THE GEOCHEMISTRY OF STREAM SEDIMENTS, PANAMA: WEATHERING IN A TROPICAL WATERSHED

A Senior Thesis

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By

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ABSTRACT

Chemical weathering of Earth's surface is the primary process controlling landscape and soil development, as well as the geochemistry of natural waters. In addition, chemical weathering of silicate minerals, which consumes atmospheric CO_2, is a major control of long-term climate variation. Although much has been published related to the rates and intensities of chemical weathering for temperate and high-latitude settings, few data exist on chemical weathering in mountainous tropical regions.

This study focuses on the Río Chagres watershed. The Río Chagres is one of Panama's most important rivers. This 414 km^2 watershed produces a total runoff of $4.4x10^5$ m^3 per year during years of higher flow, supplying almost half the water required to operate the Panama Canal. The highest areas of the watershed rise to elevations of 1000m. The high rainfall (c. 2000mm/yr), warm temperatures (mean annual T° ~19°C), and steep forested topography all increase rates of chemical weathering in the watersheds relative to more temperate geographic settings.

Samples have been analyzed for the purpose of establishing the intensity of chemical weathering in this environment using X-Ray Fluorescence Spectroscopic (XRF) techniques for both major and trace element composition. Stream sediment geochemistry has been compared to the geochemistry of local bedrock lithologies and normalized to upper continental crust values. XRF analyses of sediments from the Río Chagres headwaters demonstrate depletion in Ca^{2+}, Sr^{2+}, Ba^{2+}, K^+ and Rb^+ relative to average upper continental crust, suggesting rapid loss of these elements. Grain-size analyses of the stream sediments suggest there is a positive relationship between sediment size, the rate of chemical weathering and the watershed geology. Watersheds draining mostly altered volcanic lithologies have mainly sand-size sediments by comparison to watersheds draining mainly intrusive mafic lithologies which tend to have coarser sediments. These data, combined with previously reported water geochemical data, suggest intensive weathering of the altered volcanic lithologies and that the intrusive mafic lithologies are not being weathered at the same rate or intensity as the volcanic lithologies.

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TABLE OF CONTENTS

LIST OF FIGURES

Chemical Weathering

Introduction

Chemical weathering is one of the most important processes occurring on the Earth's surface. This process affects water chemistry, develops soil and shapes the landscape. Because atmospheric CO_2 is consumed during chemical weathering, the process also has long term effects on the global climate.

During the chemical weathering of silicate rocks, "primary" minerals, which formed at high temperatures and pressures are converted to "secondary" minerals or "weathering products", and elements such as Na, Ca and K are lost into solution, thereby increasing river/stream water in these elements and leaving cation-deficient "secondary" minerals or weathering products behind.

The intensity of chemical weathering is influenced by several things but the lithology of the bedrock and the climate (i.e. temperature and precipitation) are probably the most important. The high annual rainfall and warm temperatures make tropical regions of the Earth ideal for study of weathering of silicate minerals. Climates primarily composed of tropical temperatures, exhibit much faster rates of weathering as opposed to temperate and polar climates which generally have much slower rates of weathering (Berner and Berner, 1996).

Precipitation also has a direct control on weathering. According to the general chemical weathering equation:

$$\textbf{aluminosilicate mineral} + H_2O + CO_2 \rightarrow \textbf{clay mineral} + \textbf{cation} + H_4SiO_4 + 2\,HCO_3^-$$

Increased amounts of carbon dioxide in the atmosphere and water as introduced to the system as precipitation coupled with more readily weathered lithologies, especially mafic rocks, increases rates of chemical weathering dramatically.

As noted above, rock lithology is also an important control of chemical weathering. Igneous rocks formed at high temperatures and pressures, relative to the Earth's surface, are much more easily weathered than other rock types. Tectonic uplift and enhanced erosion rates such as those observed in mountainous regions also enhance chemical weathering rates (Carey et al., 2005).

Weathering in a Tropical Rainforest Ecosystem

When water supply is abundant, vegetation plentiful and the mean annual temperature above 19°C, the effects and rate of chemical are easily predicted. It is assumed that under these conditions, chemical weathering should be greatest, yet very little data exist on chemical weathering rates in tropical rainforest areas such as those in Panama and other similar locales. Hence, the motivation for this study was to analyze stream sediments from tropical watersheds underlain by a suite of different lithologies and establish the intensity of weathering.

Figure 1: Río Chagres outlet into the Caribbean Sea (Photo by Gregg McElwee).

Study Area

Geography and Climate

The Río Chagres basin is located in central Panama at approximately 9° 13'-9 24' N latitude and 79° 16'-79° 33' W latitude, constituting approximately 414km^2 (Figure 4). Panama's climate is considered tropical based on it's latitudinal location 7-10°N and it's monthly mean temperatures all lying above 18°C (64°F). Using the Köppen climate classification system (Palka, 2005), Panama is divided into two different climates types. On the Atlantic side of the continental divide the country exhibits an ***Af*** climate (sufficient precipitation all months), whereas on the Pacific side an ***Aw*** climate (dry season during winter) is prominent. The Río Chagres basin is located in central Panama at approximately 9° 13'-9 24' N latitude and 79° 16'-79° 33' W latitude (Figure 2). The Río Chagres watershed lies in the middle of these two climate zones.

On Panama's northern side temperatures are slightly higher and precipitation rates are greater averaging 2,970mm on the Atlantic coast compared to 1,650mm on the Pacific (Microsoft, 2001) Climate controls such as insolation, pressure, ocean currents, maritime influence, altitude, and topographic barriers effect Panama's climate because of its mountainous terrain, equatorial proximity, coastal position between the Pacific Ocean and Caribbean Sea, and its location relative to the inter-tropical convergence zone (ITCZ) (Palka, 2005). During the summer and winter months there is little temperature variation due to high amounts of insolation throughout the year.

Topographic barriers play a major role in precipitation rates across the country. The sustained offshore wind flow from the Caribbean Sea results in orographic precipitation effects. These effects include higher precipitation totals throughout the year, and only short dry season during the winter months (December-April) (Palka, 2005).

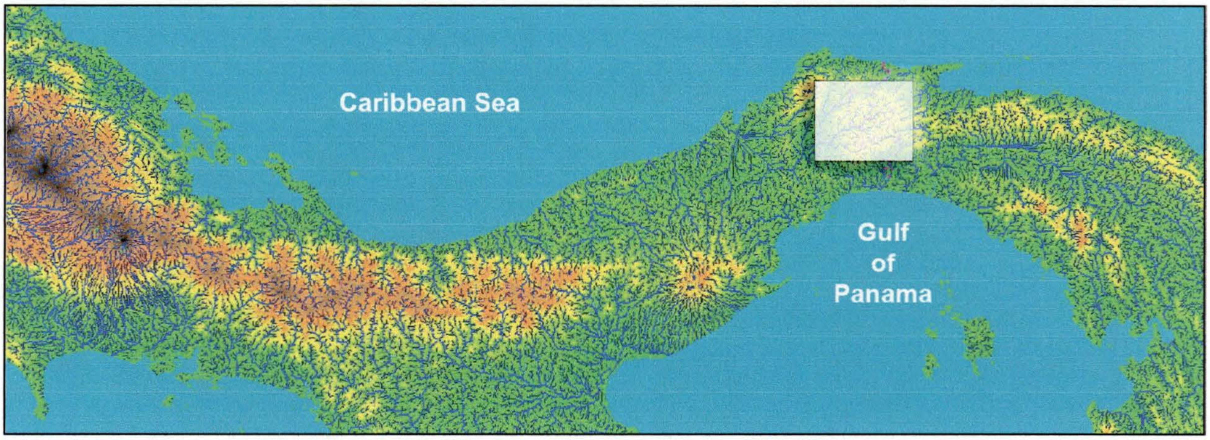

Figure 2: A Digital Elevation Map (DEM) of Panama from the Shuttle Radar Topography Mission (SRTM) data. The white box represents the Río Chagres watershed area. Rivers and streams have been emphasized (Mitasova, 2006).

Geologic Features

The development of the Panamanian isthmus resulted from the interaction of the North American, Caribbean, South American, Cocos, and Nazca plates with the Panama microplate over the past 150 Ma (Harmon, 2005). Beginning in the late Jurassic (c. 140 Ma), when a proto-Caribbean seaway existed between North and South America, the proto-Greater Antilles arc began to develop approximately where modern day Panama exists. Because of continuous seafloor spreading, which also began the separation of South America and Africa at the same time, by the middle Cretaceous (c. 100 Ma) the proto-Caribbean seaway had become very wide. By the late Cretaceous, seafloor spreading had ceased and the initiation of the subduction of the Farallon plate beneath the western edge of the Caribbean plate creating the volcanic arc responsible for much of the Panamanian terrane. The Farallon plate had been almost completely subducted by the middle-to-late Miocene (c. 50-40 Ma) and the Costa Rica-Panama arc was in place to form the proto-Central America magmatic arc. During the middle-to-late Miocene, the Farallon plate split into two: the Nazca and Cocos plates. The closure of the Pacific-Caribbean seaway occurred between 10 and 20 Ma (Coates et al., 2004) and after 5 Ma the resulting uplift had changed global oceanic circulation. Today the Panama microplate is moving northward which has led to regional uplift and left-lateral strike slip faulting (creating the s-curve of Panama).

According to Wörner et al. (2005), four basic rock types, between 100 Ma and 50 Ma, are observed underlying the upper Río Chagres basin:

- volcanic rocks, including basalts and andesites, that were erupted as submarine lava flows
- volcaniclastic rocks from the submarine eruption and fragmentation of lavas
- coarse-grained igneous rocks, mainly granite and tonalite, that intruded into the volcanic pile and cooled slowly
- basaltic and andesitic dikes

Because of the dense tropical rainforest present, bedrock exposures within the Río Chagres Basin are limited to river channels, so it is impossible to fully reconstruct the areal extent and structural relations of the underlying lithologies. Goossens et al. (1977) noted the Cretaceous to Eocene age range for these four rock types, later described by Wörner et al. (2005), and their tholeiitic character, proposing their correlation from northern Costa Rica to the northern Colombian Andes. The Río Chagres is also very prone to landslides because of the steep slopes, on average greater than 45°, which are present in over 90% of the basin (Rengers and Wohl, 2006). Heavy tropical rainfalls and frequent landsliding leads to substantial physical weathering and erosion rates (Nichols et al., 2005) which in turn can enhance chemical weathering rates (Lyons et al., 2006 GSA Presentation).

Figure 3: Landslide in the upper reaches of a tributary to the Río Chagres; approximately three (3) meters in height (Photo by Gregg McElwee).

Analytical Methods

Sample Collection

Stream sediment samples were collected during Panama's wet (August 2006) and dry (February 2007) seasons. One to eight samples were collected from four different watersheds east of the Panama canal. This study will only be focusing on the eight samples collected from the Río Chagres watershed (Figure 4).

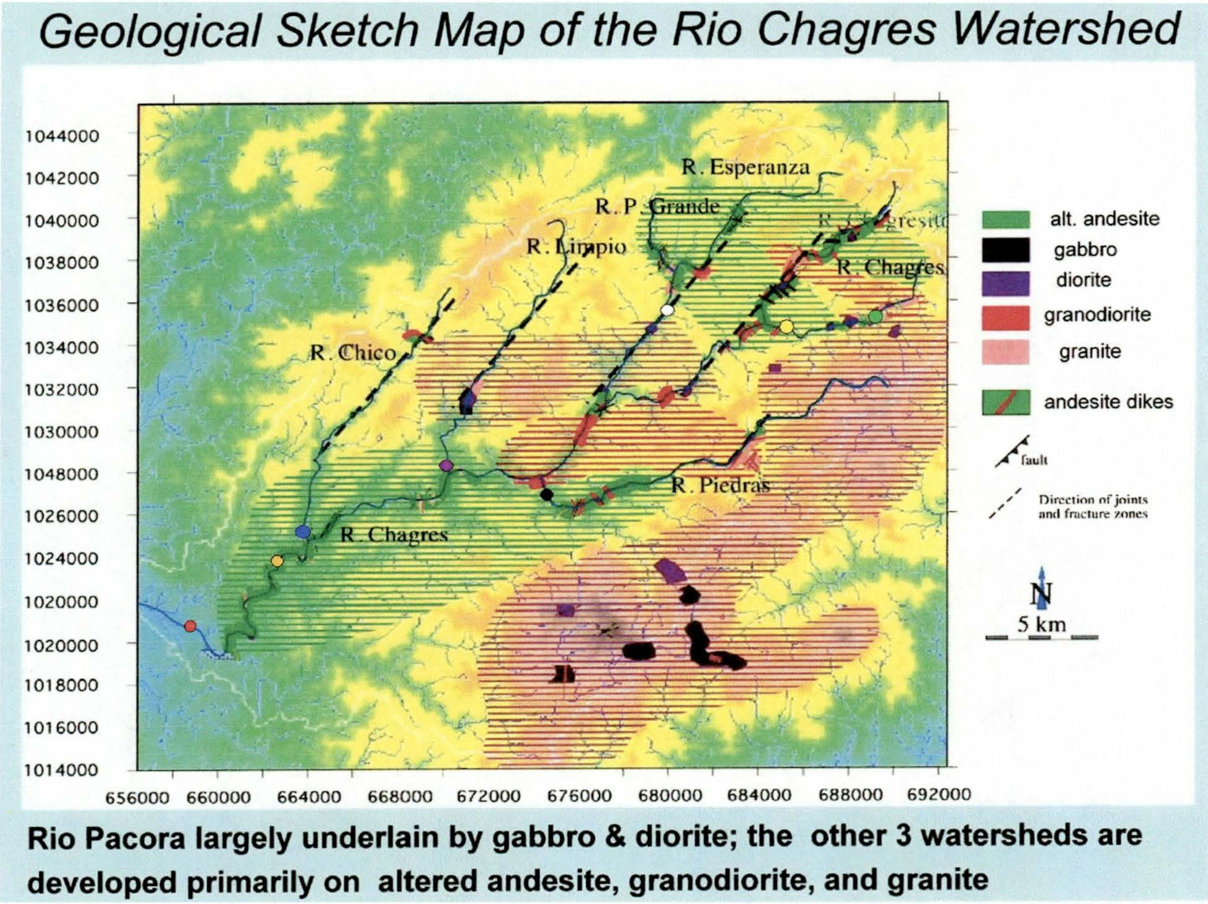

Figure 4: Geologic Map of the Río Chagres watershed with sediment sample sites marked with colored circles (Wörner et al., 2005).

Sampling Equipment

The sampling equipment used at each site included latex gloves, clean four ounce plastic sample containers later to be sealed with electrical tape, a plastic sampling spoon as well as a GPS unit.

Sampling Procedure

Samples were collected where sediments appeared representative of upstream geology. One sample was taken at each sample site along with a GPS reading to provide geographical location. Sediment was collected as close to the center of the streams as possible and stored in clean (distilled-deionized water rinsed), four-ounce plastic sample containers.

Sample Preparation

Upon return to the US, planned analyses of the sediment samples included dry sieving and X-Ray Fluorescence (XRF) analysis.

Sieve Analysis

Samples were dried at room temperature then crushed lightly in a mortar and pestle but only to disaggregate individual grains. The sediments were then sieved into three portions: a fine fraction (<63um), a sand fraction (between 63um and 2mm), and a coarse fraction (>2mm). Each fraction was weighed then reconstituted for XRF analysis.

XRF Analysis

The grain size samples were reconstituted, crushed and homogenized in a shatterbox for 5-7 minutes to produce approximately 10g of silt-size sediment. This was then dried at 105° C for at least twenty-four hours. After drying, approximately three grams of sample were weighed into aluminum sample dishes then combusted at 1025° C for one hour. Samples were then reweighed to determine loss on ignition (LOI). 2.5000 grams of sample were mixed with 10.0000 grams of lithium tetraborate ($Li_2B_4O_7$) and fused into a bead using a Phillips® Perl'x 3® automatic bead machine. The bead was then analyzed in a PANalytical® MagiX Pro® XRF spectrometer to determine bulk geochemistry data of the sediments (Goldsmith et al., in review). Element concentration was corrected for loss on ignition (LOI) and averaged over three consecutive runs. The worst standard deviations were <10% and the majority were better than <1% (Rb was the only inconsistent result). The standard run was the USGS W-2 (Diabase), and was analyzed every four samples. Most values were within the range of the standard or within 2.5% of the upper limit of the USGS recommended value (the exceptions were: Cu, 8.3%; Ni, 13.6%; Rb, 9.5%; Zn, 6.2%; and Zr, 6.7%)

Results

Sieve Data

Thirteen sediments from the Río Chagres and neighboring watersheds were compared by their elemental oxide concentrations and grain-size fraction. The majority of the samples were primarily composed of a large sand fraction (>75% sand-size grains). Figure 5 is a plot of relative distance from the termination of the watershed into Lago Alajuela (Figure 4) compared to the percent fine, sand and coarse fractions of the four sediment samples collected from the Río Chagres.

A few conclusions were able to be drawn from the sediment and elemental abundance data. As shown in Figure 6, as the sand fraction increases, so does the Si content of the sediment, while Al, Fe, Ba, Zn and V decrease as the sand fraction increases (Figures 7, 8 and 9, respectively). All other major and trace elements do not show any correlation with grain-size (Figures 10 and 11).

XRF Data Normalization

Eight sediments from the Río Chagres watershed were normalized to both the regional lithologies using data from Wörner (unpublished) and the Upper Continental Crust using data from Taylor and McLennan (1985) (Figures 17 and 18, respectively). To normalize to the regional lithologies, an approximation was made as to the distribution of rock types upstream of each sample site based on the geologic map in Figure 4. By plotting each rock specimen collected by Wörner the average rock type (diorite, andesite, basalt, etc.) for each watershed could be established. Then using the approximate distribution a weighted average was computed to establish an "ideal" rock which we could normalize our sediments. This was done for each sample, using only rock specimens upstream of each sample site. In addition, the samples have also been normalized to the more traditional Upper Continental Crust (UCC) (Taylor and McLennan, 1985) and plotted in spider-plots to more easily recognize trends in element abundance (Gaillardet et al., 1997). Historically, UCC values have been used to normalize sediment data in watersheds of mixed lithologies (Gaillardet et al., 1997).

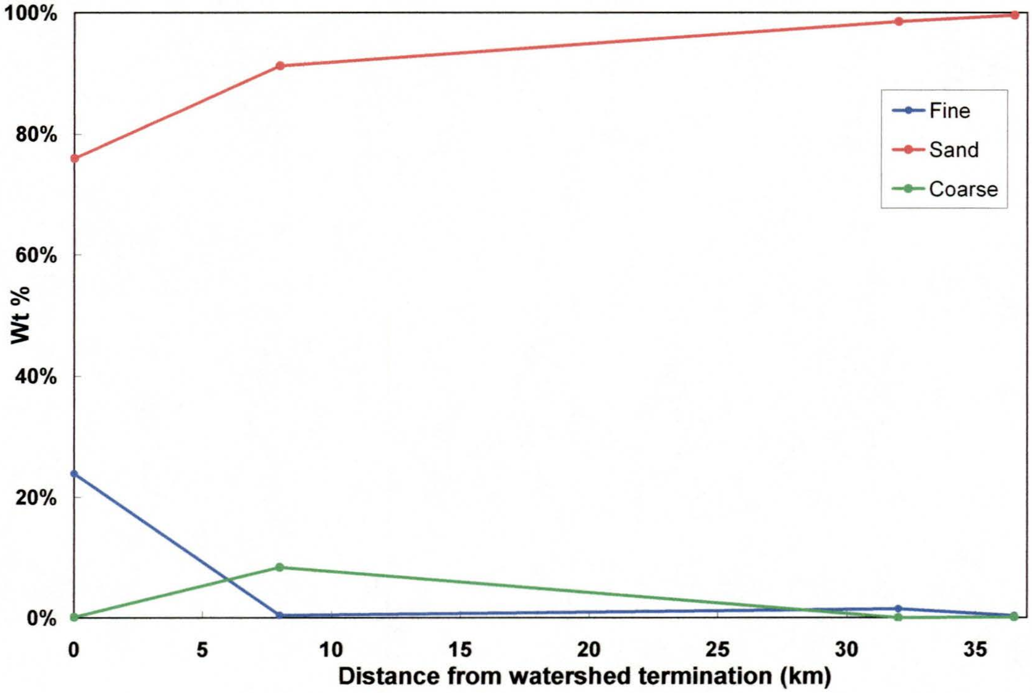

Figure 5: Plot of Distance from watershed termination point vs. wt % size fraction

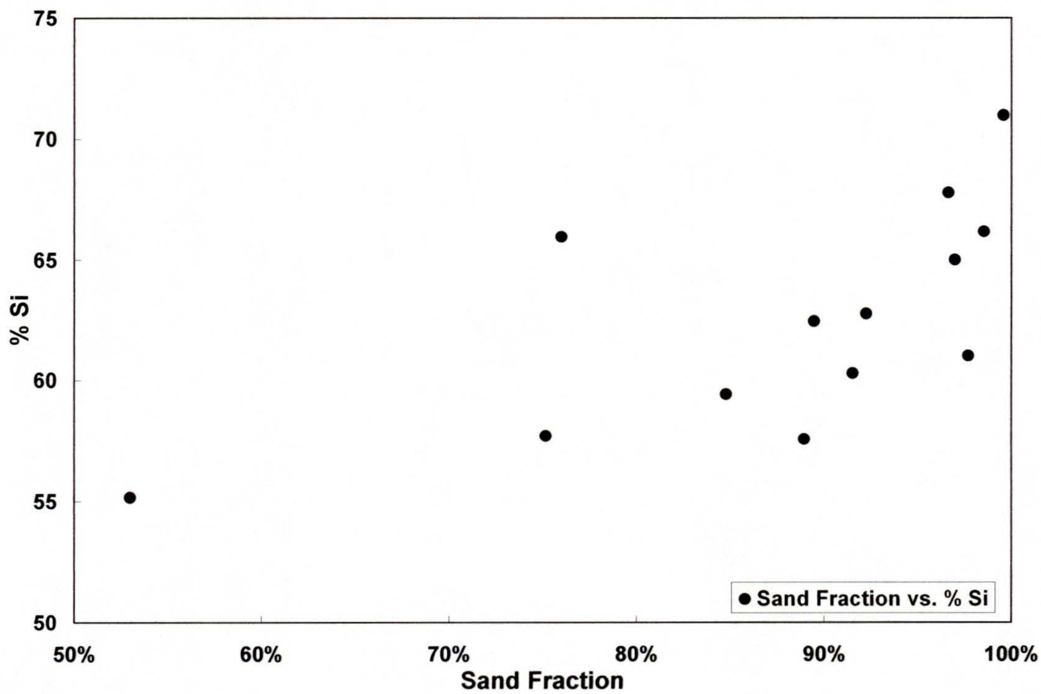

Figure 6: Plot of Sand Fraction vs. % Si

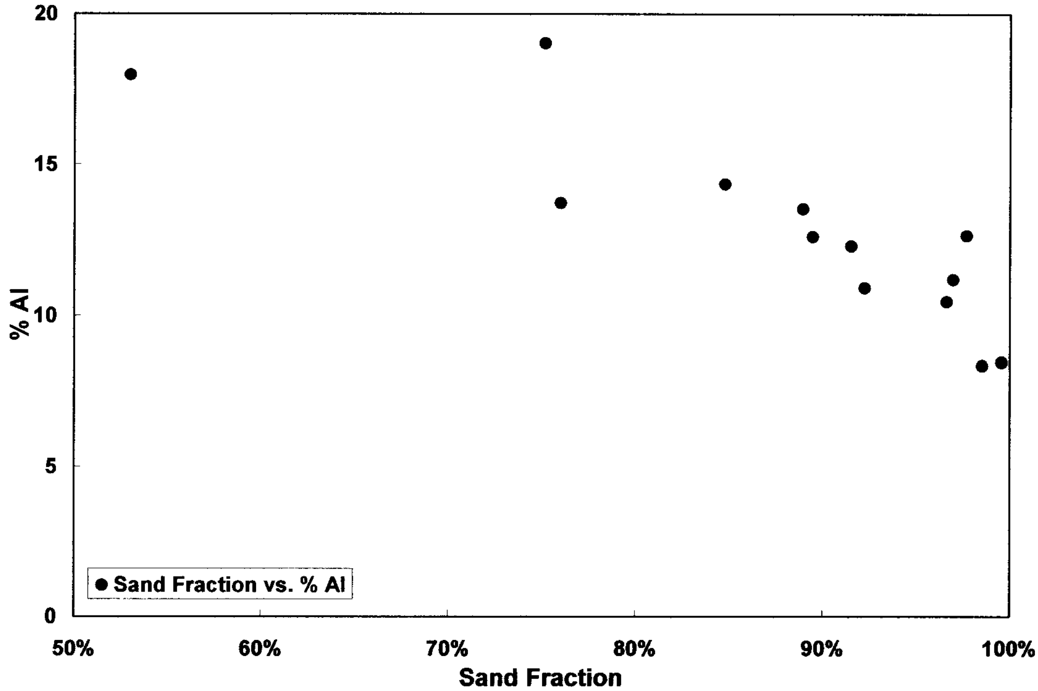

Figure 7: Plot of Sand Fraction vs. % Al

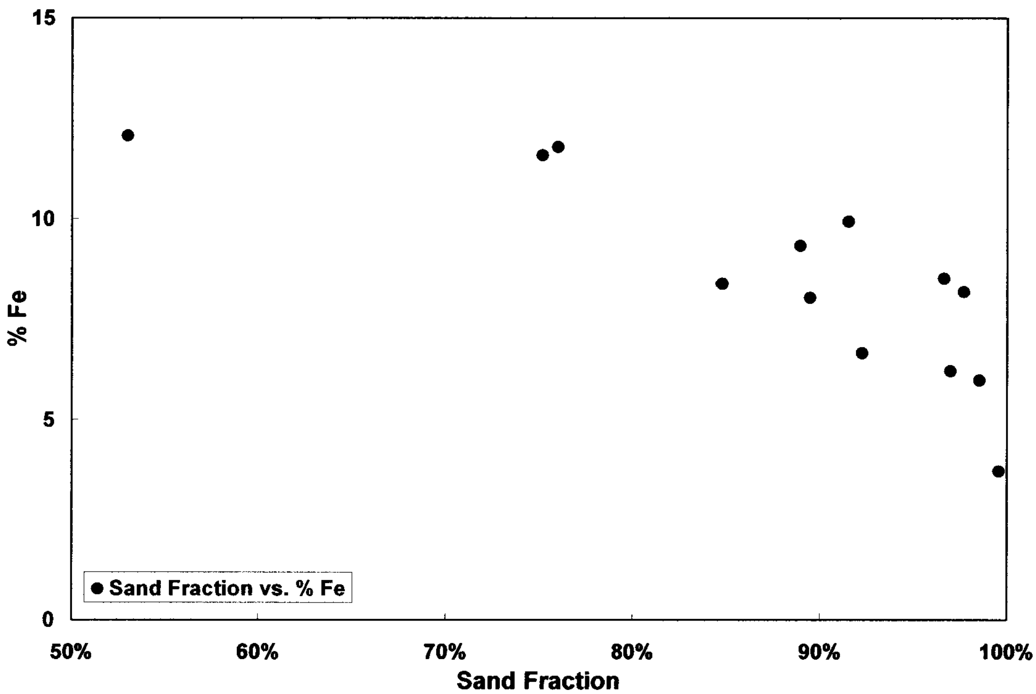

Figure 8: Plot of Sand Fraction vs. % Fe

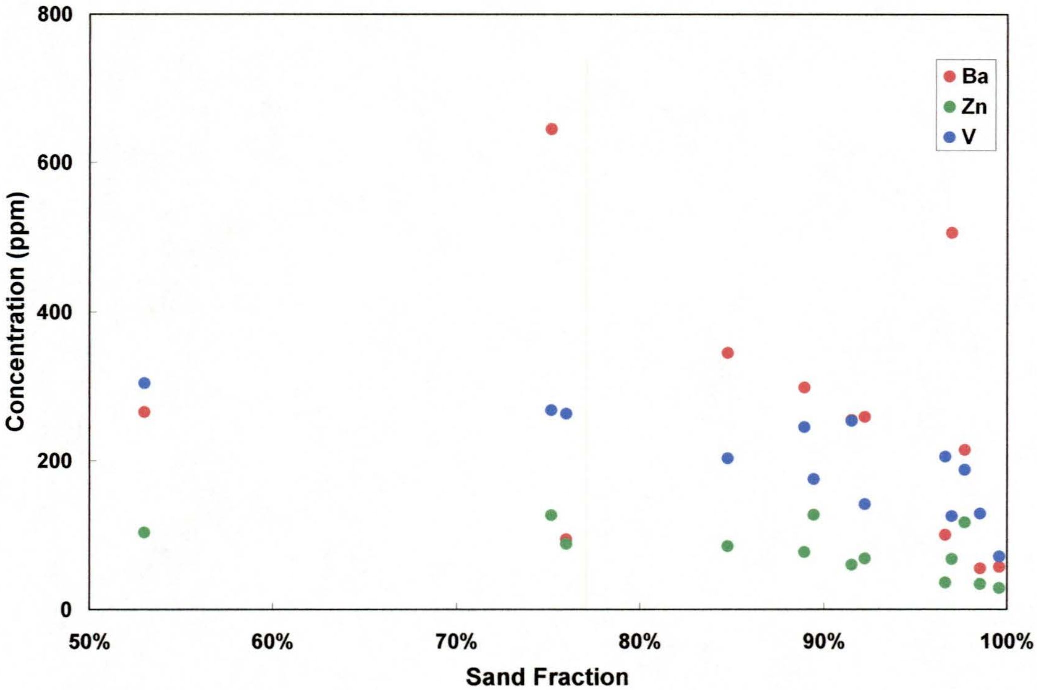

Figure 9: Plot of Sand Fraction vs. Ba, Zn and V Concentrations

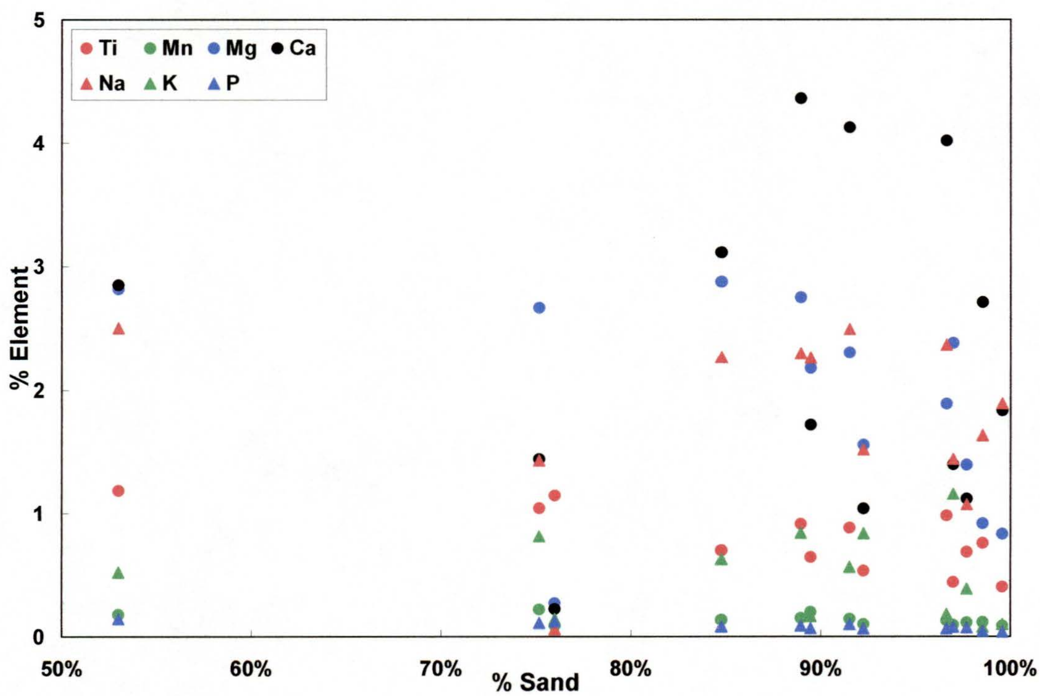

Figure 10: Plot of Sand Fraction vs. % Elemental Abundance

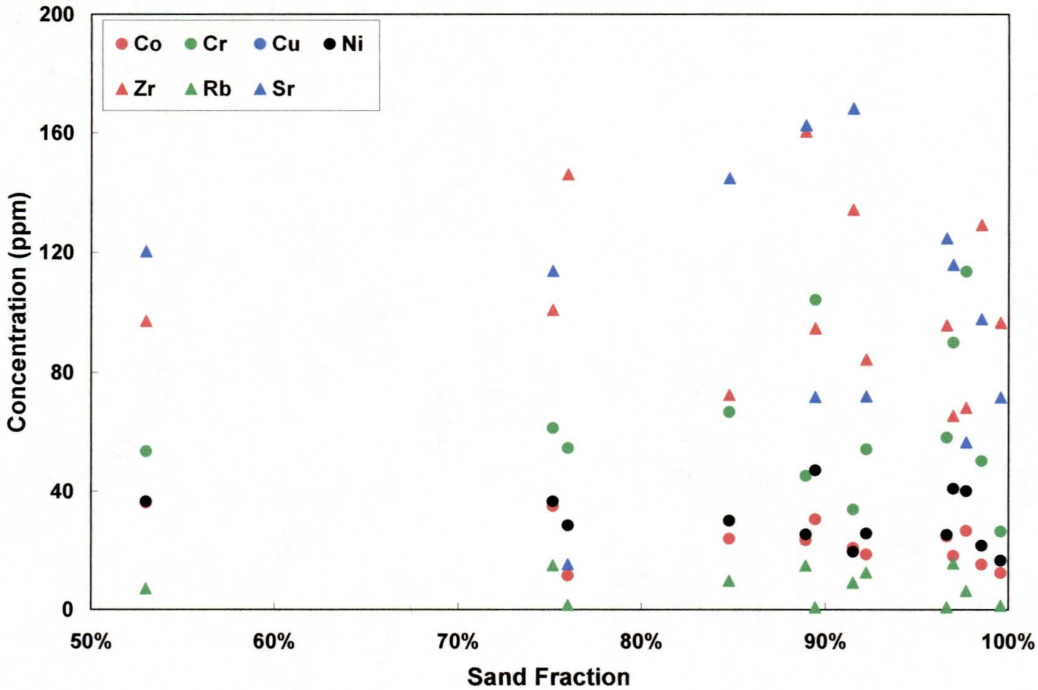

Figure 11: Plot of Sand Fraction vs. Co, Cr, Cu, Ni, Zr, Rb and Sr Concentrations

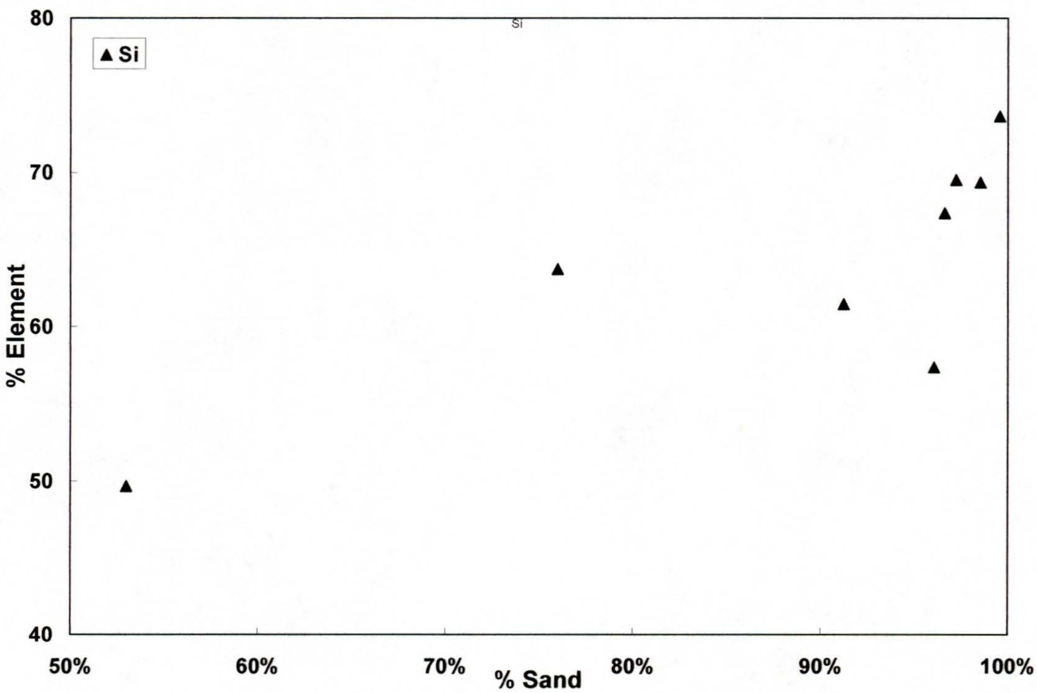

Figure 12: Plot of Sand Fraction vs. % Si in the Río Chagres watershed only

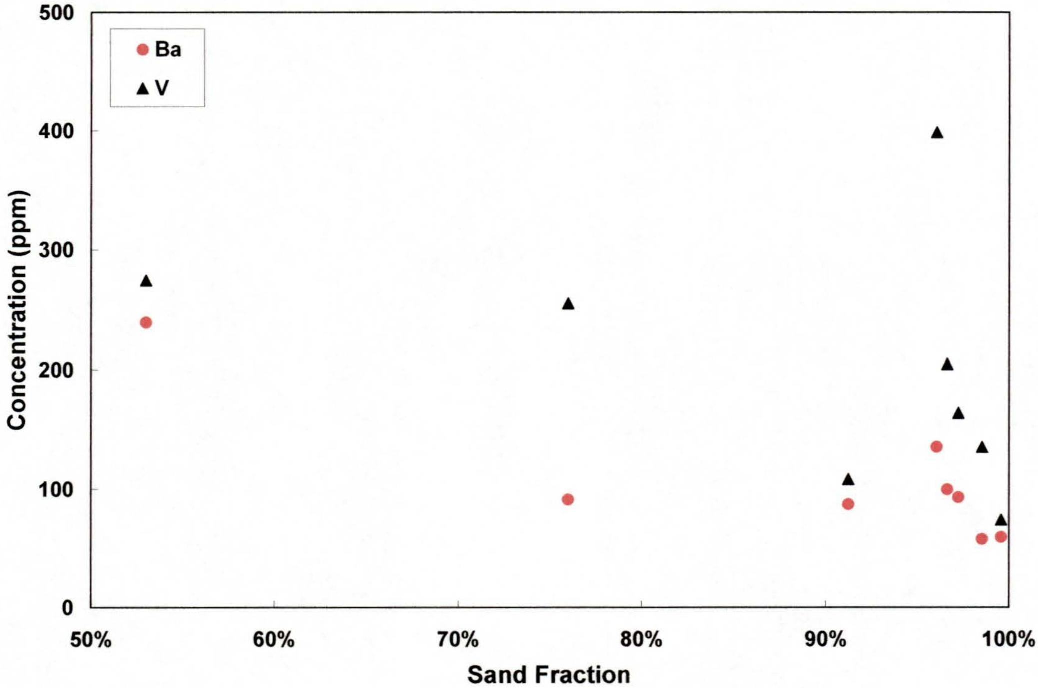

Figure 13: Plot of Sand Fraction vs. Concentration of Ba and V in the Río Chagres watershed only

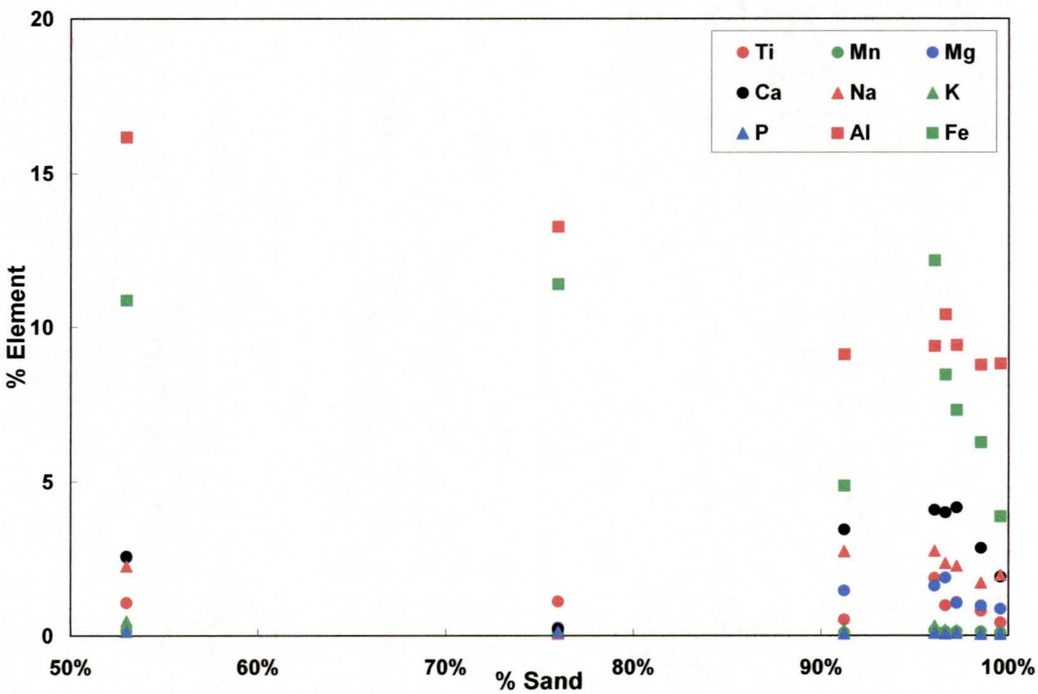

Figure 14: Plot of Sand Fraction vs. Wt. % of Major Elements in the Río Chagres watershed only

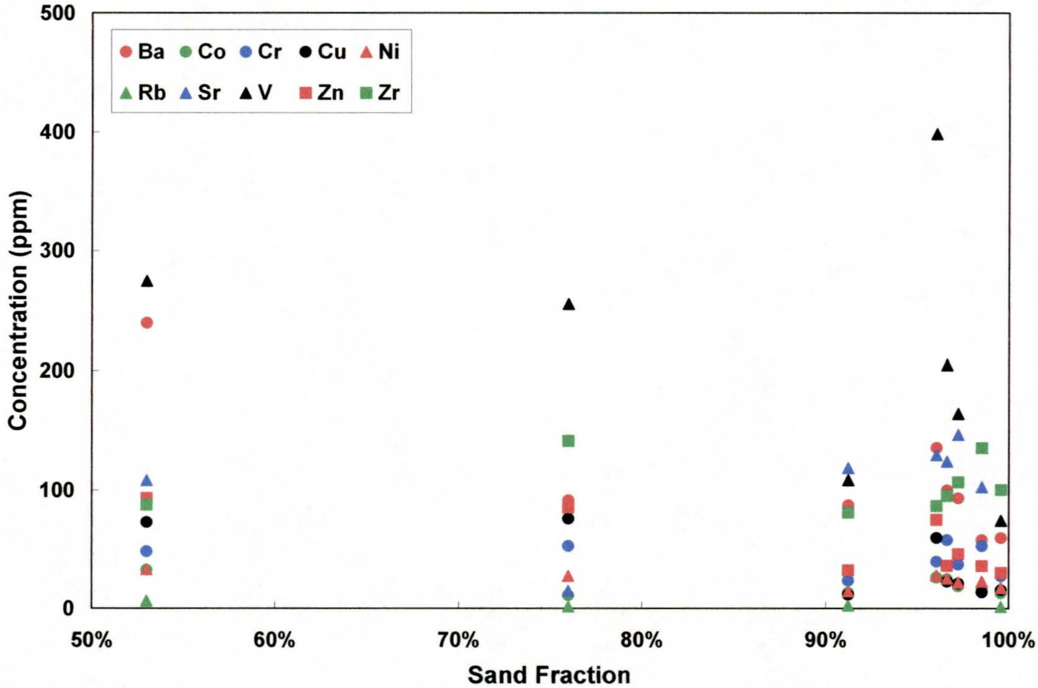

Figure 15: Plot of Sand Fraction vs. Concentration of Trace Elements in the Río Chagres watershed only

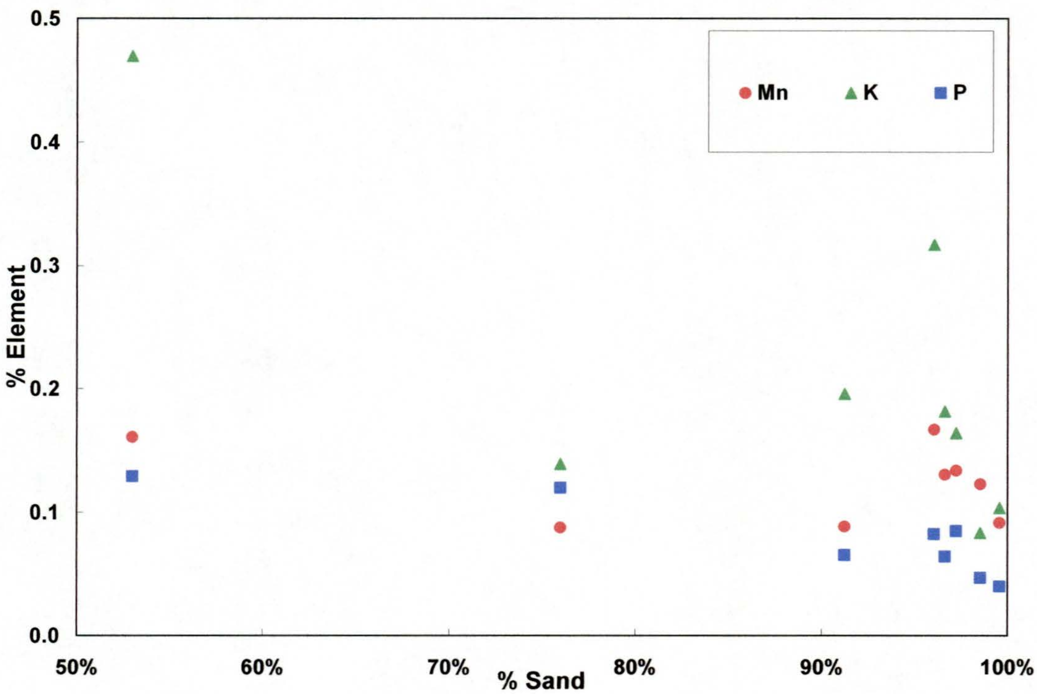

Figure 16: Plot of Sand Fraction vs. Wt. % Mn, K and P in the Río Chagres watershed only

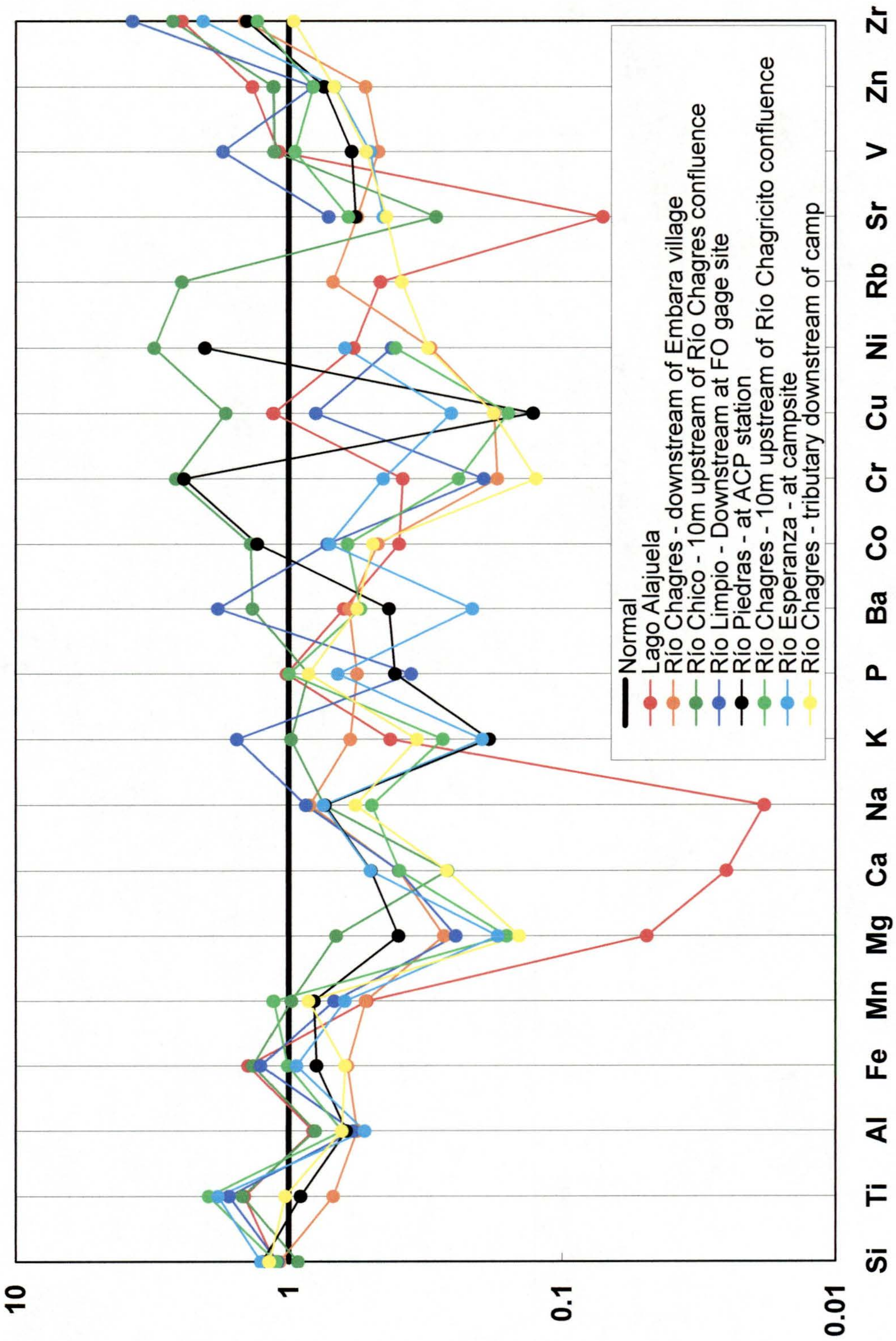

Figure 17: All Río Chagres Watershed Sediments Normalized to Weighted Average of Watershed Lithologies (Wörner, unpublished data)

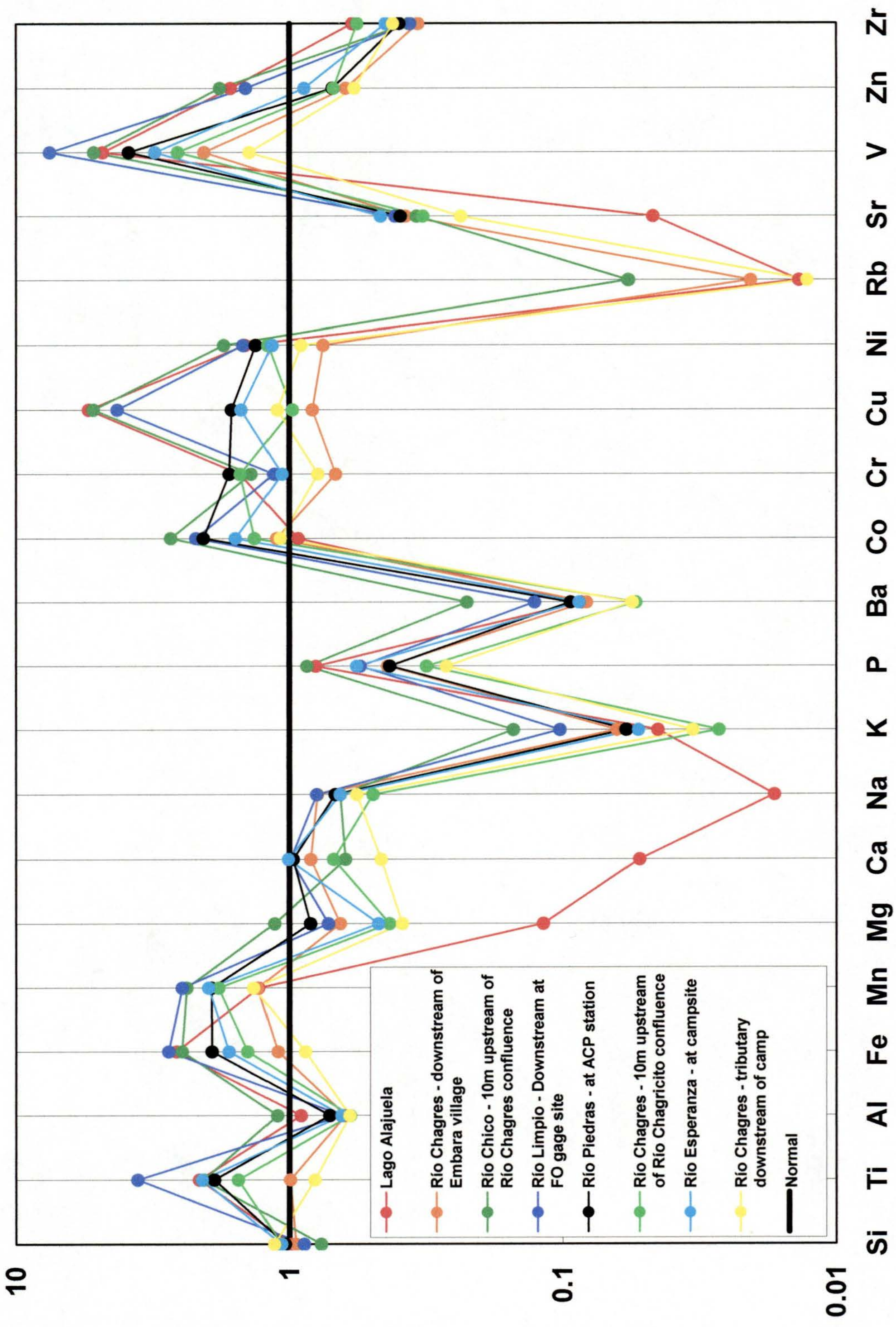

Figure 18: All Río Chagres Watershed Sediments Normalized to Upper Continental Crust (Taylor and McLennan, 1985).

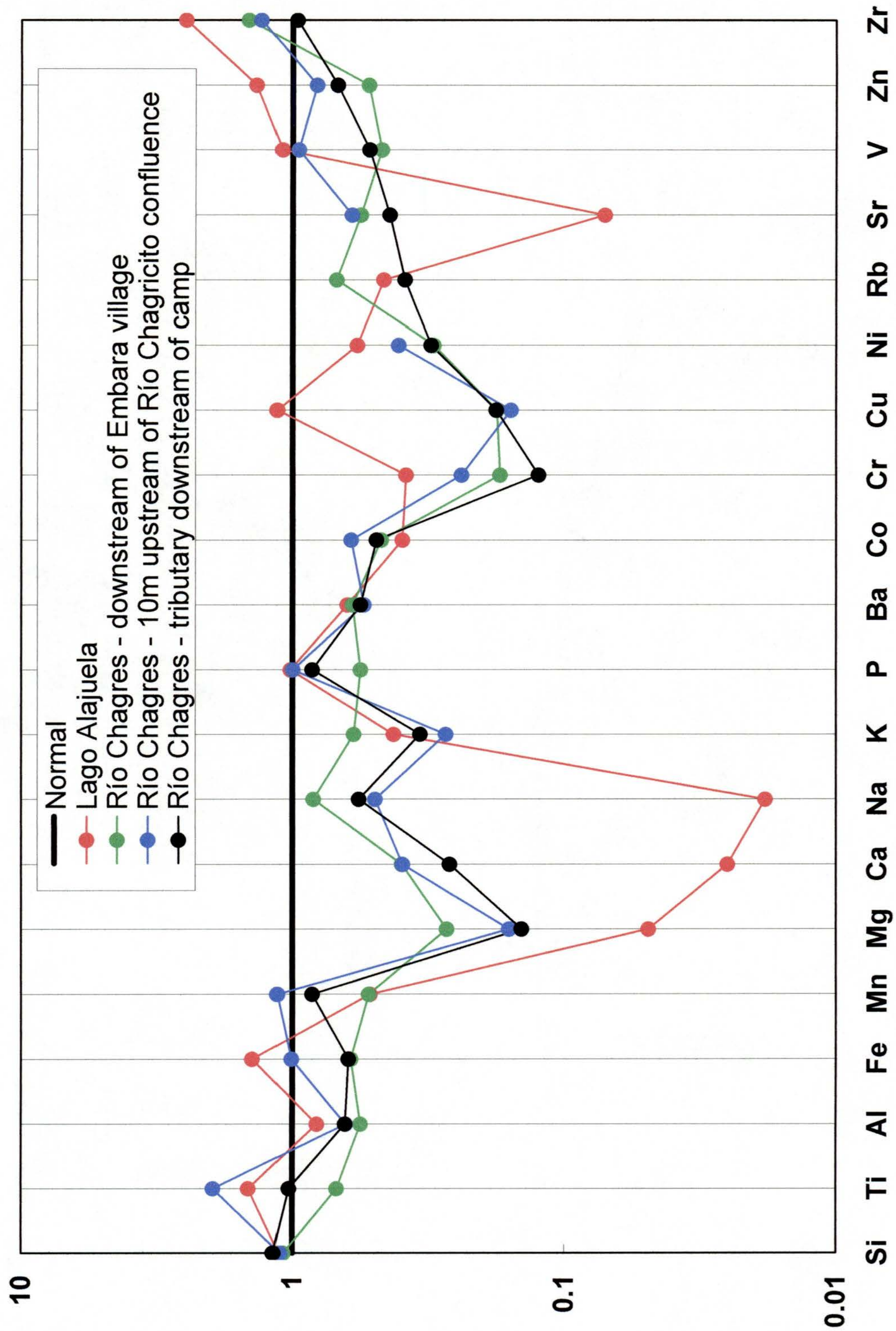

Figure 19: Río Chagres Main Body Sediments Normalized to Weighted Average of Watershed Lithologies (Wörner, unpublished data)

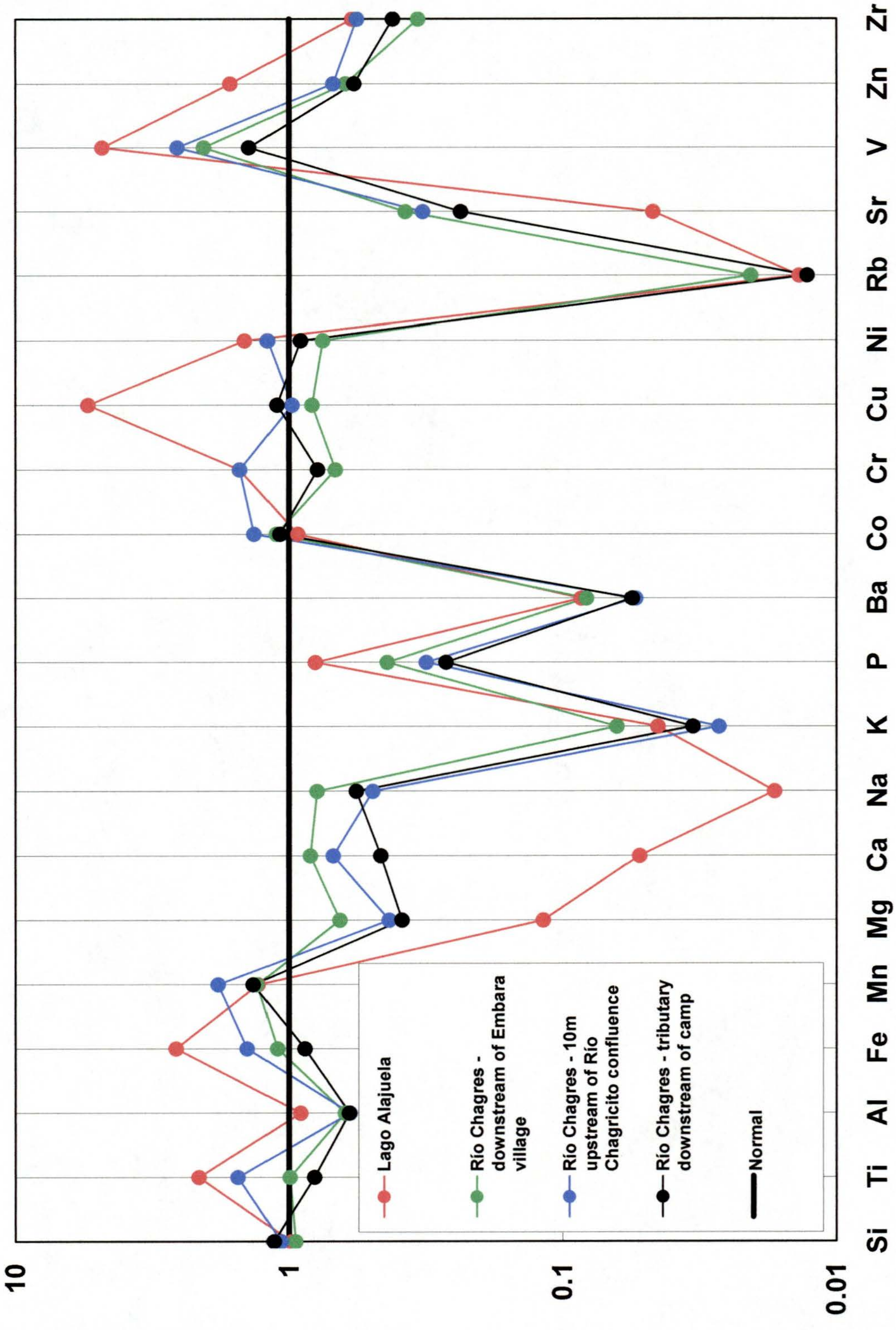

Figure 20: Río Chagres Main Body Sediments Normalized to Upper Continental Crust (Taylor and McLennan, 1985).

Discussion

Correlation Between Grain Size and Elemental Abundance

Grain size in sediments appears to be heavily influenced by lateral inputs of coarse sediments from tributaries as well as landslide processes. Overall, a weak downstream fining of grain-size is observed in agreement with Rengers and Wohl (2006) who found that the lack of fining downstream could be due to either strong hydraulic forces capable of moving large sediments downstream, contributions of large sediments from landslides, a lack of a steep gradient between tributaries, or a combination of the above. The Río Chagres watershed has both landslides (Figure 3) and strong hydraulic forces (Figure 21), which complicate the matter of following and predicting sediment geochemical changes moving downstream while collecting water and sediment from several large tributaries.

Figure 21: Debris washed down from upper reaches of the Río Chagres watershed. (Photo by Gregg McElwee)

As we hypothesized, the sediments showed distinct decreases in Ba (Figure 9) with increasing sand-grain fraction because they are more easily solubilized than Ti or Si, which increases with decreasing grain size (Figure 6). Al decreases as the finer material (i.e. clay minerals) is lost. Looking at just the Río Chagres watershed plots (Figures 12-16) one sees a distinct rise in Si with decreasing grain size and decreases in Zn, Rb, Sr, P and Al as with the other watersheds near the Río Chagres. The decreases in Fe, V, and Zn are more puzzling (Figures 8 and 9). Compared to the spider-plots normalized to the Upper Continental Crust (Figure 18), one might expect increases in these elements as grain-size decreases, which is not the case. This may be a consequence of the input of varying lithologies from different tributaries as one proceeds downstream. This would be the case if the Fe, V and Zn content of the rocks varied significantly from one lithology to another and from one watershed to another. If lithologies higher up in the watershed are enriched in these elements, and the lithologies in the lower reaches depleted, then these elements would appear to decrease with decreasing grain size. We see little change in the Río Chagres values for Ni, Cr and Co; and the plots of V and Fe are too scattered to discern any real pattern. The other elements analyzed (Figures 10 and 11) do not appear to have a significant relationship with grain-size.

Spider-Plot Analysis

When normalized to the weighted average of the upstream lithologies (Figures 17 and 19), trends were very difficult to discern, some elements behaving erratically or in the opposite way than we expected (i.e. loss through chemical weathering or "relative" gain by remaining behind in the insoluble fraction). This is due at least in part to the absence of data to verify my approximations of lithology distribution within the watershed. With better geographic coverage, or better yet, a more detailed geologic map a more realistic normalization could be achieved. As such, I have normalized the sediments to what has been traditionally used: the Upper Continental Crust (Taylor and McLennan, 1985) (Figures 18 and 20). By comparison, expected depletions (K, Rb, Sr, Ca, Na, Mg, and Ba) and enrichments (Si and Ti) are much more easily recognized when the data are normalized to the Upper Continental Crust.

Because of differences in lithologies and sub-watershed sizes, I have focused on the four sediment samples taken from the main stem of the Río Chagres (Figure 20). The two samples collected from high in the watershed (Río Chagres - tributary downstream of camp and Río Chagres – 10m upstream of Río Chagricito confluence) behave as expected. The sediments become enriched in Ti, Fe and Mn and depleted in Na, K and Ba as we move downstream. This pattern is similar to those observed in other, larger watersheds with mixed lithologies (Gaillardet et al., 1997).

Conclusions

The main conclusions of this research are the following:

- Sediment samples from the lower order streams of the Río Chagres watershed are highly weathered and as highly weathered as higher order stream samples.

- Sediment data support our earlier work on stream geochemistry suggesting most intense chemical weathering occurs in the upper reaches of the watershed.

- These data, along with earlier work by Lyons et al. (2006) and Harmon and Lyons (2007), suggest that chemical weathering is very rapid in these volcanic terranes.

- A thorough geological survey of the watershed would greatly aid in tracking chemical weathering patterns between lithologies.

Appendix

Number	Name	UTM-E	UTM-N	Sediment Size Fraction (%)		
				Fine	Sand	Coarse
823-01	Lago Alajuela	657434	1016585	23.92%	75.99%	0.10%
824-15	Río Chagres - downstream of Embara village	662344	1023444	0.40%	91.22%	8.38%
824-14	Río Chico - 10m upstream of Río Chagres confluence	664040	1025009	47.01%	52.99%	0.00%
824-13	Río Limpio - Downstream at FO gage site	670170	1029141	3.36%	96.04%	0.60%
824-12	Río Piedras - at ACP station	675721	1026457	3.38%	96.62%	0.00%
823-15	Río Chagres - 10m upstream of Río Chagricito confluence	684279	1035279	1.47%	98.53%	0.01%
823-14	Río Esperanza - at campsite	680312	1036822	1.03%	97.23%	1.74%
824-08	Río Chagres - tributary downstream of camp	689197	1035173	0.34%	99.56%	0.10%

Table 1: Eight samples were chosen for analysis; this table lists the sample number, corresponding GPS location and sediment size fraction.

Sample Site	Approximate Lithologic Distribution Upstream of Sample Site
Lago Alajuela	45% andesite, 40% diorite, 15% all else
Río Chagres - downstream of Embara village	45% andesite, 40% diorite, 15% all else
Río Chico - 10m upstream of Río Chagres confluence	100% alt. andesite
Río Limpio - Downstream at FO gage site	50 % diorite, 50% alt. andesite
Río Piedras - at ACP station	100% alt. andesite
Río Chagres - 10m upstream of Río Chagricito confluence	50 % diorite, 50% alt. andesite
Río Esperanza - at campsite	100% alt. andesite
Río Chagres - tributary downstream of camp	50 % diorite, 50% alt. andesite

Table 2: Approximate distribution of lithologies upstream of each sample site

Number	Name	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO
GTM-823-01	Lago Alajuela	63.7	1.11	13.3	11.4	0.088
GTM-824-15	Río Chagres - downstream of Embara village	61.4	0.52	9.11	4.86	0.089
GTM-824-14	Río Chico - 10m upstream of Río Chagres confluence	49.7	1.07	16.2	10.9	0.161
GTM-824-13	Río Limpio - Downstream at FO gage site	57.3	1.86	9.38	12.2	0.167
GTM-824-12	Río Piedras - at ACP station	67.4	0.98	10.4	8.45	0.131
GTM-823-15	Río Chagres - 10m upstream of Río Chagricito confluence	69.4	0.80	8.77	6.26	0.123
GTM-823-14	Río Esperanza - at campsite	69.5	1.08	9.41	7.31	0.134
GTM-824-08	Río Chagres - tributary downstream of camp	73.6	0.42	8.80	3.86	0.092

Table 3: Weight % of major oxides present in each sediment sample.

Number	Name	MgO	CaO	Na_2O	K_2O	P_2O_5
GTM-823-01	Lago Alajuela	0.26	0.22	0.06	0.139	0.120
GTM-824-15	Río Chagres - downstream of Embara village	1.46	3.44	2.73	0.196	0.066
GTM-824-14	Río Chico - 10m upstream of Río Chagres confluence	2.54	2.57	2.25	0.470	0.129
GTM-824-13	Río Limpio - Downstream at FO gage site	1.61	4.08	2.75	0.317	0.083
GTM-824-12	Río Piedras - at ACP station	1.88	3.99	2.35	0.182	0.064
GTM-823-15	Río Chagres - 10m upstream of Río Chagricito confluence	0.96	2.84	1.71	0.083	0.047
GTM-823-14	Río Esperanza - at campsite	1.06	4.15	2.26	0.164	0.085
GTM-824-08	Río Chagres - tributary downstream of camp	0.86	1.90	1.96	0.104	0.040

Table 4: Weight % of major oxides present in each sediment sample.

Number	Name	Ba	Co	Cr	Cu	Ni
GTM-823-01	Lago Alajuela	91.3	11.1	52.8	75.8	27.5
GTM-824-15	Río Chagres - downstream of Embara village	87.3	13.3	23.7	11.5	14.3
GTM-824-14	Río Chico - 10m upstream of Río Chagres confluence	239	32.5	48.2	72.8	32.9
GTM-824-13	Río Limpio - Downstream at FO gage site	136	26.3	39.7	59.5	28.0
GTM-824-12	Río Piedras - at ACP station	100	24.7	57.9	22.7	25.2
GTM-823-15	Río Chagres - 10m upstream of Río Chagricito confluence	57.9	16.0	52.8	13.7	22.7
GTM-823-14	Río Esperanza - at campsite	93.3	18.8	37.2	20.9	21.9
GTM-824-08	Río Chagres - tributary downstream of camp	59.6	12.9	27.5	15.5	17.2

Table 5: Concentration (ppm) of trace elements in each sediment sample.

Number	Name	Rb	Sr	V	Zn	Zr
GTM-823-01	Lago Alajuela	1.51	14.8	255	85.2	141
GTM-824-15	Río Chagres - downstream of Embara village	2.26	119	108	32.4	81.1
GTM-824-14	Río Chico - 10m upstream of Río Chagres confluence	6.33	108	275	93.1	87.4
GTM-824-13	Río Limpio - Downstream at FO gage site		129	399	75.0	86.7
GTM-824-12	Río Piedras - at ACP station		124	205	36.1	95.1
GTM-823-15	Río Chagres - 10m upstream of Río Chagricito confluence		102	135	35.9	135
GTM-823-14	Río Esperanza - at campsite		147	164	45.9	107
GTM-824-08	Río Chagres - tributary downstream of camp	1.41	74.5	74.1	30.1	100

Table 6: Concentration (ppm) of trace elements in each sediment sample.

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