Stream Sediment Geochemistry of Four Small Drainages on the North Shore of Kauai West of Hanalei

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Cover. Photograph of Ha`ena Beach Park and hillslopes of Manoa watershed, Kauai, under low clouds on August 1, 2016 (U.S. Geological Survey photograph by Renee Takesue).

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as:
°F = (1.8 × °C) + 32.

Datum

Horizontal coordinate information is referenced to the World Geodetic System standard of 1984 (WGS84).

Abbreviations

GS	grain size
Ma	millions of years ago
mg/kg	milligram per kilogram
TC	total carbon
TIC	total inorganic carbon
USGS	U.S. Geological Survey

Chemical Symbols Used

Cd	cadmium
Co	cobalt
Cr	chromium
Cu	copper
Ni	nickel
Pb	lead
Rb	rubidium
REE	rare earth elements
Ti	titanium
Zn	zinc
Zr	zirconium

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Abstract

Geochemical compositions of fine-grained stream sediment from four drainages on the north shore of the island of Kauai, Hawaii, west of Hanalei and two back-beach sites were explored to increase understanding about land-based runoff and ecological risk from runoff to nearshore coral communities. Stream and beach sediment was collected between July 30 and August 2, 2016, and major, minor, and trace elements in the less than 63 micrometer-diameter fraction were analyzed by inductively coupled plasma optical emission spectroscopy and mass spectroscopy. The potentially toxic metals Cr, Cu, Ni, and Zn exceeded levels at which adverse biological effects could be observed; however, these metals seemed to be largely mineral-bound and thus were unlikely to harm organisms. Cd and Pb were below levels of ecological concern. Only a small amount of fine-grained sediment was retained on beaches west of Hanalei sampled in summer 2016 (mean=8.8 percent, median=0.4 percent, range=0–92.8 percent, n=41). Although the scarcity of fine-grained sediment precluded land-based runoff sourcing to the nearshore region, it did indicate that fine-grained sediment and associated contaminants did not accumulate over the long term in the sampled intertidal, subtidal, and reef-flat environments, which would reduce sediment-related pressures on coral communities there.

Introduction and Study Description

Human development and use of coastal zones is linked to increased deliveries of land-based sediment, nutrients, and contaminants to coastal ecosystems (Mee, 2012). Owing to the substantial economic and cultural benefits that healthy and productive coral reefs provide, the State of Hawaii has prioritized the reduction of land-based pollution impacts (Hawaii Department of Health, 2015). The study described in this report aimed to identify watershed sources of terrigenous, or land-derived, sediment and any sediment-bound potentially toxic metals to the coastal zone in the Wainiha region on the north shore of the Island of Kauai, Hawaii, west of Hanalei. The coastal road in this region is used daily by 2,300 vehicles on average (Hawaii Department of Transporation, 2017) and crosses four streams that deliver land-derived materials to the nearshore region. This study is part of a larger study exploring the role of land-based runoff as a factor contributing to coral disease in Kauai (Aeby and others, 2011). Such knowledge would help guide watershed restoration and runoff mitigation efforts to areas where they are most needed.

The study consisted of two components that characterized the geochemical compositions of stream and nearshore sediment. For the watershed component, the geochemical compositions of fine-grained stream sediment (<63 micrometers) from four drainages west of Hanalei (from west to east: Limahuli, Manoa, Wainiha, and Lumahai; fig. 1) were explored to determine whether any had distinctive compositional characteristics, or signatures, that would allow downstream sediment deposits to be attributed to geographic and geologic source regions, and whether any had elevated levels of potentially toxic metals. Sediment geochemical sourcing requires that contributing basins contain compositionally distinct rock types whose geochemical signatures are quantitatively transferred into eroded and transported sediment exported from the basins (Fralick and Kronberg, 1997). For the nearshore component, the percentage of terrigenous material in bulk beach sediment was determined along the 6-kilometer-long stretch of shore from Ke’e Beach to Lumahai Beach (fig. 1). Additionally, the geochemical compositions, including potentially toxic metal contents, of fine-grained sediment on those beaches were determined and compared to ecological thresholds in order to assess potential impacts of land-derived sediment and contaminants on nearby coral reef communities.

Geologic Setting

Kauai is the second oldest of the Main Hawaiian Islands (Garcia and others, 2010), and its highly eroded volcanic peaks and lavas are covered with thick soils (MacDonald and others, 1960). The Waimea Canyon Basalt forms most of the island of Kauai and consists largely of shield stage olivine basalts and post-shield stage transitional alkalic lavas (MacDonald and others, 1960) that erupted 4–6 million years ago (Ma) (Garcia and others, 2010). Rejuvenated-stage alkalic lavas of the Koloa Volcanics erupted 0.1–4 Ma (Cousens and

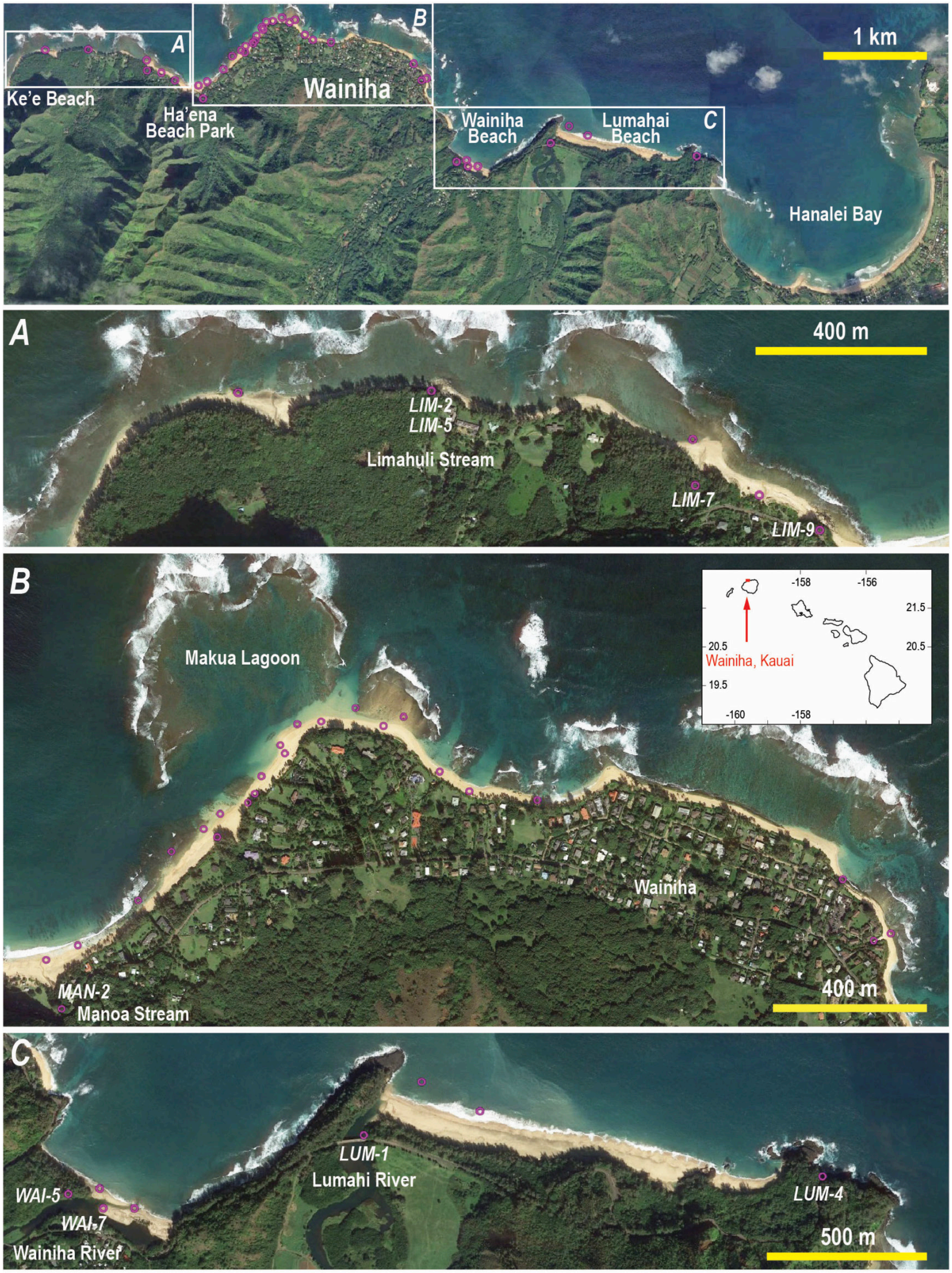

Figure 1. Google Earth satellite images of the study area showing sampling sites (open circles). Nine sites with geochemical data are labeled in (*A*) Limahuli Stream, (*B*) Manoa Stream and Makua Lagoon, and (*C*) Wainiha and Lumahai Rivers. Inset shows the study location in the main Hawaiian Islands.

Clague, 2015) and comprise less than 5 percent of the volume of the island (Garcia and others, 2010). The drainages on the north shore of Kauai west of Hanalei formed in Waimea Canyon Basalt and contain outcrops of alkalic Koloa lavas at Wainiha Beach and Lumahai Beach (Sherrod and others, 2007).

Methods

Sediment Collection

Forty-one sediment samples were collected between July 30 and August 2, 2016, from the banks (7 samples) of Limahuli Stream, Manoa Stream, Wainiha River, and Lumahai River on the north shore of Kauai west of Hanalei, and from nearby beaches and Makua Lagoon (34 samples) (fig. 1; table 1). Sampling targeted deposits of fine-grained sediment. Acid-cleaned sampling tools were used to collect stream and beach sediment and were disinfected with a 10 percent bleach solution between stream sites to prevent the spread of organisms. The upper 2 centimeters (cm) of stream bank and intertidal beach sediment were scooped into plastic wire-top sample bags. Subtidal beach sediment was scooped into 250 milliliter (ml) polypropylene sample jars. Samples were shipped and stored frozen until processing.

Sediment Analyses

Grain Size, Carbon, and Percent Carbonate Analyses

Bulk sediment was analyzed for grain size (GS) distribution and percent carbonate (calculated from total inorganic carbon [TIC] content) by the U.S. Geological Survey (USGS) Pacific Coastal and Marine Science Center sediment laboratory. Particles with diameters greater than 2 millimeters (mm) were separated by dry-sieving into quarter-phi intervals (size in mm=2^{-phi}) and weighed by size class. Sediment GS distributions were determined on organic- and salt-free sediment. Organic matter was removed from the less than 2-mm-diameter sediment fraction with hydrogen peroxide, and soluable salts were removed by centrifugation in freshwater. Sand- and mud-sized particles (2 mm–63 µm and <63 µm) were separated by wet sieving and quantified using a laser particle diffraction counter (Beckman Coulter Life Sciences). GS parameters were calculated with in-house statistical software according to the methods of Folk and Ward (1957). Total carbon (TC) and TIC were determined coulometrically (UIC, Inc.). Percent carbonate was calculated as TIC multiplied by 8.333, the mass ratio of calcium carbonate to carbon. The terrigenous fraction was calculated as 100 minus the percent carbonate value.

Compositional Analyses

Sediment was oven dried at 60 degrees Celsius and gently disaggregated with a mortar and pestle to avoid altering grain sizes. Disaggregated sediment was dry-sieved in stainless steel sieves to obtain 2 grams (g) of the <63 µm-diameter (fine sediment) fraction, which was sent to the USGS Central Mineral and Environmental Resources Science Center Analytical Chemistry Project for geochemical compositional analyses. Total sediment decomposition with a sodium peroxide fusion and quantification by inductively coupled plasma optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectroscopy (ICP-MS) was used to analyze contents of major, minor, and trace elements (Morrison and others, 2009). The total decomposition was optimal for determinations of rare earth elements (REEs) and other elements in refractory minerals such as chromium (Cr) and zirconium (Zr). Near-total sediment decomposition with a four-acid mixture and quantification by ICP-OES and ICP-MS was used to analyze contents of major, minor, and trace elements, and was optimal for trace element determinations (Goldhaber and others, 2009).

Major element contents are reported in units of percent, and minor and trace element content are reported as milligrams per kilogram (mg/kg). Duplicate samples had a relative standard deviation no greater than 15 percent, and compositional values were within ±15 percent at five times the lower limit of determination. To account for differences in the terrigenous content of the fine sediment fraction, compositional data were referenced to titanium (Ti), a component of primary basaltic minerals that does not have an urban source in Hawaii (Sutherland and Tolosa, 2000). A positive correlation with Ti is characteristic of a basalt-hosted element, and a lack of correlation with Ti is characteristic of an element associated with non-basaltic material, such as an alkalic lava (Hanano and others, 2010).

Results

Sediment Grain Size Distributions

Seventeen of 41 samples were composed of 1 percent or more fine sediment (table 1). The median grain sizes of 7 stream samples ranged from medium sand (250–500 µm) to clay-sized (<4 µm) sediment. The median grain sizes of 34 beach samples ranged from very coarse sand (1–2 mm) to medium sand (0.250–0.500 mm).

Terrigenous and Carbonate Fractions of Bulk Sediment

Bulk stream sediment consisted of 56–100 percent terrigenous material (table 1), with a mean of 87 percent and a

Table 1. List of sediment collection dates, locations, descriptions, types, and percentages of less than 63-micrometer-diameter particles (FIN) and terrigenous material (TERR).

[ID, identification number; %, percent; LIM, Limahuli Stream; MAN, Manoa Stream; WAI, Wainiha Stream; LUM, Lumahai Stream; B, beach sample.]

Site ID	Date	Latitude	Longitude	Description	Type	FIN (%)	TERR (%)
LIM-1	7/29/16	22.22379	-159.57992	Limahuli, intertidal	B	0	77
[1]LIM-2	7/29/16	22.22349	-159.57713	Limahuli, south stream bank	Stream	39	100
LIM-3	7/29/16	22.22382	-159.57590	Limahuli, intertidal	B	0	66
LIM-4	7/29/16	22.22382	-159.57590	Limahuli, subtidal	B	0	35
[1]LIM-5	7/29/16	22.22382	-159.57590	Limahuli, west stream bank	Stream	17	56
LIM-6	7/30/16	22.22289	-159.57045	West Ha’ena, intertidal	B	0	28
[1]LIM-7	7/30/16	22.22200	-159.57040	West Ha’ena, stream bank	Stream	34	67
LIM-8	7/30/16	22.22181	-159.56907	West Ha’ena, intertidal	B	0	21
[1]LIM-9	7/30/16	22.22114	-159.56781	Ha’ena, back beach	B	9	34
MAN-1	8/1/16	22.22071	-159.56561	Manoa, intertidal	B	1	49
[1]MAN-2	7/30/16	22.21958	-159.56518	Manoa, west stream bank	Stream	52	88
MAN-3	7/30/16	22.22105	-159.56481	Manoa, intertidal	B	0	29
MAN-4	8/1/16	22.22209	-159.56328	Manoa, subtidal	B	0	4
MAK-1	8/1/16	22.22323	-159.56246	Makua, subtidal	B	0	16
MAK-2	8/1/16	22.22376	-159.56164	Makua, subtidal	B	0	22
MAK-3	8/1/16	22.22357	-159.56129	Makua, intertidal	B	0	8
MAK-4	8/1/16	22.22411	-159.56123	Makua, subtidal	B	2	10
MAK-5	8/1/16	22.22437	-159.56052	Makua, subtidal	B	0	18
MAK-6	7/30/16	22.22458	-159.56034	Makua, intertidal	B	0	11
MAK-7	8/1/16	22.22499	-159.56018	Makua, subtidal	B	0	5
MAK-8	8/1/16	22.22571	-159.55971	Makua, subtidal	B	1	6
MAK-9	7/30/16	22.22552	-159.55959	Makua, intertidal	B	1	37
MAK-10	8/1/16	22.22620	-159.55929	Makua, subtidal	B	1	6
MAK-11	7/30/16	22.22626	-159.55868	East Makua, intertidal	B	0	39
MAK-12	8/1/16	22.22658	-159.55782	East Makua, subtidal	B	0	8
MAK-13	7/30/16	22.22616	-159.55711	East Makua, intertidal	B	0	14
MAK-14	8/1/16	22.22638	-159.55660	East Makua, subtidal	B	1	5
MAK-15	7/30/16	22.22510	-159.55569	East Makua, intertidal	B	0	13
MAK-16	8/1/16	22.22464	-159.55495	East Makua, intertidal	B	0	46
WAI-1	8/1/16	22.22443	-159.55324	East Makua, subtidal	B	0	37
WAI-2	8/2/16	22.22258	-159.54554	Wainiha Beach, intertidal	B	0	54
WAI-3	8/2/16	22.22116	-159.54478	Wainiha Beach, intertidal	B	1	5
WAI-4	8/2/16	22.22132	-159.54433	Wainiha Beach, intertidal	B	0	27
[1]WAI-5	7/31/16	22.21412	-159.54153	Wainiha Stream	Stream	93	100
WAI-6	7/31/16	22.21426	-159.54061	Wainiha Beach, intertidal	B	1	58
[1]WAI-7	7/31/16	22.21372	-159.54049	Wainiha sandbar	B	1	54
WAI-8	7/31/16	22.21372	-159.53956	Wainiha Beach, intertidal	B	0	78
[1]LUM-1	7/31/16	22.21573	-159.53276	Lumahai Stream	Stream	30	97
LUM-2	7/31/16	22.21720	-159.53104	Lumahai Beach, intertidal	B	0	79
LUM-3	7/31/16	22.21639	-159.52931	Lumahai Beach, intertidal	B	0	82
[1]LUM-4	8/2/16	22.21459	-159.51914	Lumahai runoff	Stream	78	99

[1]Samples with sufficient material for geochemical analysis of the less than 63-micrometer fraction.

median of 97 percent. Stream sediment samples LIM-5 and LIM-7, which were collected near the mouth of Limahuli Stream and a tributary, contained 44 and 33 percent carbonate, material that could have been deposited by large wave events or past high stands of sea level (Calhoun and Fletcher, 1996; Morton and others, 2007). Bulk beach sediment consisted of 4–82 percent terrigenous material (table 1), with a mean of 32 percent and a median of 27 percent. The skew toward low terrigenous values in beach sediment shows that beaches were composed predominantly of carbonate grains.

Fine Sediment Geochemical Compositions

Nine samples had sufficient fine material for compositional analysis (denoted by footnote in table 1). Seven were from streams and two from the back-beach areas at Ha'ena Beach Park (LIM-9) and Wainiha Beach (WAI-7). Geochemical data are available in appendixes 1 (near-total compositions) and 2 (total compositions).

Potentially Toxic Metals in North Kauai Stream Sediment

The trace metals chromium (Cr), copper (Cu), nickel (Ni), and zinc (Zn) are naturally enriched in Hawaiian soils because they are incorporated in volcanic minerals in basaltic lavas (Sutherland, 2000). Because these elements are largely mineral-bound, they are not likely to be assimilated by organisms (Sutherland and Tolosa, 2000). Therefore, although total fine-sediment contents of Cr and Ni exceeded the probable effects concentration (PEC) for freshwater sediment (MacDonald and others, 2000) above which adverse biological effects are expected to occur more often than not (table 2), and Cu and Zn exceeded the threshold effects concentration (TEC) for freshwater sediment (MacDonald and others, 2000) above which adverse biological effect are sometimes expected to occur (table 2), the fractions of these metals that were available to organisms and food webs, called the bioavailable fractions, were expected to be below levels of biological concern (Sutherland and Tolosa, 2000). Lead (Pb) was slightly elevated in fine sediment from Manoa Stream below the highway crossing, and in fine sediment collected from the bank of Lumahai Stream under the highway bridge, but did not exceed the TEC (table 2). In the fine fraction of beach sediment, Pb and Zn contents were below the effect range low (ERL) level for estuarine sediment (Long and others, 1995), below which adverse biological impacts would rarely be observed; Ni contents exceeded the effect range median (ERM) level for estuarine sediment (Long and others, 1995), above which adverse biological impact are likely to occur; and Cr and Cu contents were intermediate. Cadmium contents were below levels of concern at all sites.

Table 2. Contents of potentially toxic metals in fine sediment from Limahuli Stream (LIM), Manoa Stream (MAN), Wainiha Stream (WAI), Lumahai Stream (LUM), and back beach areas (B).

[mg/kg, milligram per kilogram; TEC, threshold effects concentration; PEC, probable effect concentration; ERL, effect range low; ERM, effects range median.]

	Cadmium, in mg/kg	Chromium, in mg/kg	Copper, in mg/kg	Nickel, in mg/kg	Lead, in mg/kg	Zinc, in mg/kg
Stream sediment						
LIM-2	0.21	845	152	317	2.8	148
LIM-5	0.19	1690	190	380	2.1	192
LIM-7	0.10	354	55	194	7.8	124
MAN-2	0.28	1160	240	386	26.1	293
WAI-5	0.15	640	127	297	3.4	128
LUM-1	0.23	930	112	407	32.8	177
LUM-4	0.12	942	161	267	7.3	166
TEC[1]	*0.99*	*43.4*	*31.6*	*22.7*	*35.8*	*121*
PEC[1]	*4.98*	*111*	*149*	*48.6*	*128*	*459*
Beach sediment						
LIM-9 (B)	0.12	317	73	127	8.3	79
WAI-7 (B)	0.09	771	106	308	3.3	111
ERL[2]	*1.2*	*81*	*34*	*20.9*	*46.7*	*150*
ERM[2]	*9.6*	*370*	*270*	*51.6*	*218*	*410*

[1]MacDonald and others (2000)

[2]Long and others (1995)

Volcanic Geochemistry of North Kauai Stream Sediment

Fine sediments of all nine stream and beach samples had Ni contents greater than 100 mg/kg and Cr greater than 300 mg/kg (fig. 2*A, B*), indicating that olivine basalts (Mukhopadhyay and others, 2003) were the dominant source of land-derived sediment to the north Kauai shore west of Hanalei. Cobalt (Co) and scandium (Sc), two other elements that are characteristic of basaltic lavas (Hanano and others, 2010), were closely correlated with Cr in stream and beach fine sediment (r >0.80). Based on basaltic compositions that plot in overlapping fields relative to Ti, sediment from the four drainages west of Hanalei Bay could not be distinguished geochemically (fig. 2*A, B*).

The alkali metal rubidium (Rb) is enriched in alkalic Hawaiian lavas (Maaløe and others, 1992; Hanano and others, 2010). The low negative correlation of Rb and Ti contents (fig. 2*C*) showed that the alkalic element Rb was not associated with sediment derived from basalt in streams on the north Kauai shore west of Hanalei. Rb contents were elevated (>8 mg/kg) relative to Ti contents in fine sediment from Manoa Stream and an eroding seacliff at Lumahai Beach (red square and purple cross in fig. 2*C*), indicating that runoff from these drainages contained material from alkalic lavas that imparted a distinctive geochemical signature. Two samples from Wainiha and Lumahai Streams with slightly elevated Rb relative to Ti contents (~4–4.5 mg/kg, green triangle and purple cross in fig. 2*C*) could also contain small amounts of alkalic material, consistent with the presence of alkalic olivine basalt outcrops at the mouths of these streams (Cousens and Clague, 2015). Fine-grained beach sediment at Limahuli and Wainiha beaches did not, however, contain distinguishable alkalic geochemical signatures relative to Ti contents (blue stars in in fig. 2*C*), reflecting the dominance of basaltic sediment sources west of Hanalei.

None of the beach-front intertidal, subtidal, or reef flat samples had sufficient fine sediment for compositional analyses, likely due to a high degree of reworking and winnowing by waves, so it was not possible to assess whether runoff from the four small drainages impacted the reef flat west of Hanalei.

Summary

Stream sediment geochemistry was determined in the sediment fine fraction (<63 µm) in four drainages west of Hanalei, Kauai: Limahuli, Manoa, Wainiha, and Lumahai in summer 2016. The potentially toxic metals Cr and Ni exceeded sediment quality guidelines at which adverse biological effects are expected to occur more often than not; however, these metals are mineral-bound in Hawaiian soils and thus are not readily available to organisms. Cu and Zn exceeded sediment quality guidelines at which adverse biological effects would sometimes be expected to occur and are also largely geologically sourced in Hawaiian soils. Cd and Pb were below levels of ecological concern in fine-grained sediment from the four sampled streams and two back-beach sites. Overall, basaltic geochemical signatures predominated in stream sediment, were relatively similar across basins, and therefore were not distinctive of runoff sources. Alkalic geochemical signatures were identified in fine-grained sediment at two sites: Manoa Stream and a seacliff at Lumahai Beach; however, intertidal beaches and adjacent reef flats contained little fine-grained sediment, which precluded the use of alkalic geochemical signatures in identifying runoff sources and transport along this stretch of shore. The lack of retention of fine-grained sediment on beaches of the north shore of Kauai west of Hanalei attests to the efficiency of removal of land-derived sediment and sediment-bound contaminants by local hydrodynamics in summer. Although rainfall is greater in winter than summer on Kauai (Ramage and Schroeder, 1999) and could

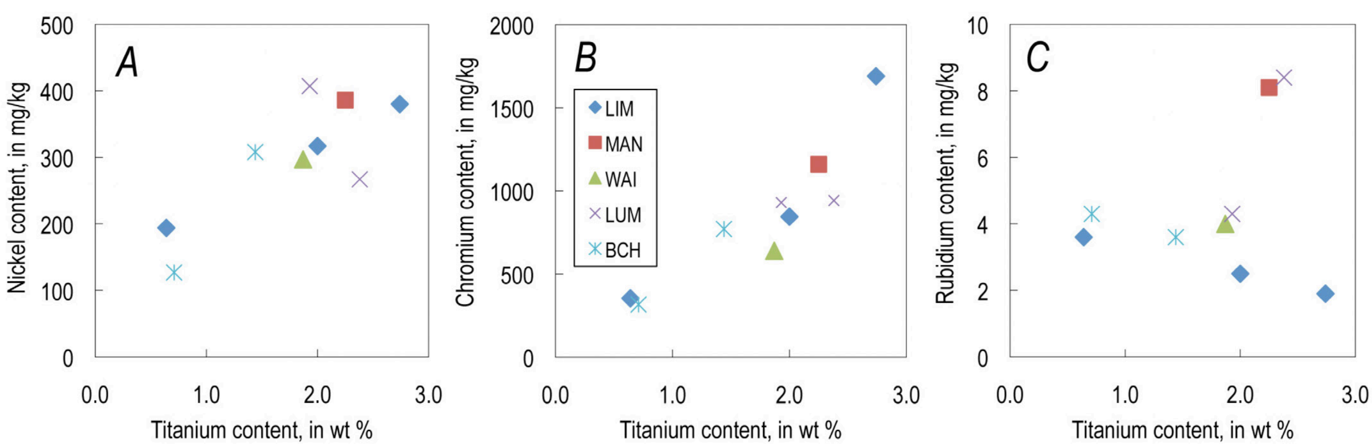

Figure 2. Scatter plots of (*A*) nickel, (*B*) chromium, and (*C*) rubidium contents relative to titanium contents in fine sediment from Limahuli Stream (LIM), Manoa Stream (MAN), Wainiha Stream (WAI), Lumahai Stream (LUM), and the back beaches (BCH) of Limahuli and of Wainiha. wt %, percentage by weight.

deliver more runoff to the coastal ocean, terrigenous sediment removal is expected to be more efficient in winter when large wave events impact the north shore (Moberly, 1968) and offset negative effects of terrigenous sediment loading (Draut and others, 2009).

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Appendix 1. Sediment Geochemical Compositions from Near-Total Digestions

[LIM, Limahuli Stream; MAN, Manoa Stream; WAI, Wainiha Stream; LUM, Lumahai Stream; (B), beach sediment; mg/kg, milligrams per kilogram. Site identification numbers correspond to locations given in table 1.]

Element	LIM-2	LIM-5	LIM-7	MAN-2	WAI-5	LUM-1	LUM-4	LIM-9 (B)	WAI-7 (B)
Major elements, in percent									
Al	7.01	7.48	2.78	2.79	6.44	6.78	5.2	6.61	9.28
C	3.38	2.7	6.77	7.15	5.62	2.16	4.09	3.17	0.88
Fe	9.86	11.9	6.84	3.84	11.8	9.23	7.73	10.5	14
K	0.08	0.07	0.07	0.17	0.19	0.1	0.1	0.11	0.25
Mg	1.49	2.58	0.89	1.96	3.74	1.52	2.54	2.21	0.83
Na	0.21	0.34	0.15	0.96	0.47	0.31	0.37	0.36	0.25
S	0.15	0.1	0.36	0.4	0.16	0.15	0.18	0.16	0.14
Ti	1.83	2.44	0.62	0.65	2.03	1.71	1.32	1.77	2.24
Minor and trace elements, in mg/kg									
Ag	0.23	0.24	0.1	0.16	0.51	0.3	0.25	0.32	0.48
As	4.7	2.2	14.1	13.4	9.6	3.4	11.4	17.5	4.5
Ba	78	86	53	35	237	115	56	87	149
Be	0.95	0.93	0.32	0.32	0.95	1.03	0.69	0.89	1.48
Bi	0.06	0.04	0.05	0.13	0.84	0.05	0.31	0.07	0.08
Cd	0.21	0.19	0.1	0.12	0.28	0.15	0.09	0.23	0.12
Ce	26.7	21.2	14.2	11.6	40.1	36.3	29.7	32.1	51.4
Co	69.1	75.4	36.4	26.5	72.4	59.4	58.1	74.9	78.1
Cr	593	1030	249	218	846	497	486	672	728
Cs	0.23	0.14	0.3	0.19	0.6	0.34	0.29	0.42	0.58
Cu	127	160	48.6	69.3	207	110	94.6	96.8	144
Ga	25.1	28	10.1	9.66	26.6	24.2	19.9	24	36.8
In	0.079	0.091	0.024	0.027	0.079	0.07	0.055	0.074	0.105
La	14	10	6.2	5.3	20.8	18.3	14.5	15.6	30
Li	10	9.5	7.5	13.5	11.4	7.9	17	16.3	19
Mn	1640	1210	945	652	1180	1200	1260	1670	1580
Mo	0.92	0.87	0.73	0.8	2.51	1.03	0.99	1.27	2.4
Nb	14.8	17.8	5.9	6.3	37.6	22.5	15.4	20.7	38
Ni	290	340	184	117	351	277	293	390	271
P	1490	1230	2160	2000	1640	1870	1470	2230	1540
Pb	2.8	2.1	7.8	8.3	26.1	3.4	3.3	32.8	7.3
Rb	2.4	1.8	3.3	3.9	7.6	3.6	3.3	4.2	8.9
Sb	0.07	<0.05	0.21	0.37	7.22	0.09	0.19	0.32	0.2
Sc	32.7	36.9	12.1	12.8	31.4	29.3	24.4	30.2	40.2
Sn	2.5	2.3	3.1	2.2	17	2.6	2.9	5.6	3.1
Sr	245	131	668	491	372	156	330	287	100
Ta	1.11	1.35	0.42	0.47	2.37	1.58	1.1	1.48	2.67
Tb	1.03	0.83	0.44	0.4	0.99	1.04	0.87	0.91	1.64
Te	<0.01	0.03	0.05	0.05	0.07	<0.01	0.01	0.04	0.07

Appendix 1. Sediment Geochemical Compositions from Near-Total Digestions—Continued.

Element	LIM-2	LIM-5	LIM-7	MAN-2	WAI-5	LUM-1	LUM-4	LIM-9 (B)	WAI-7 (B)
Th	1	0.9	0.8	0.6	3	1.8	1.4	1.7	3.4
Tl	0.03	0.02	0.03	0.03	0.04	0.03	0.02	0.04	0.04
U	0.588	0.383	1.65	0.886	1.34	0.764	0.799	1.07	1.27
V	316	435	140	114	360	286	227	317	422
W	0.6	0.5	0.5	0.3	0.7	0.5	0.3	0.4	0.5
Zn	140	177	115	74.4	282	129	105	172	168

Appendix 2. Sediment Geochemical Compositions from Total Digestions

[LIM, Limahuli Stream; MAN, Manoa Stream; WAI, Wainiha Stream; LUM, Lumahai Stream; (B), beach sediment; mg/kg, milligrams per kilogram. Site identification numbers correspond to locations given in table 1.]

Element	LIM-2	LIM-5	LIM-7	MAN-2	WAI-5	LUM-1	LUM-4	LIM-9 (B)	WAI-7 (B)
Major elements, in percent									
Al	7.45	8.1	2.82	2.94	6.91	7.17	5.67	6.84	9.75
Ca	3.6	2.89	7.36	7.61	5.91	2.26	4.29	3.28	0.91
Fe	10.4	12.6	7	4.03	12.3	9.75	8.49	10.9	13.7
K	0.07	0.07	0.08	0.17	0.2	0.09	0.09	0.11	0.24
Mg	1.61	2.75	0.94	2.11	3.97	1.59	2.78	2.25	0.88
P	0.14	0.12	0.21	0.19	0.16	0.18	0.13	0.2	0.14
S	0.1	<0.1	0.4	0.4	0.2	0.1	0.2	0.2	0.1
Si	12.3	15.1	5.96	6.07	14.2	15.4	15.1	13.4	11.7
Ti	2	2.74	0.64	0.71	2.25	1.87	1.44	1.93	2.38
Minor and trace elements, in mg/kg									
Ag	<1	<1	<1	<1	<1	<1	<1	<1	<1
As	<5	<5	12	15	8	<5	8	18	<5
Ba	85.1	90.8	56	33.5	245	120	57.3	90.2	160
Be	<5	<5	<5	<5	<5	<5	<5	<5	<5
Bi	<0.1	<0.1	<0.1	0.1	0.8	<0.1	0.3	<0.1	<0.1
Cd	0.3	0.3	<0.2	<0.2	0.3	<0.2	<0.2	0.4	<0.2
Ce	33	25.6	17.1	13.8	47.8	42.4	35.7	38.5	60.9
Co	66.4	76.6	36.6	26.4	72.5	56.8	57	70.8	74
Cr	845	1690	354	317	1160	640	771	930	942
Cs	0.2	0.2	0.3	0.2	0.7	0.4	0.3	0.4	0.6
Cu	152	190	55	73	240	127	106	112	161
Dy	6.08	5.09	2.64	2.35	5.46	5.5	4.71	5.13	8.89
Er	3.04	2.57	1.33	1.19	2.38	2.4	2.55	2.55	3.97
Eu	2.28	1.76	0.95	0.84	2.15	2.35	1.94	2.12	3.91
Ga	22.6	25.5	8.85	9.97	24.8	21.6	18	21.6	33
Gd	7.61	6.12	3.15	3	6.98	7.21	6.69	6.72	12.1
Ge	1	2	<1	<1	2	1	1	1	2

Appendix 2. Sediment Geochemical Compositions from Total Digestions—Continued.

Element	LIM-2	LIM-5	LIM-7	MAN-2	WAI-5	LUM-1	LUM-4	LIM-9 (B)	WAI-7 (B)
Hf	4	5	2	2	6	4	4	4	6
Ho	1.29	0.99	0.57	0.47	1	1.14	1.01	1.11	1.78
In	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
La	15.4	10.9	6.7	5.5	22.6	19	16.1	16.8	32.4
Li	<10	<10	<10	12	<10	<10	15	16	19
Lu	0.34	0.28	0.15	0.15	0.29	0.26	0.3	0.26	0.44
Mn	1780	1200	1010	692	1200	1220	1340	1690	1610
Mo	<2	<2	<2	<2	3	<2	<2	<2	2
Nb	14.7	19.5	6	6.8	40.9	23.6	16.4	21.5	37.6
Nd	25.5	18.9	10.8	9.5	28.1	27	23.5	23.8	47.6
Ni	317	380	194	127	386	297	308	407	267
Pb	<5	<5	8	8	30	<5	<5	35	7
Pr	5.13	3.83	2.16	1.82	6.13	5.58	4.72	5.4	10.2
Rb	2.5	1.9	3.6	4.3	8.1	4	3.6	4.3	8.4
Sb	<0.1	<0.1	0.2	0.3	8	<0.1	0.2	0.4	0.2
Sc	36	41	13	14	34	31	26	32	43
Se	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sm	6	4.6	2.5	2.4	5.8	6.2	4.8	5.1	10.5
Sn	2	3	4	3	18	2	2	7	3
Sr	281	138	748	592	424	178	370	327	103
Ta	0.9	1.1	<0.5	<0.5	2.2	1.3	0.9	1.3	2.2
Tb	1.17	0.9	0.48	0.39	0.97	1.01	0.93	0.97	1.74
Te	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Th	0.9	0.8	0.8	0.6	3.2	1.8	1.4	1.8	3.3
Tl	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Tm	0.41	0.37	0.22	0.14	0.32	0.34	0.34	0.39	0.63
U	0.63	0.41	1.68	0.9	1.32	0.81	0.84	1.06	1.28
V	321	487	149	124	402	293	259	321	459
W	<1	<1	<1	<1	<1	<1	<1	<1	<1
Y	31.3	23.9	15.6	12.8	25.8	29.3	24.1	26.3	39.7
Yb	2.4	1.9	1	1	2	2.1	1.9	2.1	3.3
Zn	148	192	124	79	293	128	111	177	166
Zr	158	188	65.1	61.7	228	173	140	172	230

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