

Geochemical Investigations of Landscape Evolution in
Oregon and Hawaii

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Abstract

Geochemical investigations of landscape evolution in Oregon and Hawaii

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In this study, I investigate the relationship between two forms of landscape steady state, geochemical and geomorphologic, by testing for geochemical steady state in small, monolithologic drainage basins where the geomorphic state is known. Geochemical steady state is a condition in which the composition of the material removed from the landscape, as measured by riverine fluxes, is the same as the composition of the parent rocks, so that bedrock weathering is in equilibrium with the erosional flux out of the system. Geomorphic steady state is a condition where the overall topography of a drainage basin remains constant through time as the mass of rock uplifted through tectonic or isostatic processes is balanced by the removal of mass from the region. Since analyses of riverine fluxes are frequently used to study the denudation of mountain ranges, rates of both physical and chemical weathering, and the amount of CO₂ sequestration due to the weathering of rock, and since these studies often depend on the assumption of one or both forms of steady state, the ability to determine how far a system is from steady state and the relationship between the two forms is increasingly important. Geochemical studies of monolithologic river basins in the Oregon Coast Range (a region generally considered to be in geomorphic steady state) and Hawaii (a region that is not in geomorphic steady state) suggest that there is a strong correlation between the two forms, and further, that the two forms of steady state may in fact be interdependent. As a result, making the relatively simple determination of whether or not a system is in geochemical steady state appears to provide information about a system's geomorphic state as well.

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Introduction

Analyses of riverine geochemical fluxes are increasingly used to examine issues ranging from the rate of denudation of mountain ranges (Harris et al., 1998; Galy et al., 1999; Tricca et al., 1999), to quantifying atmospheric CO₂ sequestration due to weathering processes (Quade et al., 1997; Blum et al., 1998; Singh et al., 1998; Gaillardet et al., 1999), and identifying the relative importance of physical and chemical weathering (Gaillardet et al., 1997; Petelet et al., 1998; Elbaz-Poulichet, et al., 1999; Galy and France-Lanord 1999; Négrel and Grosbois, 1999). Frequently these approaches assume that a system is in steady state to simplify models of the study regions. However, how far a system is from steady state is rarely quantified, and the possible influences of the variations from steady state generally are neglected.

The interpretation of riverine fluxes is further complicated by the existence of two fundamentally different views of steady state: geochemical and geomorphological. Geochemical steady state is a condition in which the elemental composition material removed from the landscape, as measured by riverine fluxes, is the same as that of the parent rocks, so that weathering of the bedrock is in equilibrium with the erosional flux out of the system. A geomorphological steady state is one in which the overall topography of a region remains unchanged through time as the mass of rock raised through tectonic and isostatic processes is balanced by the mass of rock eroded from the region. Determination of geomorphic steady state is difficult due to the stochastic nature of erosion processes, which are typically related to discrete hydrologic events. In addition, obtaining a spatially distributed suite of uplift measurements in a given mountain range against which to compare erosion rates and assess geomorphic steady state is very difficult. Consequently, the potential to examine landscape steady state through geochemical sampling of riverine systems, thereby avoiding the problems associated with determination of geomorphic steady state, is appealing.

Understanding the relationships and interdependencies between the forms of steady state is crucial for interpreting the signatures of landscape steady state. Previous geochemical studies of riverine fluxes have been limited by the complexities of large river basins (Gaillardet et al., 1995, 1997; Galy and France-Lanord, 1999), and in other cases by the difficulty of controlling for hydrothermal inputs in volcanically active regions (Gíslason et al., 1996; Louvat and Allègre, 1997). For this study, we chose to work in relatively small, monolithologic river basins that do not have significant hydrothermal inputs, allowing us to test directly the relationships between geochemical and geomorphic steady state. We focused on two regions, one in the Oregon Coast Range, an area generally considered to be in geomorphic steady state, and the other on the island of Oahu in Hawaii, an area that is not in geomorphic steady state. We analyzed the bedrock chemistry and the chemical composition of the material being shed from each of these regions to determine if they are in geochemical steady state, and then compared the geochemical results to the known geomorphic state of these regions. This comparison allows us to test our understanding of the relationships between the two forms of steady state. We also expand on previous studies by monitoring the Oregon basins on a monthly basis throughout an entire annual cycle, to document possible seasonal influences on the geochemical signature of the system.

Conceptual Framework

Geochemical Steady State

The concept of a geochemical steady-state, in which there is a balance between the rates of weathering and sediment removal, is commonly invoked in studies of soil formation and river geochemistry. The central idea of this concept is that soil and regolith profiles evolve to a constant, average, depth and form such that the production of regolith by extension into the bedrock is in equilibrium with the removal of soil material by surficial processes. Soil properties, such as thickness, mineral proportions, organic content, etc., change as a soil profile matures, but with sufficient time will approach a steady state. It is unknown over what time scales all components of a soil approach steady state; however, the general pattern is a rapid initial change that slows with time as a consequence of several types of negative feedbacks that depend on lithology, climate, and slope, amongst other factors (Birkeland, 1999). As the thickness of the regolith increases, the amount of bedrock weathering decreases as the result of soil cover development and subsequent insulation from water circulation, freeze thaw, and other weathering mechanisms (Anhert, 1987). Slope angle may also influence regolith production since it is related to denudation rates; as slope angles increase due to erosion, the regolith thickness decreases. This will result in a proportional increase in the rate of bedrock weathering and regolith production (Gilbert, 1877). Alternatively, the regolith may be too thin or the slope too steep to hold soil in place. As a result, bedrock will outcrop at the surface and weathered material will be removed rapidly from the hillslope and exported from the system (e.g., Dietrich et al., 1995).

At geochemical steady state, the flux of river-born material, including dissolved, suspended, and bed loads, should equal the mass flux of material weathered and eroded from the bedrock. Geochemical mass balances have been used to study relations between physical and chemical weathering as well as continental denudation rates (e.g., Négrel et al., 1993; Stallard,

1995; Louvat and Allègre, 1997). This idea can be quantified as a mass budget model in the form used by Gaillardet et al. (1995):

$$M_c C_c(X) = M_s C_s(X) + M_p C_p(X) + M_w C_w(X) \quad \text{eq. 1}$$

For any element X

M_c is the mass of bedrock weathered in units of mass per time (t/yr)

M_w is the total mass of water discharged from the basin in units of volume per time (L/yr)

M_p is the total mass of suspended sediments and M_s is the total mass of bedload exported from the basin in units of mass per time (t/yr)

C_w is the concentration of the element X in the dissolved load (e.g., $\mu\text{g/L}$)

C_p , C_s , and C_c are the concentrations of the element X in the suspended load, bedload and basement, respectively ($\mu\text{g/g}$).

By measuring the concentrations of a variety of elements in the material exported from the system, one can develop mass balance equations for each of the chemical constituents.

Comparison of the weathering rate with the rate of exportation from the basin for each element can then be used to determine if the system is in geochemical steady state.

In order for the mass balance to be accurately calculated, it is important to use only the concentrations of the elements that are derived from bedrock weathering, not material derived from other sources such as dust and seawater. As a result, it is necessary to correct the chemical measurements for atmospheric contributions, especially in drainage basins near the ocean. The concentration of these elements may vary with altitude and with distance inland, so utilizing tracer elements, such as Cl for seawater, allow for correction of these inputs.

Geomorphic Steady State

The concept of a geomorphic steady state holds that fluvial and hillslope erosion rates are mutually interdependent and that they adjust to transport the sediment supplied and fluvial discharge shed from the landscape (Mackin, 1948). By this theory, topographic form may change in response to external forcing, but landscapes do not simply evolve through Davis's (1899) erosional cycles of young, mature, and old basins. The concept of a dynamic equilibrium landscape was proposed by Hack (1960) as the condition in which all parts of a landscape are downwasting at a constant rate, so that basin-wide relief does not change over time. Today, Hack's concept of a dynamic equilibrium is interpreted to mean that the net denudation rate can equilibrate with the rate of tectonic uplift, resulting in maintenance of the mean elevation as well as landscape form (e.g., Anheer, 1987; Kooi and Beaumont, 1996; Willett, 1999). Study of steady-state orogens and particularly the feedbacks and relationships between tectonics, erosion, and the topography of mountain ranges (e.g., Brandon et al., 1998; Willett, 1999) is providing new understanding of crustal dynamics. Surface process models have shown that steady-state topography can develop for a range of tectonic uplift rates, climate, substrate, and boundary conditions, but that the development of steady state depends on the time scale over which such conditions are maintained (Kooi and Beaumont, 1996). As a result, the concept of geomorphic steady state is most valuable when viewed on temporal and spatial scales large enough to average the effects of short-term perturbations.

Methods available for addressing steady-state in landscape processes range from fission track or He dating techniques that address rates of rock exhumation over millions of years (e.g., Brandon et al., 1998; House et al., 1999), to event-driven modeling or sampling of sediment and/or dissolved loads in river systems to quantify the amount of material exported from an orogen (e.g., Stallard, 1995). Since sediment transport is episodic, it remains an open question as to over what time scale the natural variability in erosional processes can be considered to be integrated in a steady-state landscape. Over a short enough time frame no landscape is in steady

state due to the discrete, event-driven nature of most erosional processes. In contrast, over geologic time, rock exhumation rates as determined by thermochronologic methods can show long periods of steady state exhumation (e.g., Brandon et al., 1998). At temporal scales between these classical types of measurements, cosmogenic radionuclides can be used to quantify landscape scale erosion rates, but most cosmogenic approaches to assessing erosion rates depend on the assumption of steady state. In some regions, uplift rates are not rapid enough to be measured by traditional fission track and He dating techniques making the development of new techniques vital to understanding landscape dynamics in these regions.

Regardless of the difficulty of determining appropriate time scales over which to view steady state, the assumption of steady state remains a common and extremely useful tool in geomorphological research. A topographic steady state allows quantitative investigation of river profile morphology to yield constraints on river incision laws (Howard et al., 1994; Whipple and Tucker, 1999; Snyder et al., 2000), and evaluation of catchment scale erosion rates from analyses of cosmogenic radionuclide concentrations in sediment samples (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). The assumption of steady state further provides an end-member condition against which to evaluate landscape evolution models.

Evaluation of geomorphic steady state is complicated by the stochastic nature of sediment transport. Consequently, determination of representative erosion rates can require many years of data. In contrast, determination of geochemical steady state is independent of annual changes in sediment fluxes since the method depends on the bulk chemical budget of the sediment components at any point in time. As a result, if the relationships between the two forms of steady state were understood, knowledge of one form would provide us with knowledge about the system as a whole. Thus, making the relatively easy determination of whether or not a system is in geochemical steady state would also determine if the system is in geomorphic steady state.

Relationship between geochemical and geomorphic steady states

The theoretical foundation of this project is to evaluate the hypothesis that geomorphic and geochemical steady states are conditions that inherently depend upon attainment of each other. If these two forms of steady state are mutually dependant, or if one is a necessary precondition for development of the other, then knowing whether a system has reached geochemical steady state would allow one to draw conclusions about the system's geomorphic state. Four possible relationships between these two forms of steady state are outlined in Figure 1. As is discussed below, two cases certainly can occur, regions 1 and 4 of the matrix, those where both forms of steady state are present, or neither form of steady state is present. The more complex questions lie in the opposite corners of the matrix: is it possible to reach a geochemical steady state without being in geomorphic steady state and vice-versa?

Region 1 of the matrix is the condition in which a basin is in both geochemical and geomorphic steady state. This implies that the rate of denudation of the basin has equilibrated to the uplift rate of the topography, and the hillslopes and streams in the basin are graded in Mackin's (1948) terminology. This is the condition we expect to arise in most tectonically active basins if given sufficient time. Previous work suggests that the Olympic Mountains and Oregon Coast Range have reached the condition of geomorphic steady state (Reneau and Dietrich, 1991; Brandon et al., 1998). This project seeks to determine if the Oregon Coast Range is also in geochemical steady-state. In direct contrast is region 4 of the matrix, which includes basins that are neither in geochemical nor geomorphic steady state. Examples of this condition are basins that are not tectonically active (e.g., cratons), and active basins that have not had sufficient time to reach steady state.

Region 2 of the matrix characterizes systems in geomorphic steady state, but not in geochemical steady state. This condition could arise if more material is being eroded from the

hillslopes than is being produced by weathering of the bedrock. In order to maintain geomorphic steady state, the uplift rate would have to be fast enough to compensate for the excess loss of the eroded material. However, the loss of material will eventually mine the soil and erode the regolith down to bare bedrock. If uplift continues at a constant rate, then the rate of bedrock denudation will not be able to keep pace with the uplift, forcing the system out of geomorphic steady state, and into region 4 of the matrix above. Alternatively, if the system is not in geochemical steady state because more regolith is being produced than eroded, one would expect the system eventually to be forced into region 1 of the matrix, as the thickening soil profile will slow weathering of the bedrock, leading to reestablishment of steady state with a deeper soil profile. This insulating effect has frequently been suggested as a control on chemical weathering rates (Stallard and Edmond, 1987; Bluth and Kump, 1994).

Region 3 of the matrix includes basins that are in geochemical steady state, but not in geomorphic steady state. This condition could arise in drainages that are in steep, mountainous regions, where the slope of the entire basin is too steep to allow for significant soil development (and thereby sediment storage) over long periods of time, however it is unlikely to be maintained in a basin of significant size. A system can also be out of geomorphic steady state because the range is uplifting more rapidly than it is being denuded, the uplift rate is decreasing, or tectonic activity has ceased. We could hypothesize that under any of these conditions, maintenance of a geochemical steady state would be improbable because the angle of the slopes, and therefore the amount of sediment stored in the system, would be expected to change as well, forcing the system into region 4 of the matrix.

The previous discussion suggests that drainage basins will eventually shift into regions 1 and 4 of the matrix and that the two versions of steady state are therefore mutually interdependent under most conditions. In other words, a geochemical steady-state is a necessary condition for a geomorphic steady state, and vice-versa. If this dependency is true, then testing for one form of

steady state allows one to reach conclusions about the alternative form of steady state. It is difficult to test directly for geomorphic steady state as both rates of rock uplift and erosion must be known in order to infer a steady state for the ground surface (Molnar and England, 1990). In contrast, geochemical steady state is readily tested by sampling river water and sediment *if* bedrock composition is accurately known, an assumption that is commonly made in studies of large drainage basins (Gaillardet et al., 1995, 1997; Galy and France-Lanord, 1999). Establishing whether a demonstrated geochemical steady state implies a geomorphic steady state will clarify relationships between these two fundamentally different views of steady state landscapes.

Previous Work on Geochemical Steady State

Several previous projects have utilized the assumption of geochemical steady state to facilitate the study of weathering processes in river basins, but few have directly studied the validity of this assumption. Geochemists have frequently studied large river systems to quantify the supply of continental material to the ocean, and improve understanding of global nutrient cycling (e.g. Elbaz-Poulichet, et al., 1999; Galy and France-Lanord, 1999). Milliman and Syvitski (1992) also recognized the importance of small river systems in tectonically active regions to the global nutrient cycle since these basins have a large supply of fresh, unaltered rock material that can weather rapidly. Studies such as these highlight the importance of understanding weathering processes along continental margins, especially with respect to the uptake of CO₂ due to mineral weathering and the resultant carbon sequestration, since these processes are central to models of long-term climate change (Berner and Berner, 1997).

Identifying global nutrient cycling patterns and pathways requires knowledge of the long-term denudation rates of the upper continental crust. Geochemical studies have attempted to estimate the net denudation rate of a variety of landscapes, ranging from the large basins of the Amazon, Congo, and Himalayas (e.g. Dupre, et al, 1996; Elbaz-Poulichet, et al., 1999; Galy and France-Lanord, 1999), to much smaller basins such as those found on volcanic ocean islands (Louvat and Allegre, 1999). In order to determine landscape denudation rates, it is necessary to estimate both the chemical and physical denudation rates. The chemical rate is normally assumed equal to the flux of the riverine dissolved load out of a basin. The physical denudation rate can be determined in one of two ways: 1) by direct measurement of the sediment flux out of a basin; or 2) by assuming geochemical steady state. The first method is problematic due to the stochastic nature of sediment delivery in riverine systems. In order to accurately measure sediment export, it is generally necessary to have several decades of sediment data. The second method is the one examined in this paper. If the chemical composition of the upper continental crust in the study

basin, and the chemical composition of the riverine dissolved load are known, assuming geochemical steady state allows the physical denudation rate to be calculated by mass balance (Gaillardet, et al., 1997).

Previous studies have illustrated some of the difficulties with using the geochemical method. First, determining the composition of the upper crust and the relative proportions of different lithologies can be problematic in large basins, especially those that are difficult to map (Dupre, et al., 1996; Gaillardet, et al., 1997; Galy and France-Lanord, 1999). Secondly, movement of groundwater can result in inputs from other basins, as well as other elements through hydrothermal activity (Louvat and Allègre, 1998). Also, in large basins it is difficult to account for the influence of a variety of land use activities such as changes in vegetation, erosion due to deforestation, and inputs from pollution. Finally, collection of water and sediment samples on an annual or biannual basis may not allow for accurate determination of possible variations in composition. This project seeks to test the applicability of the geochemical steady state assumption by working in basins that minimize these problems.

Study Sites

To test the conceptual framework of the steady state matrix (Figure 1) we selected two regions in which to analyze riverine geochemical fluxes. Specifically, we contrast the Oregon Coast Range, a region independently interpreted as being in geomorphic steady state (Reneau and Dietrich, 1991), with the Hawaiian Islands, which formed by hot spot volcanism and therefore cannot be in geomorphic steady state. Comparisons of these two regions provide us with insights into the relationships between the two different forms of steady state. The basin characteristics are summarized in Table 1.

Each of the specific drainage basins studied in these areas was chosen to meet four simplifying criteria:

- 1) All of the basins drain monolithologic, basaltic terrains, thereby simplifying the bedrock geochemistry, since the ability to test for geochemical steady state is only as accurate as the chemical characterization of the bedrock.
- 2) The field sites are limited to basins that are large enough to average out individual mass wasting events, yet small enough to be geologically homogenous. Our basins range from 16 to 129 km².
- 3) Each of the basins have complete and relatively mature forest cover, and are little affected by anthropogenic influences such as clear-cutting, slash-burning, and road construction which might alter the chemical signals by increasing sediment discharge in particular areas (Brown and Krygier, 1971; Beschta, 1978).
- 4) None of the basins were glaciated. Glaciation removes the soil profile and alters slope angles forcing a system out of steady state. The amount of time required for a system to return to steady state is unknown.

Oregon Coast Range

We have identified two areas of the Oregon Coast Range that satisfy all these requirements, the Trask River in the Tillamook area and two small coastal watersheds (Rock and Cummins Creeks) south of Newport, Oregon (Figures 2 and 3). Reconnaissance fieldwork in the selected basins confirms previous mapping (Snively et al., 1976; Wells et al., 1983) indicating that each basin drains a single, basaltic unit. Furthermore, the petrologic variation in the streambed clasts is quite limited. The Oregon Coast Range study basins primarily consist of Eocene plagioclase phyric and aphyric basalt, with the exception of minor Eocene to Miocene mafic, intrusive dikes that occur in a relatively small portion of the exposed bedrock. In addition to meeting the criteria identified above, these areas have been the objects of a number of geomorphological studies pertinent to this work. Of particular value is Dietrich and Dunne's (1978) study of the sediment budget of Rock Creek, which quantified the total solid and dissolved loads for this basin. Reneau and Dietrich's (1991) subsequent work showing an equilibrium between hillslope lowering rates and riverine sediment fluxes provides evidence that portions of the Oregon Coast Range are in geomorphic steady state. Hydrologic work at a steep "zero-order" drainage basin in the Oregon Coast Range showed that all runoff was generated by shallow bedrock flow via event-driven displacement of old water by infiltration of precipitation into highly conductive soils and a near surface zone of bedrock fractures (Anderson et al., 1997; Montgomery et al., 1997; Torres et al., 1998). The predominance of old water in runoff generated at channel network sources suggests that there may be little seasonality to the chemical composition of the dissolved load, an hypothesis that our monthly sampling design described in the next section allows us to test.

Hawaiian Basins

We also identified a drainage basin in the Hawaiian Islands, Kipapa Stream on Oahu that satisfies all of our criteria (Figures 2 and 3). Geologic maps of the Koolau range show that the lithology is also basaltic, with only slight variations in the chemical composition between different flows (Frey et al., 1994). Work in this basin, in addition to the Oregon basins, provided us with information about a region that is clearly not in geomorphic steady state for complete analysis of the steady state matrix. Furthermore, Kipapa Stream is gauged for discharge and there are detailed sediment concentration records allowing us to have an independent estimate of the sediment flux.

Methods

Sampling Techniques

At each of the Oregon study sites (Figures 2 and 3), water samples were collected periodically from June 2000 to June 2001. In the Trask River basin, samples were collected at several locations within the basin to test for scaling factors in the dissolved load. Upon collecting samples, they were immediately filtered for later chemical analysis of the total dissolved (TDS) and total suspended loads (TSS) of the streams. In June 2000, two types of sediment samples were collected from the bed of the river: 1) fine grained sediment that was clearly mobile as suspended load during higher flow conditions as it was found only in slack water areas and low velocity regions of the streams, and 2) larger grained (gravel to cobble size) sediment, which appeared to be the highly mobile portion of the bedload during higher flow conditions. At each of the Hawaiian field sites (Figures 2 and 3), water and sediment samples were collected in the same manner described above in August 2000. At each sampling location, cross-section and long-profile surveys were completed using an engineers level, as well as Wolman Pebble Counts (1954) where water depths and velocities allowed for safe wading in the streams.

Analytical Methods

Stream water samples were filtered onsite through 0.45 μm cellulose acetate filters using a vacuum filtration unit. The filtered water samples were stored in acid washed polyethylene bottles, and acidified with sub-boiling distilled HNO_3 . Samples for anion determination were not acidified, and the pH and alkalinity were determined onsite by titration and the Gran plot method. The TSS samples were collected by filtering river water through 0.45 μm cellulose acetate filters, as well as by direct sampling of the riverbed, then dried and weighed in the laboratory. The TSS samples were next subjected to standard Li-tetraborate fusion and dissolution procedures for

analysis (Johnson et al., 1999). Samples of the bedload and bedrock were dissolved by the same methods for analysis.

The water samples were analyzed for major elements by ICP-AES at the University of Washington (UW), and for trace elements by ICP-MS at the Washington State University Analytical Laboratories (WSUAL). Major element analyses of the silicates were determined by XRF, while trace element analysis of the silicates was done by ICP-MS also at WSUAL. The anion concentrations in the TDS and rainwater samples were determined by ion chromatography in the UW School of Forestry.

For Rock Creek and Cummins Creek, an average bedrock composition was calculated using the samples from both basins since these creeks are incised into a single lithologic unit. For the Trask River sites, the samples were separated into three groups, East Fork, South Fork, and the Main Stem, and average compositions were calculated for each. The samples from all three groups were then used to estimate the composition for the basin area contributing to the Main Stem of the Trask. In the Trask Basin, several dikes were identified and sampled in addition to the country rock. In order to calculate the composition for the Trask sites, a weighted average based on the estimated surface area covered by the dikes relative to the country rock was computed. For the Hawaiian site, previously published data was used to determine the bedrock composition.

Correction for Atmospheric Inputs

Since we are interested only in the portion of the dissolved load that is derived from rock weathering, not that from atmospheric inputs, it is necessary to correct for the input of aerosols and sea spray into the basin. The first step in making this correction is to assume that all of the Cl in the dissolved load comes from the atmosphere, not from the weathering of rock in the basin (a fair assumption for Basaltic lithologies without carbonates). Next, Cl-normalized seawater ratios

can be used to determine the amount of each element in the dissolved load that was input through seawater derived atmospheric deposition. This portion is removed from the geochemical mass balance. Since all of the basins are located close the ocean, no significant fractionation between the elements due to orographic effects should occur. We collected samples of the rainwater in each basin to confirm this assumption.

Results

Bedrock Composition

We characterized the chemical composition of the bedrock in the Oregon Coast Range sites by collecting several samples throughout each basin. The results of the XRF and ICP-MS analyses of these samples are shown in Tables 2 and 3. A substantial amount of work has already been completed to characterize the bedrock composition of the Hawaiian Islands, and specifically the Koolau Range where Kipapa Stream is located. We did not collect bedrock samples in this field area, but instead used data from Frey, et al.'s (1994) study, which included samples collected in the area around Kipapa Basin. The chemical data from these samples is shown in Table 4.

Suspended Sediment and Bed load Composition

Samples of the suspended sediment and bed load were collected from each of the study areas, except for the South Fork of the Trask River and Steampot Creek (a tributary to the Trask River). The results of the XRF and ICP-MS analysis of these samples are shown in Table 5. In the Oregon basins, there is very little variation in the chemical composition of the suspended load and bedload, except with respect to P, Na, and Mg, which have coefficients of variation in the range of 27-41%. However, there are often significant differences between the suspended load and bed load compositions within each basin, especially for the elements that weather rapidly out of the bedrock.

Dissolved Load Composition

As stated previously, the riverine dissolved load composition was measured at each of the Oregon field sites on a monthly basis, and then analyzed for major elements by Ion Chromatography and ICP-AES, and for trace elements by ICP-MS (Table 6). Monthly sampling

allowed us to determine if there are significant variations in the chemical composition of the river water on a seasonal basis, and to evaluate what sampling frequency is required to accurately measure the amount of material exported from the basin as dissolved load. During the one-year sampling period, the variance in the ionic concentrations was minimal with coefficients of variation ranging from 2-16% (Table 7). Furthermore, the variations measured in the dissolved load concentrations correlate inversely with fluvial discharge from the basin; at high levels of discharge the dissolved ions are diluted (Figure 4). This suggests that even in rivers with seasonal patterns of discharge, the error associated with only taking a single grab sample is minimal, except during storms or extreme discharge events. In basins with wide seasonal discharge fluctuations, samples should be collected during a variety of conditions to avoid over estimating the mass of material transported in the dissolved load.

Scaling factors for the dissolved load composition also were minimal during the sampling year, as the ionic concentration of elements in the river water did vary systematically with the contributing drainage area (Figure 4). This suggests that regardless of where in the basin sampling occurs, the results do not vary significantly.

The dissolved load composition for the Hawaiian stream was measured from a sample collected in August 2000 (Table 6). The ionic concentrations in this stream are significantly less than those found in Oregon, even in the dry summer months. This suggests that removal of material in the dissolved load is less important in the Hawaiian basin, perhaps due to the age of the soil as the most soluble components of the soil profile were removed in the early stages of soil formation.

Atmospheric Inputs Correction

Since this study is primarily interested in the export of weathering products from the study basins, it is necessary to correct the riverine dissolved loads for inputs of ions from aerosols

and sea spray. The corrected values for the dissolved loads are shown in Table 8. The ratios of each of the major elements to seawater are shown, as well as the range of compositions in the rainwater samples from each of the basins in Table 9. The seawater ratios are similar to those of the rain samples, but we have relied on seawater ratios for the correction since we did not collect an adequate number of rain samples to fully characterize the rainwater composition in each basin. Furthermore, we were unable to obtain rainwater samples from the Hawaiian basin, so the use of the seawater ratios provides consistency throughout the study. Based on either seawater or rainwater corrections, the largest atmospheric inputs to the dissolved load were Na and Mg, with minimal inputs of K and Ca.

Calculation of the Geochemical Mass Balance

We calculated a geochemical mass balance for each of the study sites using equation 1. The results of these calculations are shown expressed as a Percent Mass Imbalance:

$$\% \text{ Mass Imbalance} = (X_w - X_e) / (X_w + X_e) \quad (\text{eq. 2})$$

Where X_w is the amount of element X weathered from the bedrock, and X_e is the amount of element X exported from the basin in the dissolved load, suspended load, and bed load.

None of the basins are in a perfect geochemical mass balance with respect to the major elements, although some are closer than others (Figures 6 and 7). This result immediately brings the question of how close to steady state a system has to be in order to consider it in steady state? To address this question, it is necessary to evaluate the amount of error that is inherent to the types of measurements made for this analysis.

The first source of error is in our determination of the average bedrock composition. Since only a discrete number of samples can be analyzed, within basin variability may be larger

than our samples indicate. Most of our samples from Cummins Creek, Rock Creek, and the Trask River basins have coefficients of variation $<30\%$, with a few samples exceeding that value (you have not stated any limits yet) (Tables 2 and 3). However, relative to previous work done in more lithologically complex basins, this error should be minimal.

A second source of error is in the estimation of the mass of bed load transport. Bed load transport is difficult to measure accurately, and few studies attempt to measure it at all (NCASI, 1999). Researchers commonly assume that bed load is 10% of the suspended sediment load, regardless of the type of river system. However, previous work on sediment budgets in the Oregon and Washington Coast Ranges have shown that bed load is typically only 3-4% of the sediment load in these rivers (Larson and Sidle, 1980; Collins and Dune, 1989), and we have used an estimate of 4% for our mass balance. Since we were unable to find any previous work on the sediment budgets of the Hawaiian stream near our field site, we have assumed that the bed load is 10% of the suspended sediment load in Kipapa Stream. However, calculating the mass balances with bedload estimates of both 4% and 10%, results in a difference in the mass balance of less than 1%.

The third possible source of error is in the estimates of suspended sediment loads. For the Oregon basins, our suspended sediment data is based on long-term studies of the sediment budgets in the Oregon Coast rivers and denudation rates of the Oregon Coast Range (Dietrich and Dunne, 1978; Reneau and Dietrich, 1991), thus annual variations in sediment delivery are accounted for. For Kipapa Stream, the only suspended sediment flux data available is a 5-year study conducted by the USGS. Thus, more error is associated with the mass balance calculated for this basin, although an exact measurement of this error cannot be made (NCASI, 1999).

The fourth source of errors are the estimates of discharge for the Oregon sampling sites. No gauging stations are located in the Cummins Creek or Rock Creek basins, so we extrapolated the average annual discharges in these basins from the data on gauged basins of similar size in the

Oregon Coast Range. This was done by a least squares linear regression of the discharge relative to drainage area in the gauged streams (Figure 7). This method should be appropriate in the Oregon Coast Range because the watersheds in this area have similar slope distributions and precipitation patterns. In the Trask River Basin, a USGS discharge gauging station is located downstream of our sampling sites. We used the data from this gauge, and corrected it for each of the sites based on the drainage area that contributes to each of the sampling sites. For Kipapa Stream, we sampled at the site of a USGS gauging station.

The fifth source of error is that due to dust inputs into the basins. This may be particularly important in Hawaii where a significant amount of the nutrients available to the vegetation are derived from Asian dust inputs (Chadwick et al., 1999), however, there are also likely to be dust inputs into the Oregon basins. In Hawaii, the age of the island is the main control on the significance of the Asian dust to the nutrient balances; young islands like Hawaii are dominated by weathering of the bedrock and have high concentrations of cations such as Ca, Mg, and K, while on older islands like Molokai, the supply of cations is limited to atmospheric inputs. Oahu, where Kipapa stream is located, falls in the middle of the two extremes, making it difficult to predict the proportion of the elements that are derived from dust relative to bedrock weathering (Chadwick et al, 1999). As the Hawaiian soils are weathered, not only does the amount of rock derived cations decrease due to incongruent weathering, but the ability of the soil to retain cations from other sources such as atmospheric deposition also decreases (Torn et al., 1997). As a result, predicting the pathways that ions derived from dust inputs will take within the Hawaiian soils and vegetation is complex, and determining the proportions of rock derived versus atmospherically derived elements in the streams of Oahu is difficult as well. Since we sampled in the dry season, water flowing in the stream should only consist of groundwater derived base flow. Thus, a greater proportion of the dissolved load should be rock derived, than is found in soil solutions during the rainy season, or in the vegetation. Although sampling in the summer may reduce the influence of

the dust, the complexities of the system prevent us from quantitatively determining the amount of the dissolved load that is dust derived. As a result, we will assume that in our samples all of the dissolved load composition is derived from weathering of Hawaiian rocks, or from sea spray (which we have already corrected for). If this assumption is invalid and a significant portion of the dissolved load is derived from Asian Dust, we will demonstrate below that our result would not be different because this would only show Kipapa Stream to be further from geochemical steady state. In contrast to Hawaii, the Oregon sites are further from Asian dust sources and, due to tectonic activity in the range, have a continuous supply of fresh bedrock to weather, suggesting that dust inputs are less significant relative to the contribution of the bedrock.

Analytical errors associated with the ICP, XRF, and IC sample analysis are the final source of error in our mass balance. For the dissolved load, these errors are minimal as shown by the charge balances that are generally within 5% for the river water (Table 6). For the analysis of the silicates, all but two of the bedrock and bedload samples have total weight percents of $100 \pm 3\%$, while the error in the suspended load samples is generally larger. LOI analysis of the suspended load samples accounts for the difference (Table 5).

Upon recognition of these sources of error, it is useful to look at previous works which have attempted to determine if systems are in steady state based on flux models. When analyzing the possible balance between hillslope erosion and sediment yield, Reneau and Dietrich (1991) assumed that a system with 0-17% error in the mass balance was in steady state. Other work by Allègre et al. (1996) looking at erosion rates in the Amazon and Congo River systems assumed that systems with 0-30% error were in steady state. As such, for errors >30% we are comfortable rejecting the hypothesis of steady state, but for errors <30% a system is close enough to steady state that our methods of measurement cannot discern a departure from the steady state condition. This boundary is indicated on Figures 6 and 7.

Figures 6 and 7 show that central Oregon basins (Rock Creek and Cummins Creek) are in geochemical steady state for all of the major elements that we analyzed. The basins in the northern portion of the Oregon Coast Range are also in steady state with respect to most mobile (easily weathered) elements (Na, K, Mg, Ca, and even Si), but the basins are retaining a significant portion of the Al, Fe, and Mn, in the soils and sediments forcing the basins out of steady state with respect to the less mobile elements. This suggests that there are significant differences between the two regions of the Oregon Coast Range, as discussed further below.

Determination of the geochemical mass balance for the Hawaiian study basin is more complicated because the bedrock lowering rate is not independently known. As a result, we calculated the geochemical mass balance for Kipapa Stream in two different ways. First, we used the lowering rates calculated for a variety of basalts in other areas. These rates range from 0.04 mm/yr in Argentina (Benedetti, 1994), to 0.03-0.05 mm/yr in New Caledonia (Trescases, 1975 as cited in Benedetti, 1994), to an average rate of 0.03 mm/yr for the Pacific Northwest of the US (Dethier, 1986). We calculated the mass balance using a median value of 0.04 mm/yr, the results of which are shown on Figures 6 and 7. Secondly, we determined the range of lowering rates for which each of the elements would be in steady state and plotted them in Figure 8. This method showed that regardless of the lowering rate selected, Kipapa basin can not be in geochemical steady state for all of the major elements, although a lowering rate of 0.2 ± 0.1 mm/yr would put the basin in steady state for all of the elements studied except for Na, K, and Ca, which would be retained in the system (Figures 6 and 7). The influence of the lowering rate chosen on our understanding of the geochemical mass balance for the Kipapa basin is discussed in detail below.

Discussion

Landscape evolution in Oregon and Hawaii

The mass balances shown in Figures 6 and 7 suggest that the central portion of the Oregon Coast Range, where Rock Creek and Cummins Creek are located, is in geochemical steady state as well as the geomorphic steady state determined previously by Reneau and Dietrich (1991), placing the area in region 1 of the steady state matrix (Figure 1). This result is consistent with our initial hypothesis that the two forms of steady state, geochemical and geophysical, are interdependent conditions.

In contrast, the northern portion of the Oregon Coast Range does not appear to be in geochemical steady state. The geochemical data shows that the basin is in geochemical steady state with respect to the most soluble elements, Mg, K, Ca, and Na, but the regolith is not in steady state with respect to the transition metals, Al, Fe, Mn. This result can be explained by incongruent weathering reactions. Incongruent weathering, or the preferential removal of some elements from the bedrock, often follows a common pattern in oxidized environments. The Na and K cations are weathered most rapidly out of the bedrock, followed by Mg and Ca ions, which are also easily removed. These cations are generally soluble in natural waters, and therefore significant amounts of these ions can be transported out of river basins in the dissolved load. Transition metals such as Fe, Al, and Mn are important clay- and oxide- forming elements and therefore tend to be less mobile during the early stages of soil formation, and accumulate in high concentrations in the soil and saprolite layers. As a result, these ions can only be removed from river basins by physical transport of silicate material. Thus, the pattern of the geochemical data for the Trask basins is not unusual. The basins are in steady state with respect to Na, Mg, K, and Ca, all elements that can be transported in the dissolved load. But the basins are not steady state with respect to the transition metals, suggesting that the physical denudation rate in the basin is not high enough for the region to obtain geochemical steady state.

Although the geochemical state of the northern portion of the Oregon Coast Range is easily interpreted from this study, the geomorphic state of the basin is not as well constrained. As discussed above, previous work in the Oregon Coast Range has shown that portions of the range are in geomorphic steady state. The most detailed evidence for this is derived from the mass flux study of Rock Creek by Reneau and Dietrich (1991) which showed that the hillslope lowering rate of the basin is in equilibrium with the removal of dissolved and suspended sediment from the basin. The interpretation of geomorphic steady state is further supported for this area because Reneau and Dietrich's estimated denudation rate for the Rock Creek basin correlates with the uplift rates for the coast range measured by Kelsey (1994). However, since the mass flux study was limited to the central portion of the Oregon Coast Range, it does not necessarily provide information about the geomorphic state of the northern portion of the range.

The northern portion of the range has several geomorphic differences from the central range, including a higher mean elevation, and slightly steeper slopes, which suggests that the balance of erosional and tectonic processes in the northern portion of the range is different from the central range (Personius, 1994). In addition, comparisons between the channel incision rates and the uplift rates in the Oregon Coast Range show significant differences between the central and northern portions of the range. In the central region, channel incision rates are equal to the long term uplift rates, a condition required for geomorphic steady state. In contrast, in the northern portion of the range channel incision rates are significantly higher than the long term uplift rates, showing that this portion of the range is not in geomorphic steady state (Personius, 1994). The work by Personius further showed a regional change in several geomorphic parameters occurs just north of the central Oregon Coast study sites (Rock and Cummins Creeks), in the area of the Trask River basin. Personius concluded that this change is likely attributed to along-strike variations in the strain accumulation of the Cascadia subduction zone. Although the causes of these along-strike variations are unknown, they might be attributed to changes in plate

geometry, wedge accretion, or variations in individual subduction zone earthquakes (Personius, 1994). Although the geomorphic state of the northern Oregon Coast Range has not been studied directly, this evidence suggests that the northern portion of the Oregon Coast Range is not in geomorphic steady state. As a result, this area should be placed in region 4 of the steady state matrix (Figure 1), supporting our hypothesis that the two forms of steady state are interdependent conditions.

The mass balance for the Hawaiian basin suggests that it is not in geochemical steady state either, placing it in region 4 of the steady state matrix. Without knowing the bedrock lowering rate, a complete understanding of the system is not possible due to the dramatic variation in the mass balance as a function of the lowering rate (Figures 5, 6, and 8). However, it is important to note that regardless of the assumed lowering rate chosen, the Kipapa Stream basin is not in geochemical steady state. Analysis of the geochemical mass balances for Kipapa Stream shows two populations of elements which could obtain geochemical steady state for different assumed lowering rates: Na, K, and Ca would be in steady state if the bedrock lowering rate is low (0.02-0.06 mm/yr) and Mg, Si, Al, Fe, and Mn would be in steady state if the bedrock lowering is much higher (0.1-0.3 mm/yr) (Figure 8).

The existence of these two populations may indicate that the Kipapa basin is in steady state, but an outside source or sink of elements is distorting the data. For example, a possible source of excess ions is the input of Asian dust from the atmosphere, and a possible sink for ions would be the uptake of nutrients by the vegetation since there is a limited supply of rock-derived nutrients in the highly weathered soils of this region (Chadwick et al., 1999).

An alternative explanation for the geochemical mass balance of Kipapa Stream is one based on typical incongruent weathering patterns in soils. The highly soluble elements might be expected to remain in an approximate steady state, since these ions are primarily mobilized by chemical weathering so they can be removed from the system as fast as bedrock weathering

proceeds and groundwater is able to contact the primary minerals. The transition metals would be expected to accumulate in the soils during the early stages of soil formation. Mg would be expected to follow the pattern of the transition metals, at least during the early stages of weathering, because it preferentially replaces the less stable Ca ions when secondary minerals form. As a result, the suspended sediment and bedload material in the stream are enriched in Al, Fe, Mn, Mg, and Si relative to the initial bedrock composition. Kipapa Stream has suspended sediment loads that are ten times larger than those found in the Oregon Coast study basins, so it would not be surprising if the transition metals were exported out of the basin at a higher rate than they are weathered out of the bedrock. In contrast, on a younger island such as Hawaii, the transition metals would tend to accumulate as the soil profiles thickened. Only once the hillslopes of a basin are highly dissected and the slopes become sufficiently steep is the physical erosion rate high enough to export large amounts of the highly weathered soil and saprolite. If this interpretation is correct, the bedrock lowering rate for the Kipapa Stream basin is in the range of 0.02- 0.06 mm/yr, a rate which correlates with those observed for basalt lowering rates in other regions (Trescases, 1975; Dethier, 1986; Benedetti, 1994).

Calculation of the Enrichment Factor

The steady state matrix shown in Figure 1 is a simplified version of the wide variety of landscape conditions that may exist. For example, region 2 of the steady state matrix, the condition in which a range is in geomorphic steady state but not geochemical steady state, could occur because (1) the region is out of geochemical steady state because the thickness of the regolith is increasing; or (2) the region is out of geochemical steady state because the thickness of the regolith is decreasing (Figure 9). In a similar manner, region 4 can be expanded into 4 subdomains (Figure 10). Application of the geochemical mass balance and determination of the amounts of each element exported out of a basin can aid in the determination of the mechanisms

that are forcing the system out of geochemical steady state, and provide the information necessary for placing a system on these expanded matrixes.

The retention or loss of elements in a geochemical balance can be quantified by the Enrichment Factor (E). Calculation of E allows for determination of whether a system is out of steady state because the regolith is increasing in thickness or because it is decreasing in thickness, and it is calculated by:

$$E = (\alpha/\beta)_{\text{exported}} / (\alpha/\beta)_{\text{bedrock}} \quad (\text{eq. 3})$$

where α is the mass of a soluble element that can be removed easily from a system by dissolution into the dissolved load (generally an alkali earth or alkali metal), and β is the mass of an element that is retained in secondary minerals during incongruent weathering (generally a transition metal). The ratio of the two elements in the exported load relative to the ratio of the two elements in the bedrock gives a quantitative method for assessing changes in the regolith as a function of the geochemical mass balance. If $E > 1$, the system is becoming enriched in the transition metals relative to the bedrock, suggesting that the regolith is thickening. If $E < 1$, the system is exporting excess amounts of the transition metals, suggesting that the system is denuding large amounts of highly weathered material and the regolith is thinning. If $E = 1$, the system is in a geochemical mass balance. The enrichment factors for the study basins (Figures 11a, b, and c) show that although both the northern portion of the Oregon Coast range and Hawaii are out of geochemical steady state, they are out of steady state for different reasons. As discussed previously, the northern Oregon Coast Range is retaining elements like Al, Fe, and Mn in the regolith, causing the regolith to thicken, and resulting E values greater than 1. In contrast, the Hawaiian basin is exporting large amounts of weathered material, decreasing the thickness of the regolith, and resulting in E values less than 1. With knowledge about a region's geomorphic state, a particular

region can be placed on the expanded steady state matrixes as well. For example, the volcanoes on the island of Oahu are no longer active, so the island is not uplifting, but is instead decreasing in elevation. As a result, Kipapa Stream should be placed in region 4b of the expanded steady state matrix (Figure 10). Thus, calculation of the enrichment factor provides a unique method for quantitatively assessing the relationship between chemical and physical weathering processes operating within a basin.

Conclusions and Implications for Geochemical Studies of River Basin Morphology

In summary, our results indicate that there is a strong correlation between geochemical and geomorphic forms of steady state. We do not expect that the two forms of steady state always occur in conjunction, as the full range of conditions formalized in Figure 1 could develop over short time scales. However, our limited data set does support the interpretation that there is a coupling between the two forms, which forces basins into regions 1 and 4 of the steady state matrix, and makes regions 2 and 3 transient conditions. Hence, making a series of relatively simple measurements may allow us to ascertain how far a system is from steady state, thereby improving landscape evolution models, and our understanding of the processes that control the denudation of mountain ranges. In other words, testing for geochemical steady state would allow us to determine a system's geomorphic state as well.

Attempts to use chemical weathering rates, as inferred by the dissolved load of rivers, to measure the physical weathering rates within river basins often rely upon the assumption of geochemical steady state, and an inferred codependency of geochemical and geomorphic steady states (Gaillardet, et al., 1995, 1997; Louvat and Allegre, 1997, 1998). Although this relationship is complex, especially in basins with variable lithologies, these assumptions may be valid and provide a useful method for studying weathering and denudation patterns in a variety of basins. Furthermore, application of the geochemical mass balance approach to river basins provides a method for opening up black box models of landscape dynamics, especially in regions hypothesized to be in geomorphic steady state. The introduction of the Enrichment Factor (E) provides a quantitative method for viewing weathering and erosion patterns in a comprehensive manner, enabling us to better address some of the processes that control landscape dynamics.

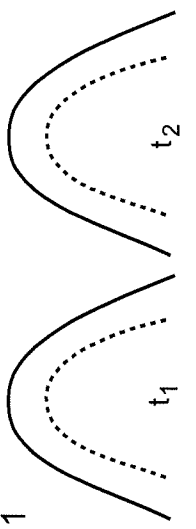
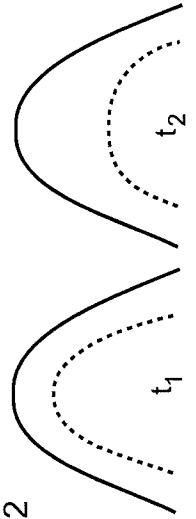
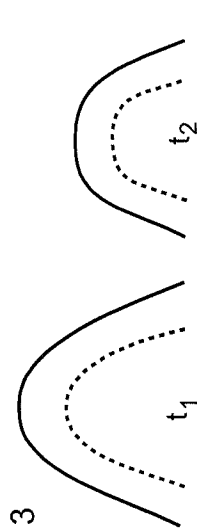
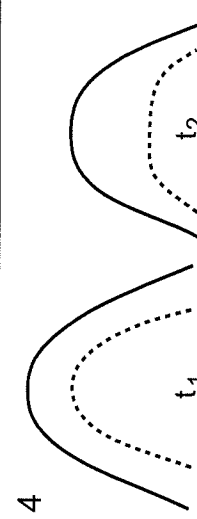
	Geochemical Steady State	Not in Geochemical Steady State
Geomorphic Steady State	<p>1</p>  <p>Both the elevation of the hillslope surface and the thickness of the regolith remain constant through time.</p>	<p>2</p>  <p>The elevation of the hillslope surface remains constant, but the thickness of the regolith increases through time.</p>
Not in Geomorphic Steady State	<p>3</p>  <p>The elevation of the hillslope surface changes, but the thickness of the regolith remains constant through time.</p>	<p>4</p>  <p>Both the elevation of the hillslope surface and the thickness of the regolith change through time.</p>

Figure 1: The Steady State Matrix
Hypothetical relationships between geochemical and geomorphic steady states

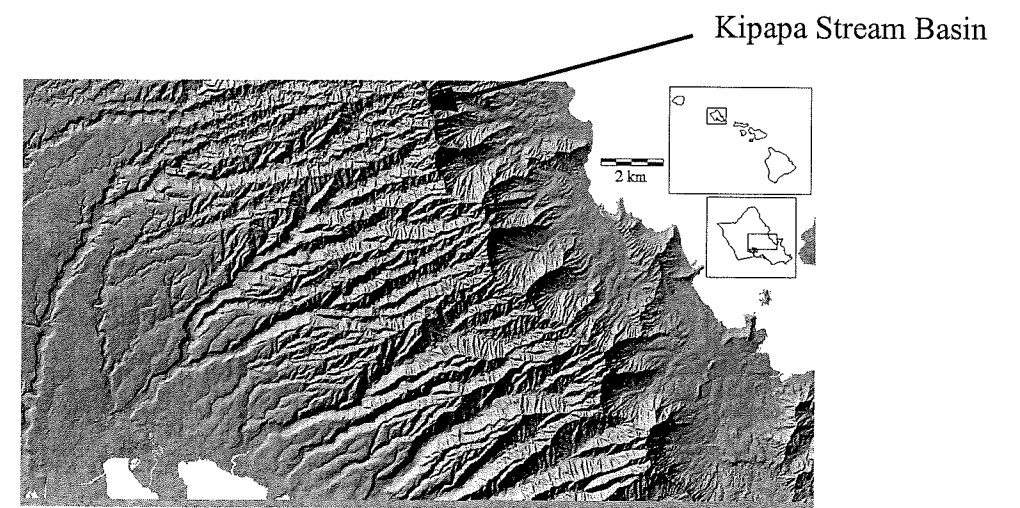
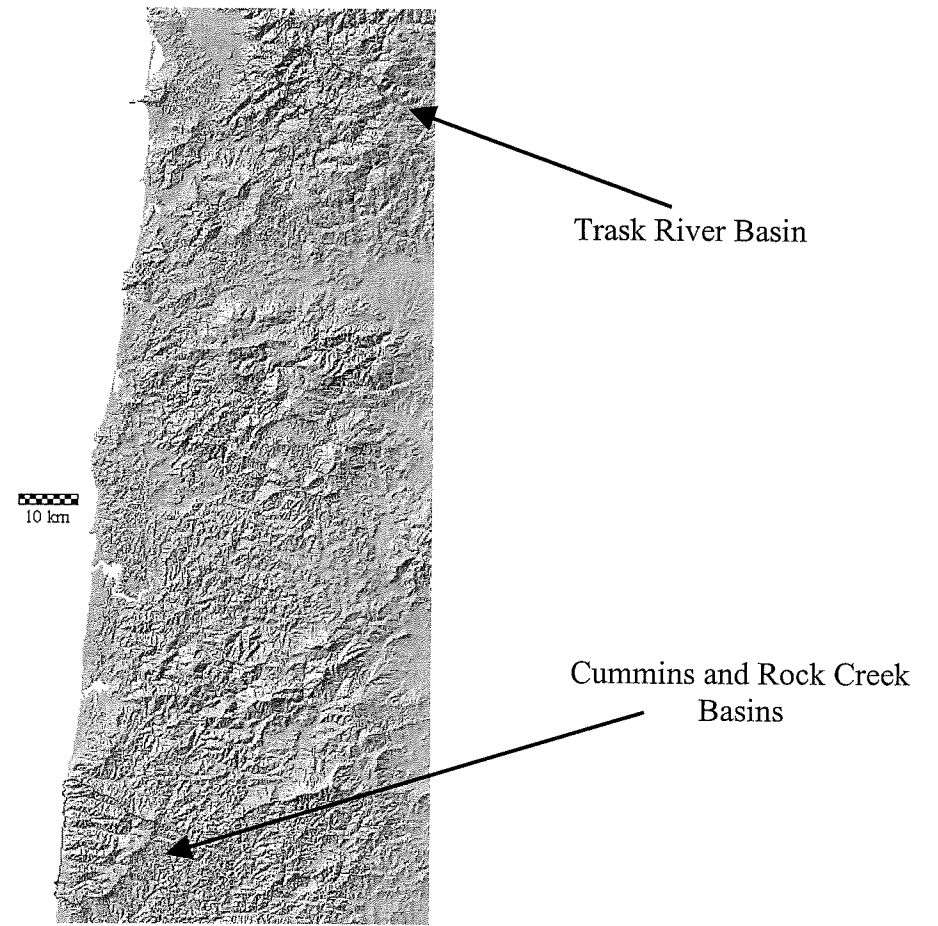


Figure 2: DEM's of the Field Sites in Oregon and Hawaii

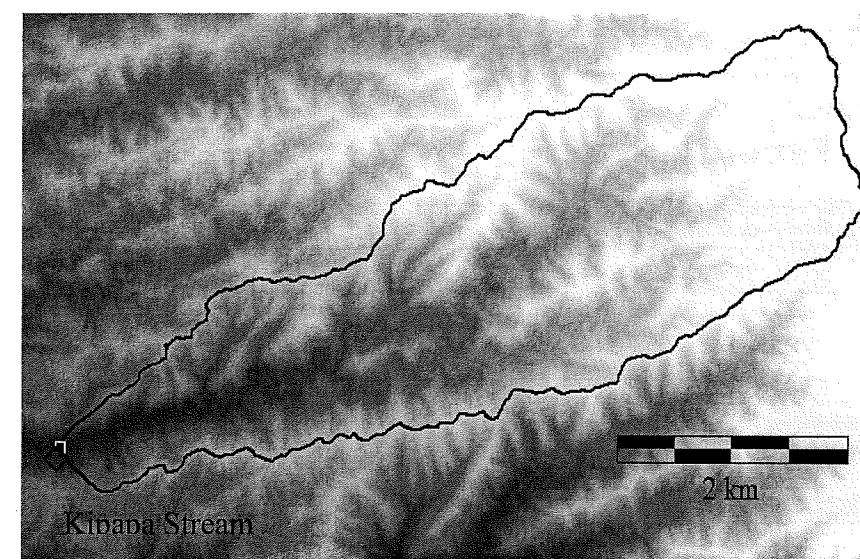
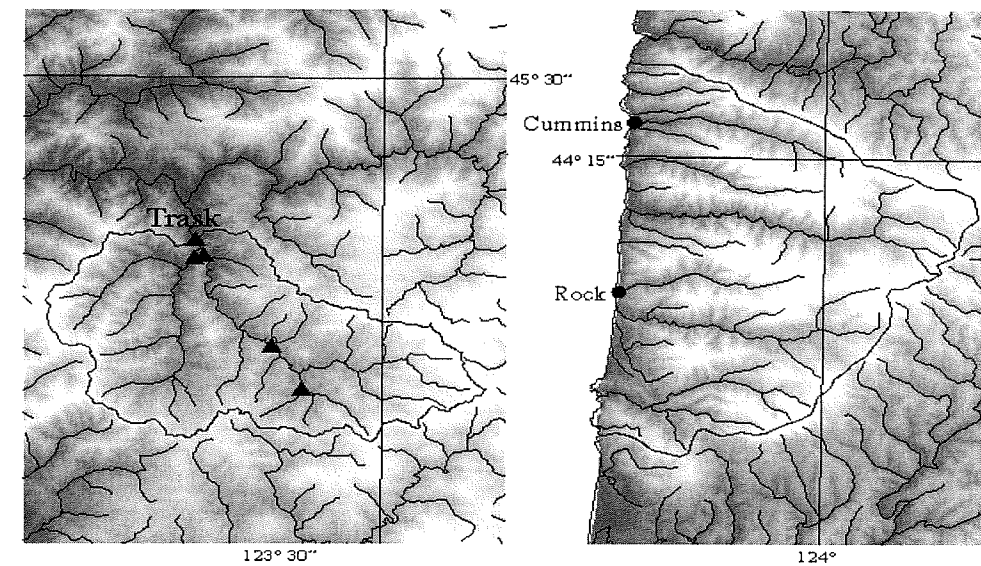


Figure 3: Detailed site map of the study basins and sample locations.

Figure 4a:
Inverse Correlation between Ionic Concentration and Discharge
For Na²⁺

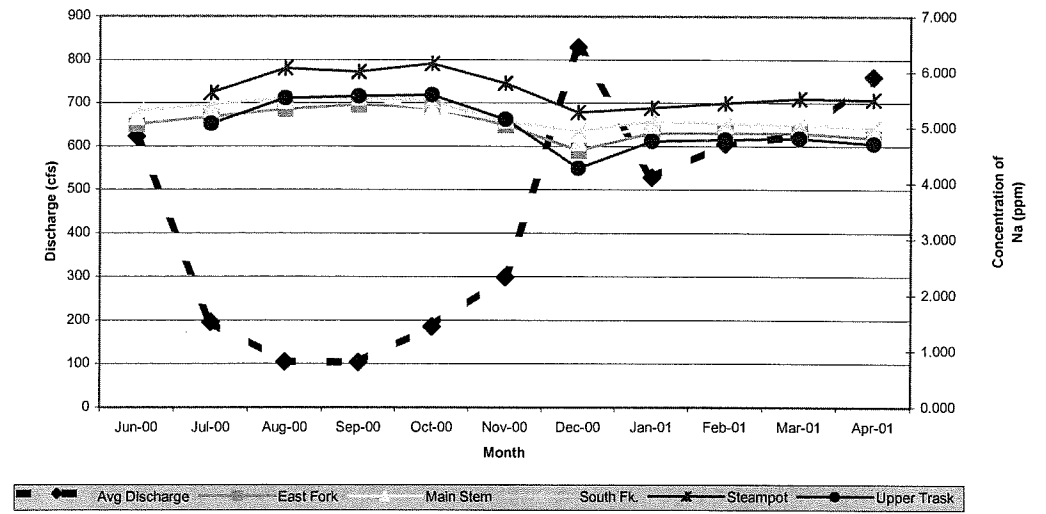


Figure 4b:
Inverse Correlation between Ionic Concentration and Discharge
For Mg²⁺

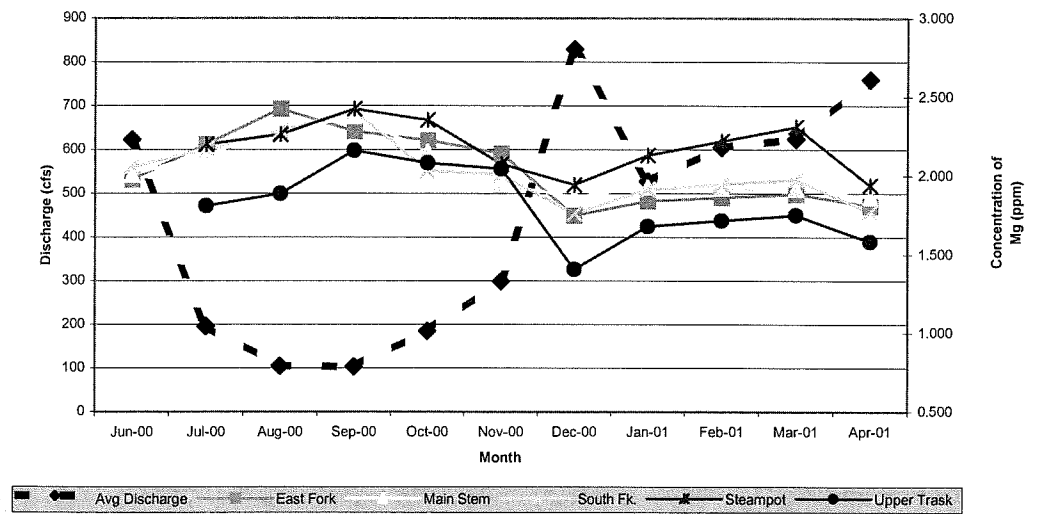
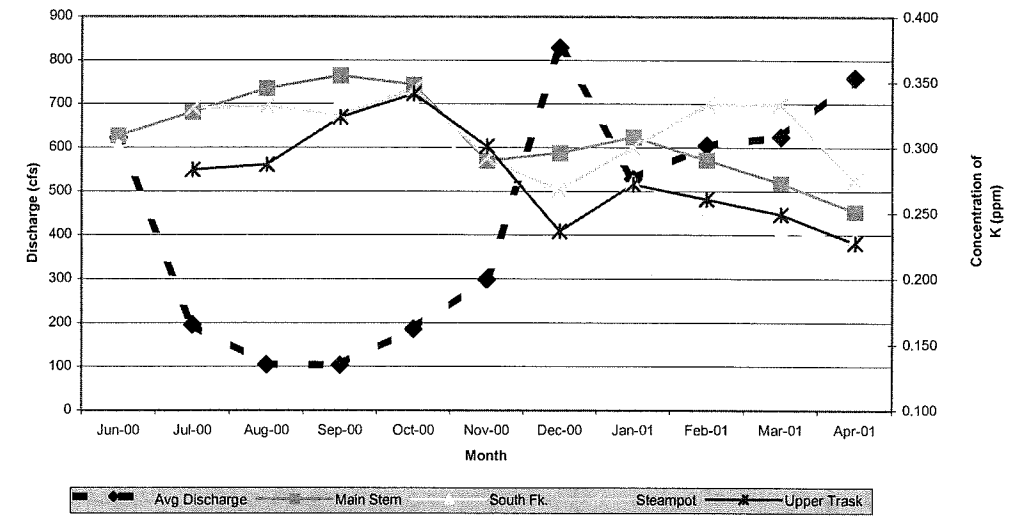


Figure 4c:
Inverse Correlation between Ionic Concentration and Discharge
For K⁺



Figures 4 a, b, and c show the relationship between discharge and ionic concentration in the Trask River. There is little seasonal variation in the ionic concentrations, and the variation that does exist is inversely correlated with discharge from the basin suggesting a dilution effect during storms. These figures also show there are no systematic variations in ionic concentration as the result of scaling effects; the small tributary streams have similar concentrations to the larger stems of the river.

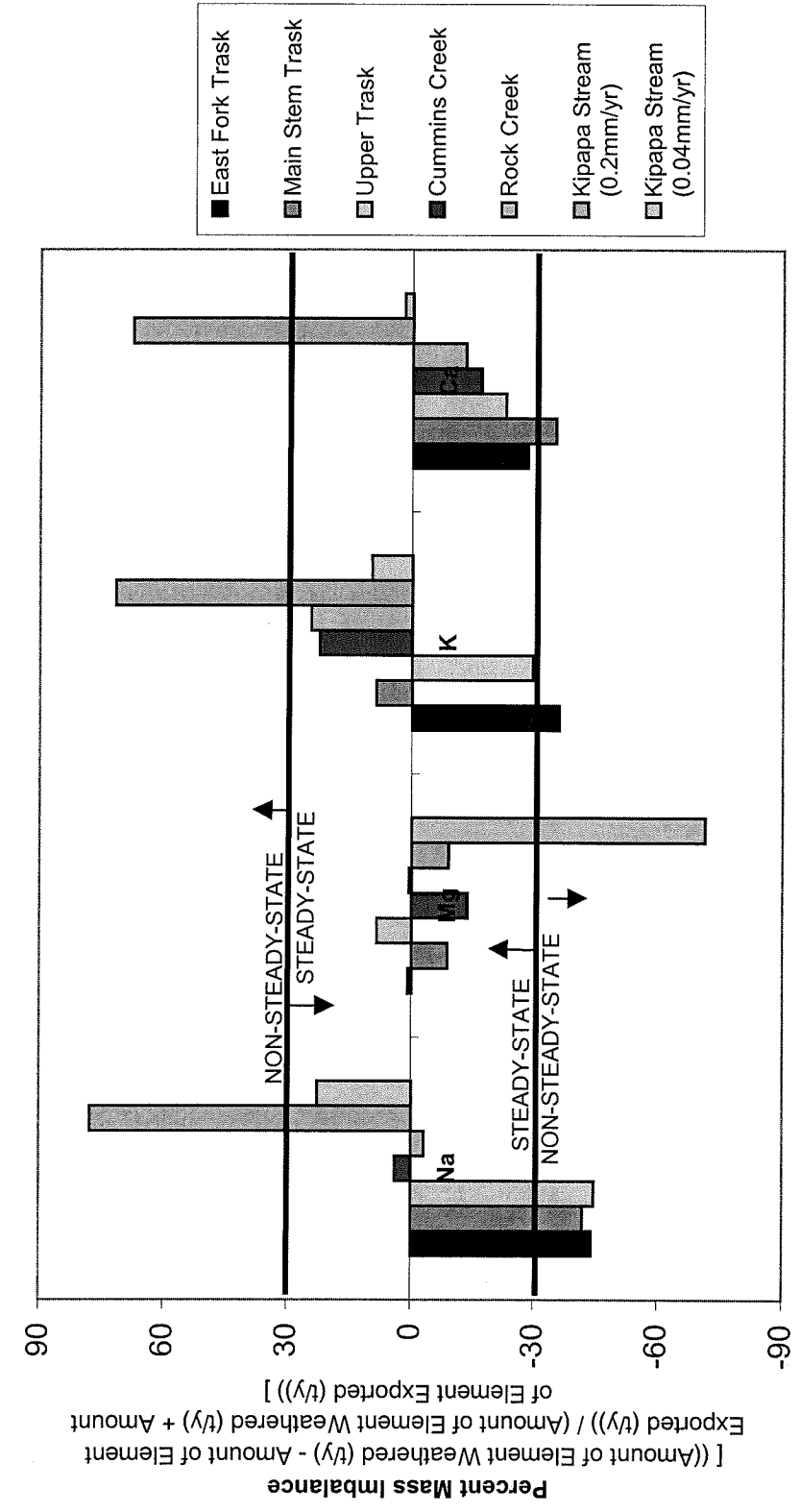


Figure 5:
Percent Mass Imbalance for Na, Mg, K, Ca
 Calculation of the percent mass imbalance for each of the study sites for selected alkali metals and alkali earths. The balance for Kipapa Stream was calculated using two lowering rates, and the results for both rates are shown.

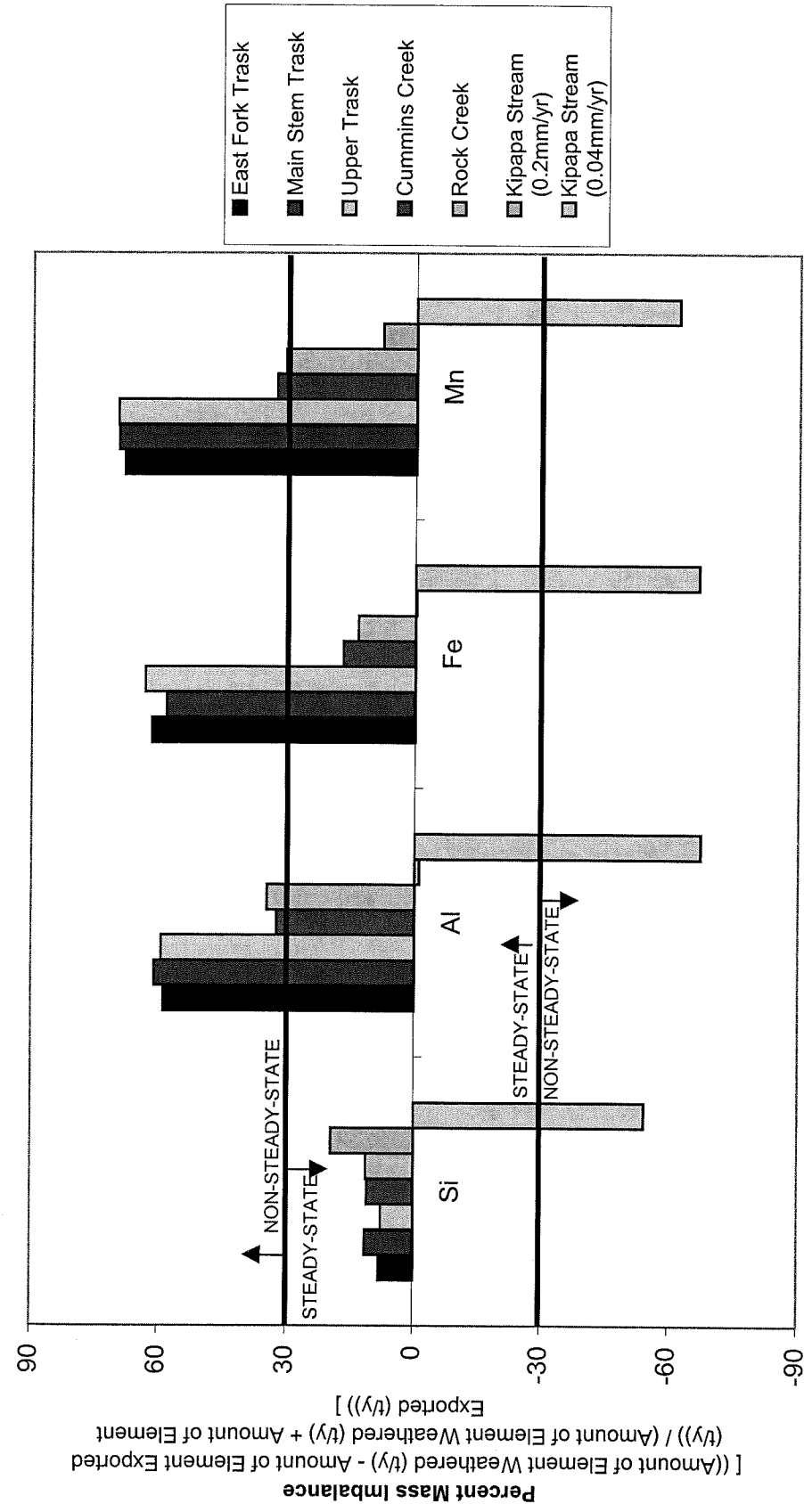


Figure 6:
 Mass Imbalance for Si, Al, Fe, and Mn
 Calculation of the percent mass imbalance for each study sites with respect to Si and selected transition metals. The balance for Kipapa Stream was calculated using two lowering rates, and the results for both rates are shown.

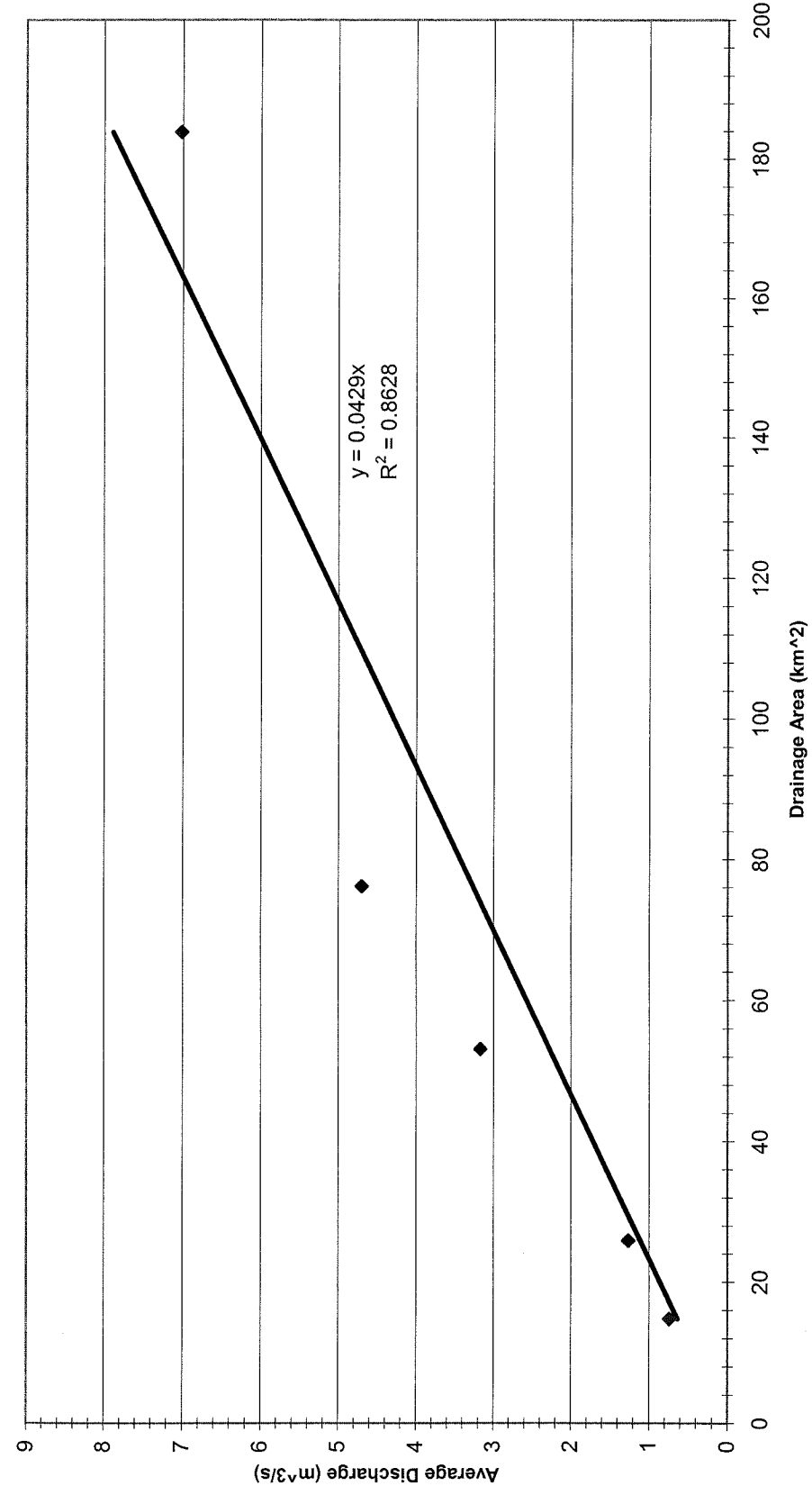


Figure 7:
Drainage Area to Average Discharge Relationships for Selected Small Streams in the Oregon Coast Range

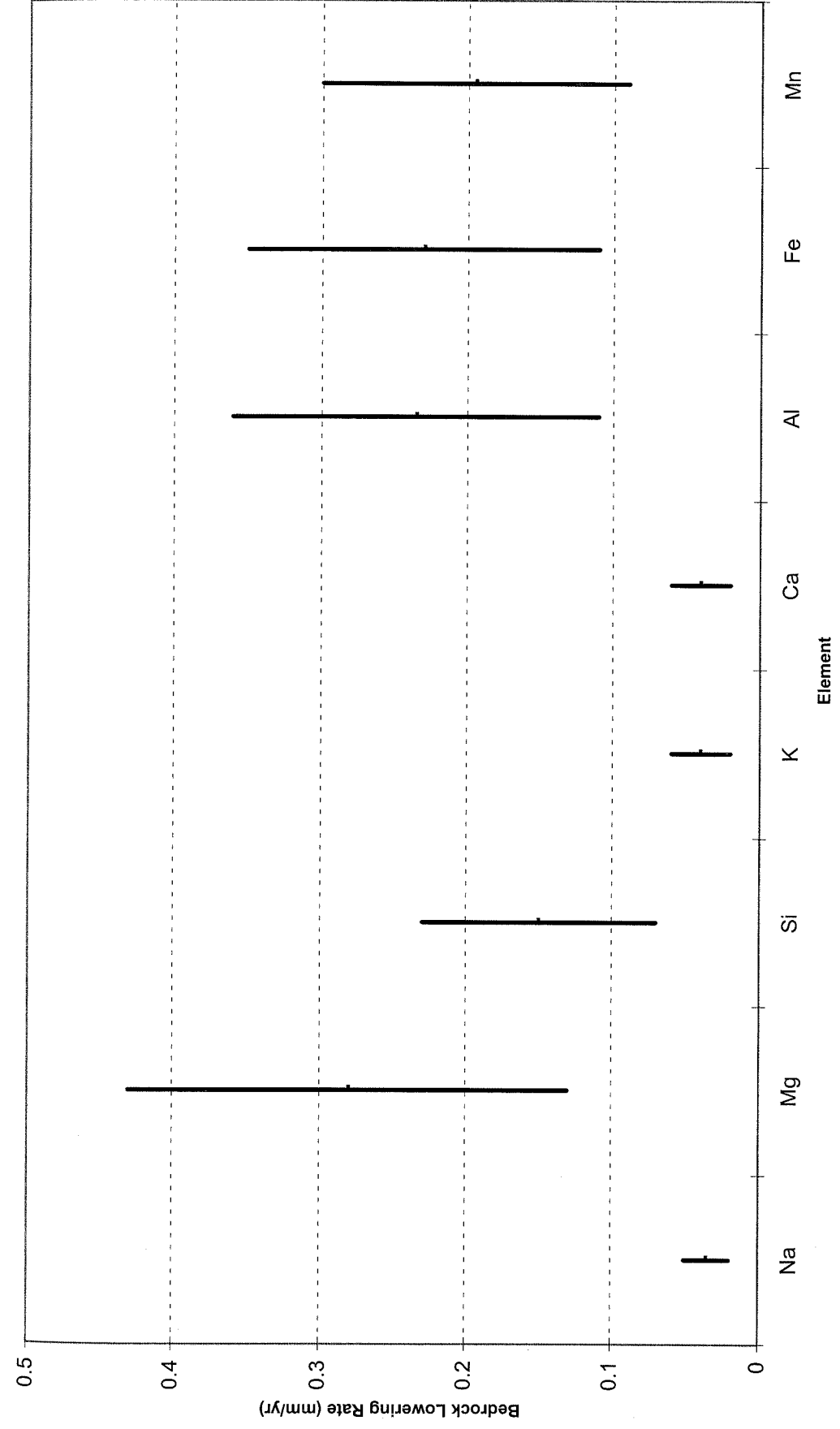
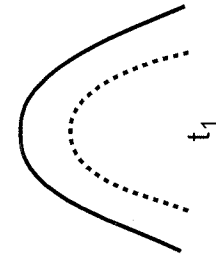
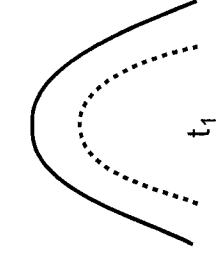


Figure 8:
Erosion Rates Necessary for Obtaining Steady State in the Kipapa Stream Basin



2a. The elevation of the hillslope surface remains constant, but the thickness of the regolith increases through time.

The enrichment factor (E) will be greater than one.



2b. The elevation of the hillslope surface remains constant, but the thickness of the regolith decreases through time.

The enrichment factor (E) will be less than one.

Figure 9: Region 2 of the Steady State Matrix (expanded)
 Hypothetical examples of a region in geomorphic steady state, but not geochemical steady state.

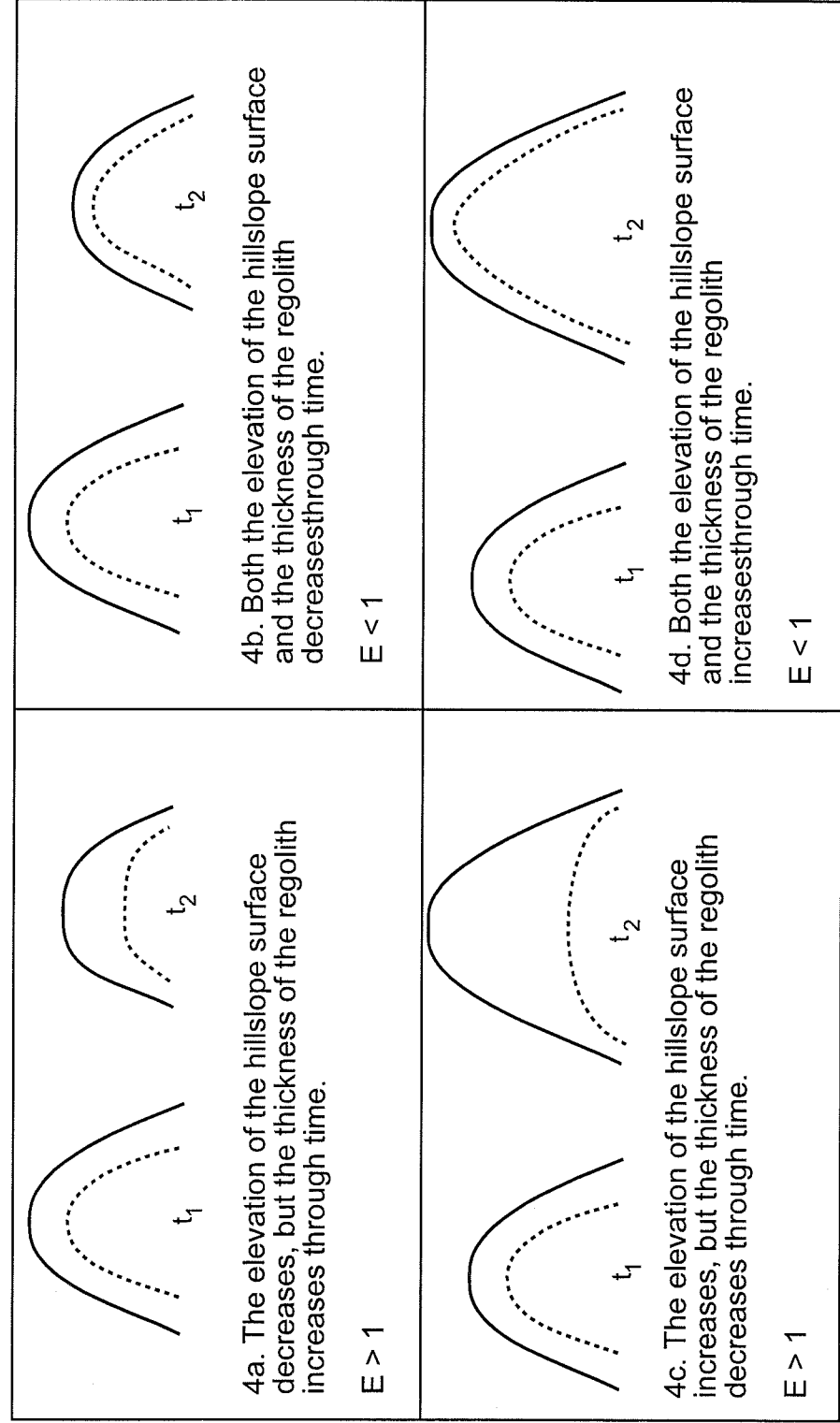


Figure 10: Region 4 of the Steady State Matrix (expanded)
 Hypothetical examples of a region that is neither in
 geochemical nor geomorphic steady state

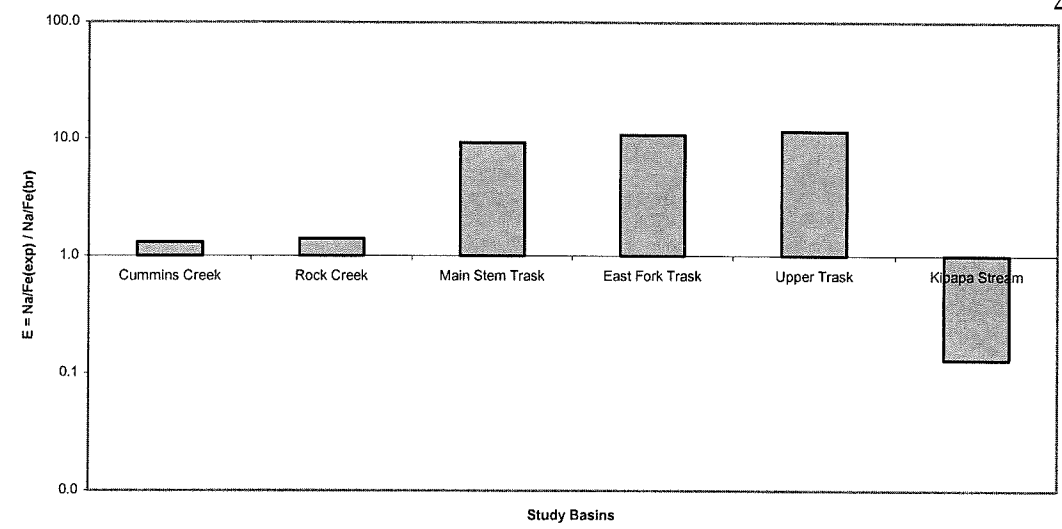


Figure 11a: Log Plot of the enrichment factor calculated for Na/Fe in each of the study basins.

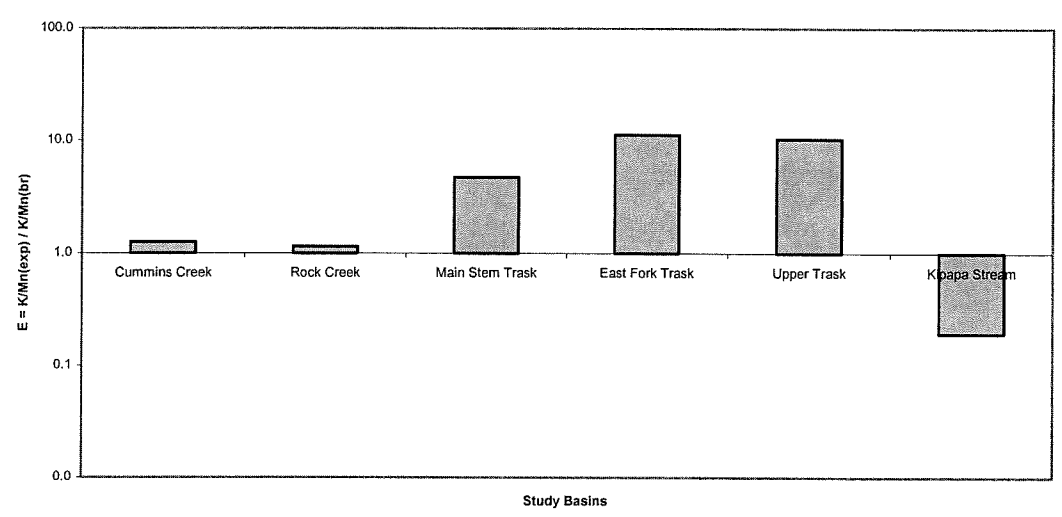


Figure 11b: Log plot of the enrichment factor calculated for K/Mn in each of the study basins.

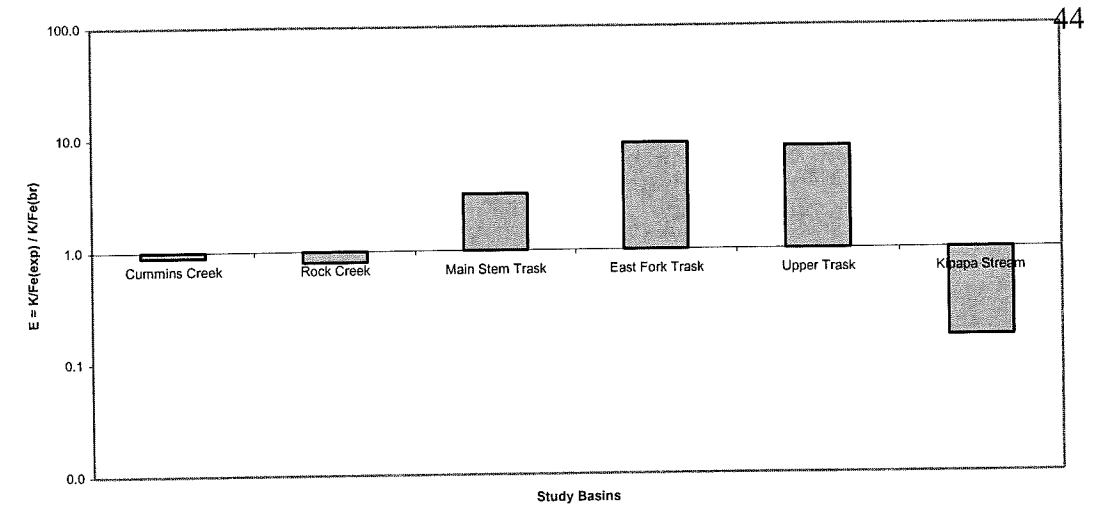


Figure 11c: Log plot of the enrichment factor calculated for K/Fe in each of the study basins.

Figures 11a, b and c show the enrichment factors (E) calculated for each of the study Basins. The central Oregon basins have E values close to 1, indicating that the Cummins and Rock Creek basins are in geochemical steady state. The northern Oregon basins have E values greater than 1, indicating that those basins are enriched in the transition metals, and the Hawaiian basin has E values less than 1, suggesting that the basin is exporting large amounts of highly weathered material, decreasing the amount of the transition metals stored in the basin's regolith.

Table 1: Summary of the Basin Characteristics

Basin	Size (km²)	Avg. Discharge (m³/s)	Mean Slope (°)
Cummins Cr. (OR)	22.0	0.94	22.5
Rock Cr. (OR)	16.2	0.70	22.5
Main Stem Trask (OR)	129.4	10.90	24.3
S. Fork Trask (OR)	52.8	4.44	24.3
E. Fork Trask (OR)	75.03	6.31	24.3
Upper Trask (OR)	10.2	0.85	24.3
Steampot Cr. (OR)	5.6	0.47	24.3
Kipapa (HI)	11.1	0.31	63.5

TABLE 2: Composition of Bedrock Samples from the Trask River Basin

Basin:	Main Stem	Main Stem	Main Stem	Main Stem	South Fork	South Fork	East Fork
Unnormalized Results (Weight %):							
SiO ₂	43.7	48.1	52.0	51.4	52.6	47.2	47.1
Al ₂ O ₃	14.7	14.5	14.2	15.9	14.9	15.0	13.5
TiO ₂	4.0	3.6	2.2	2.7	1.5	3.8	2.6
Fe ₂ O ₃	13.3	12.8	9.6	10.8	9.0	12.5	13.4
MnO	0.3	0.2	0.2	0.2	0.1	0.2	0.2
CaO	6.8	7.9	6.0	8.2	8.5	7.8	11.9
MgO	6.1	4.8	3.6	3.1	3.0	5.1	6.1
K ₂ O	1.9	1.6	5.5	1.4	0.8	1.1	0.2
Na ₂ O	3.6	3.8	2.6	3.7	1.6	4.1	2.4
P ₂ O ₅	0.6	0.5	0.9	0.7	0.6	0.5	0.3
Total	95.0	97.7	96.8	98.2	92.6	97.2	97.7
Normalized Results (Weight %):							
SiO ₂	46.0	49.2	53.7	52.3	56.8	48.5	48.3
Al ₂ O ₃	15.5	14.9	14.6	16.2	16.1	15.4	13.8
TiO ₂	4.2	3.7	2.3	2.7	1.6	3.9	2.7
Fe ₂ O ₃	14.0	13.1	10.0	11.0	9.8	12.8	13.7
MnO	0.3	0.2	0.2	0.2	0.1	0.2	0.2
CaO	7.2	8.1	6.2	8.3	9.2	8.0	12.1
MgO	6.4	4.9	3.7	3.2	3.2	5.2	6.3
K ₂ O	2.0	1.6	5.7	1.4	0.9	1.1	0.2
Na ₂ O	3.8	3.9	2.6	3.8	1.8	4.3	2.5
P ₂ O ₅	0.7	0.5	1.0	0.7	0.7	0.5	0.3
Trace Elements (ppm):							
Ni	45.0	31.0	0.0	8.0	23.0	25.0	52.0
Cr	54.0	39.0	3.0	9.0	42.0	37.0	115.0
Sc	20.0	29.0	17.0	19.0	28.0	21.0	41.0
V	277.0	345.0	115.0	194.0	200.0	331.0	397.0
Ba	328.0	398.0	557.0	355.0	427.0	508.0	73.0
Rb	37.0	47.0	158.0	32.0	14.0	26.0	1.0
Sr	415.0	1232.0	856.0	539.0	4633.0	675.0	226.0
Zr	306.0	263.0	337.0	342.0	238.0	222.0	169.0
Y	34.0	32.0	45.0	46.0	31.0	27.0	39.0
Nb	56.6	50.2	62.9	59.9	12.9	46.0	16.4
Ga	24.0	23.0	21.0	25.0	20.0	22.0	20.0
Cu	47.0	91.0	6.0	47.0	126.0	43.0	200.0
Zn	123.0	123.0	134.0	126.0	94.0	110.0	108.0
Pb	4.0	0.0	2.0	0.0	6.0	4.0	7.0
La	47.0	36.0	43.0	44.0	8.0	31.0	20.0
Ce	98.0	68.0	108.0	108.0	57.0	65.0	35.0
Th	6.0	3.0	4.0	7.0	2.0	5.0	1.0

Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO.

"R" denotes a duplicate bead made from the same rock powder.

"†" denotes values >120% of our highest standard.