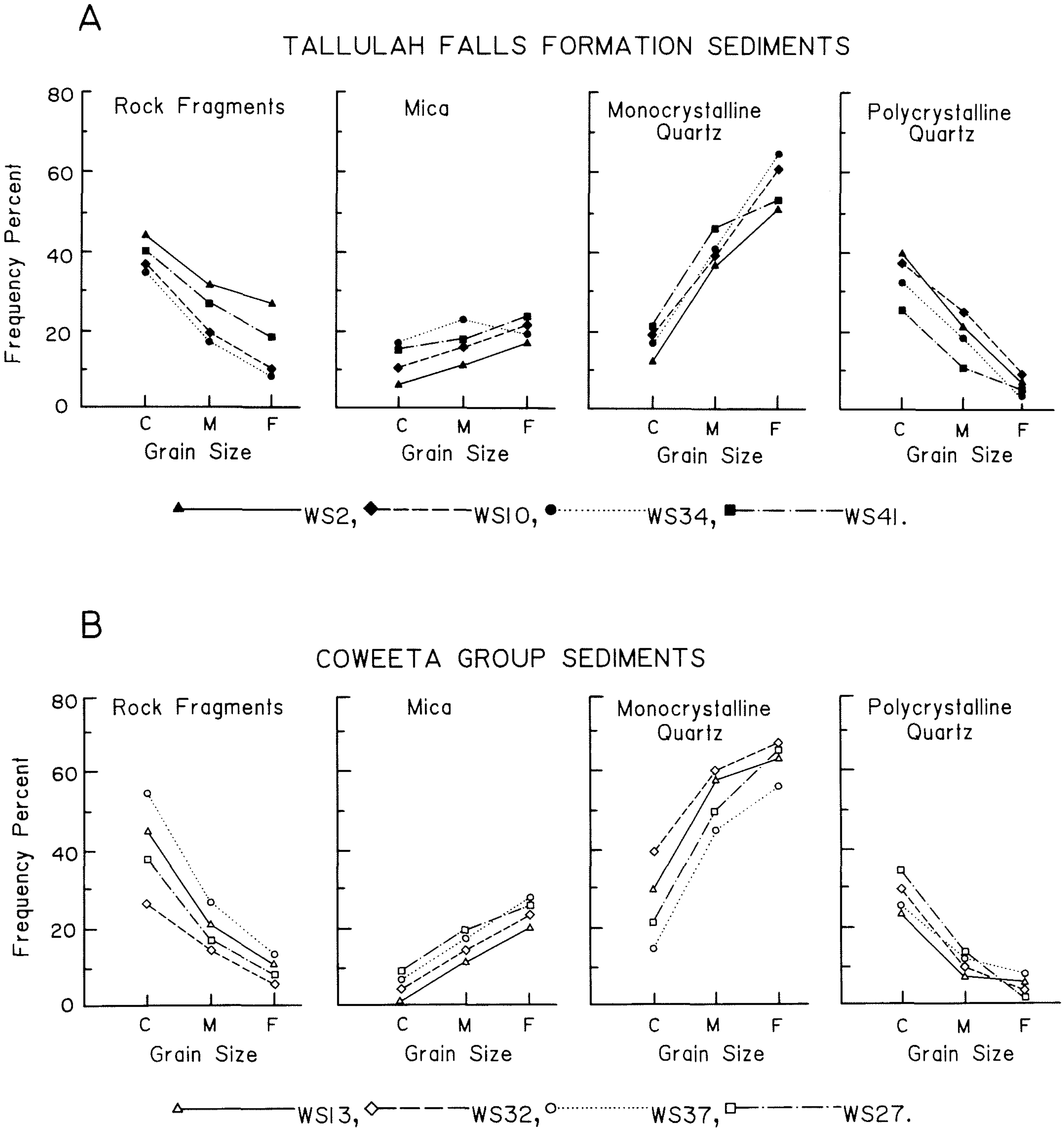

FIG. 2.—Variation in composition of fluvial sand from watersheds draining (A) the Tallulah Falls Formation and (B) the Coweeta Group bedrock.

ic distinctions exist in sediments derived from the same source-rock types between the humid southeastern U.S. and the arid northwestern U.S. Rock fragments were much more abundant in all the sediments derived from the arid climate, whereas monocrystalline and polycrystalline quartz were more abundant in sediments derived from the more humid climate. Young et al. (1975) explained these results by suggesting that rock fragments are easily destroyed by vigorous chemical weathering in a more humid environment. On the other hand, quartz (mono- or polycrystalline) is much more resistant to chemical weathering and actually increases in relative abundance in the more humid climates because of the release of quartz grains from the weathering of the rock fragments. Basu (1976) concluded that, of the sand-size fraction in fluvial sediments, rock fragments are the best climatic indicators since they are the most sensitive to destruction by chemical weathering.

The results of plotting modal abundance of grain type to grain size in this study indicate that only the mica grains in both sediment groups show a systematic relationship to the climatic variability across the Coweeta Basin. This contradicts the original hypothesis that rock fragments are the most sensitive to chemical weathering. To resolve this contradiction, the specific factors affecting the sediment composition in the Coweeta Basin must first be examined. The effects of transportation and parent-rock heterogeneity have already been shown to be minimal. Consequently, we hypothesize that the modal abundances of grain types reflect the total amount of chemical weathering that occurs in the source area, which is related only in part to climate.

The extent of chemical weathering, as measured by chemical or mineralogical changes, depends upon 1) the intensity of the weathering, and 2) the time interval over which the weathering occurs (Krynine 1942; Pettijohn et al. 1972; Suttner et al. 1981; Basu 1985). Franzinelli and Potter (1983) substantiated this by showing that quartz arenite sands could be produced from granitic bedrock in a low-relief, humid climate region of the Amazon Basin by chemical weathering alone. More recently, Johnson et al. (1986) have shown similar results for sediments derived from the Orinoco River basin in Colombia and Venezuela.

Basu (1985) also suggests that topographic slope and climate in the source area have a combined effect upon chemical weathering. He shows, using recalculated data from Ruxton (1970), that the material on the crest of hills is more highly weathered than the material on the slopes, and he attributes this to the longer duration of weathering due to lower erosion rates.

In the Coweeta Basin, chemical weathering is also a function of both time and intensity. The intensity of chemical weathering is largely dependent upon the climate, whereas the duration of weathering is inversely related to the topographic slope in the source area. Areas with high slope have higher erosion rates, which reduces the residence time of material in the weathering profile. Therefore, in the Coweeta Basin, watersheds with high discharges and low topographic slopes have the maximum extent of chemical weathering, whereas watersheds with low discharges and high slopes have the minimum extent of chemical weathering.

In this study, intensity of weathering is measured as effective precipitation (stream discharge per watershed unit area) and duration of weathering is measured as the relief ratio, maximum relief divided by the maximum length of each watershed. The intensity is the amount of weathering that occurs over a certain time interval, whereas the duration is the number of time intervals over which total weathering has occurred. An equation combining the intensity and duration of chemical weathering in watersheds from the Coweeta Basin can best be written as:

$$\begin{array}{c}\text{Effective}\\\text{Precipitation}\end{array} \times \frac{1}{\text{Relief Ratio}} = \begin{array}{c}\text{Cumulative}\\\text{Chemical}\\\text{Weathering}\\\text{Index}\end{array}$$

The Cumulative Chemical Weathering Index (CCWI) approximates the total extent of chemical weathering in each watershed from the Coweeta Basin (Table 1, CCWI). Plots of the modal abundance of rock fragments against the CCWI for each grain size show that as the CCWI increases, the percent rock fragments systematically decreases for both the Tallulah Falls Formation (Fig. 3A) and the Coweeta Group (Fig. 3B) sediments.

Correlation coefficients (r^2) show that all correlations (coarse, medium, and fine) of the modal abundance of rock fragments against the CCWI are statistically significant at the 1 percent level for both the Tallulah Falls and Coweeta Group sediments. Correlation coefficients were also calculated for each size fraction of each grain type (monocrystalline quartz, polycrystalline quartz, rock fragments, and mica) versus 1) effective precipitation; 2) relief ratio; and 3) the Cumulative Chemical Weathering Index. However, none of these correlations, including the modal abundance of mica versus the watershed discharge, are statistically significant at the 1 percent level for the three size fractions in both sediment groups except rock fragments versus CCWI.

Numerous reasons may exist why only the rock fragments in the sediments reflect the total extent of chemical weathering. Foremost is that polymineralic grains have heterogeneous crystal boundaries which are avenues for fluid movement and eventually cause physical breakdown of these grains. This would be especially true in foliated, metamorphic rocks where planar and nonplanar crystals (e.g., mica and quartz, respectively) have physically weak crystal boundaries. Second, chemical dissolution of certain minerals such as quartz occurs at such a slow rate in the weathering profile that the duration of weathering may be too short to see any chemical weathering imprints on these monomineralic grains. However, the chemical destruction of one labile crystal in a polymineralic grain may cause a more rapid physical breakdown of that grain and thus make rock fragments more prone to chemical weathering while still in the source area.

The relationship between the erosion rate as a function of the topographic slope of a watershed and the residence time of grains in the weathering profile have been discussed. Less obvious, but potentially as important to the duration of chemical weathering that grains experience in a watershed, is the relationship between topographic slope and the mineral-fluid contact time, the time that fluid resides in the weathering profile for an individual storm event. Since steeper slopes drain more quickly than shallow slopes, watersheds with high topographic slopes will have shorter mineral-fluid contact times. Velbel (1985) has suggested that the interface controlled dissolution rates of minerals may be the rate determining step for many

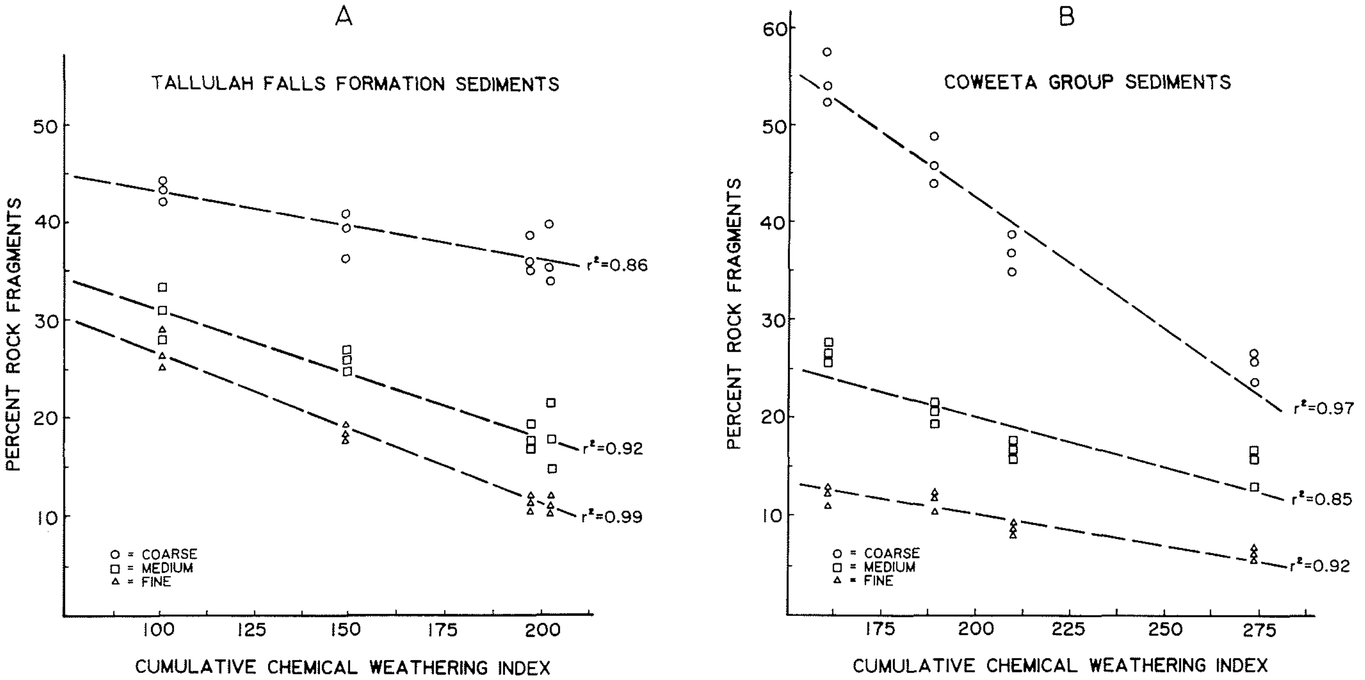

FIG. 3.—Percentage rock fragments versus the Cumulative Chemical Weathering Index for watersheds draining (A) the Tallulah Falls Formation and (B) the Coweeta Group bedrock (r^2 = correlation coefficient for each grain size).

of the mineral weathering reactions in the Coweeta Basin. Therefore, in watersheds with steeper slopes, where water drains more quickly, there is less time for the water to acquire solutes.

The duration of chemical weathering in the Coweeta Basin is a function of the total time that weathering fluids and weatherable minerals are in contact. Because of higher erosion rates and shorter mineral-fluid contact times, watersheds with high topographic slopes have overall shorter durations of chemical weathering.

In this study, we have shown that sand composition records the cumulative extent of weathering on grains while they reside in the weathering profiles. Although we have not identified compositional variations due to climate alone (e.g., Young et al. 1975; Mack and Suttner 1977; Suttner et al. 1981; Mack 1984), the results of this study indicate that climate combined with topography can yield systematic variations in sand composition. The importance of topographic factors has been discussed qualitatively for some time (e.g., Pettijohn et al. 1972; Suttner 1974; Franzinelli and Potter 1983; Potter 1984, 1986; Basu 1985). Our results suggest that topography, in combination with climate, can be quantitatively incorporated into a model of sand genesis by using easily determined and widely accepted measures of drainage-basin geomorphology.

These results reaffirm the importance of physiography in determining the compositions of sand and sandstones. By demonstrating a relationship between geomorphology, climate, and sand composition, we hope that factors like climate and topography will continue to be recognized as key aspects of sandstone provenance.

SUMMARY AND CONCLUSIONS

The abundance of rock fragments in sand-sized sediment derived from a source area with variable precipitation in the southern Appalachians does not correlate with climate but, instead, correlates with the total (cumulative) extent of chemical weathering in the source area. The total chemical weathering in the Coweeta Basin is a function of the duration and intensity of the chemical weathering in the source area. Duration of chemical weathering is related to the topography of a watershed, as measured by its relief ratio, whereas intensity is directly related to climate via the effective precipitation. The combination of climate and topography, quantified here as the Cumulative Chemical Weathering Index, yields systematic variations of rock-fragment abundance in sediments from the Coweeta Basin.

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