APPENDIX A

WEATHERING PROCESSES AND THE COMPOSITION OF INORGANIC MATERIAL TRANSPORTED THROUGH THE ORINOCO RIVER SYSTEM, VENEZUELA AND COLOMBIA

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ABSTRACT

The composition of river-borne material in the Orinoco River system is related primarily to erosion regime, which in turn is related to tectonic setting; especially notable is the contrast between material derived from tectonically active mountain belts and that from stable cratonic regions. For a particular morphotectonic region, the compositional suites of suspended sediment, bed material, overbank deposits, and dissolved phases are fairly uniform and are typically distinct from those of other regions. For each region, a consistent set of chemical weathering reactions can be formulated to explain the composition of dissolved and solid loads. In developing these formulations, erosion on slopes and storage of solids in soils and alluvial sediments are important considerations. Compositionally very mature sediment is derived from areas of thick soils where erosion is transport limited and from areas where sediments are stored for extended periods of time in alluvial deposits. Compositionally immature sediments are derived from tectonically active mountain belts where erosion is weathering limited. Weathering-limited erosion also is important in the elevated parts of the Guayana Shield within areas of steep topography. Compared to the mountain belts, sediments derived from elevated parts of the Shield are more mature. A greater degree of chemical weathering seems to be needed to erode the rock types typical of the Shield. The major-element chemistry and mineral compositions of sediment delivered by the Orinoco River to the ocean are controlled by rivers that have their headwaters in mountain belts and cross the Llanos, a region of alluvial plains within the foreland basin. The composition of sediments in rivers that drain the Shield seems to be established primarily at the site of soil formation, whereas for rivers that drain the mountain belts, additional weathering occurs during episodes of storage on alluvial plains as sediments are transported across the Llanos to the mainstem of the Orinoco. After mixing into the mainstem, there seems to be little subsequent alteration of sediment.

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INTRODUCTION

Although rivers are the dominant pathways to the ocean for erosion products and many human wastes, the phenomena that control the composition of river-borne materials are not yet adequately understood. There are various reasons for this. The properties of some inorganic and most organic river-borne phases are not well described. A complex combination of closely linked chemical, biological, and physical processes mediate erosion and the subsequent transport of material by rivers. Temporary storage of dissolved and solid material in fluvial or lacustrine deposits, soil, lakes, ground water, and biomass complicates description of mass transport. Finally, pervasive human-related perturbations further confound the biogeochemical description of developed river systems, such as those in the United States.

The Orinoco River system, like other large undeveloped river systems, represents an ideal "natural laboratory" for the investigation of weathering and erosion on a continental scale. The contribution of erosion products by the river to the ocean is substantial, and the river basin encompasses a considerable range of environments. Consequently, the effects of various factors, such as climate, landscape development, tectonic regime, and lithology may be evaluated by comparison among small, almost homogeneous subbasins. Denudation rates for different regions can be estimated from their respective contributions to the main-channel material discharge. The relative importance of processes associated with each region can be estimated similarly. Because of the large areas being drained, anomalies caused by local perturbations (such as intense localized storms; landslides; and fires) and edge effects (such as local net transport of material across a basin boundary) are damped out. Finally, mass balances are easier to construct than in small-basin studies, because much of the material in atmospheric precipitation and dry deposition, with the exception of moisture, nitrogen and sulfur compounds, and cyclic salts, is derived from within the basin.

The work described in this paper presents a summary of an ongoing study to characterize the processes that control the distribution of major elements in surface water within the Orinoco River basin. This work is part of a larger multidisciplinary study, under the auspices of the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables and the United States Geological Survey (see Meade *et al.*, in press), which has as its objective the measurement of the discharge of water, suspended sediment, and dissolved phases through the system. For the past 4 years, our research has been directed toward characterization of the chemistry and mineralogy of fine-grained sediment, sand, and a few selected soil profiles for different regions of the basin. The goal is to use these analytical data and mass fluxes through the system to describe the physical and biogeochemical processes that are important in determining sediment composition. We are focusing on describing the phenomena that are important in controlling the partitioning of the major elements (Al, C, Ca, Cl, Fe, H, K, Mg, Mn, N, Na, O, S, Si, Ti) and certain important minor elements (F, P, Sr, Zr) among river-borne phases.

In this paper, we examine how rates of chemical weathering are controlled at a landform scale and how chemical elements are partitioned among the dissolved and solid phases transported by rivers. Our approach is based on the observation that most sources of dissolved phases, including those from weathering reactions, have characteristic chemical signatures that can be used to evaluate their relative importance. Consequently, the composition of the dissolved load is especially useful in assessing the rate and nature of ongoing chemical weathering processes, provided there is little storage of dissolved phases. Models of chemical weathering that describe the composition of the dissolved load also can be used to evaluate processes controlling solid-load (suspended sediment and mobile bed material) composition. The degree to which there is consistency between the composition of the dissolved and solid loads is a measure of the degree to which erosion is near a long-term steady state, which is the simplest possible situation. Solute storage may be a problem in settings with substantial evaporation or in rivers basins with extensive lakes. There is little indication for solute storage in the Orinoco River system; thus, it is an ideal local to study natural processes affecting the composition of river-borne materials.

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The Setting

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The Orinoco River is the third largest river in the world. It has a basin area of 990,000 km^2 and a mean annual discharge of 1.1 x 10^{12} m^3 (36,000 m^3/s) (Meade *et al.*, 1983). Throughout most of the drainage basin, the climate is seasonal tropical; the rainy season extends from about April to November. Annual precipitation ranges from about 1 m in the north to about 4 m in the south. Average daily temperatures in the lowlands do not vary greatly from the annual mean of 25–30 °C (MARNR, 1983).

There are three important tectonic provinces within the Orinoco River basin (Fig. A.1). These are the Guayana Shield which is located along the southern margin of the basin and in the southeastern one-third of the basin, the fold-and-thrust terrains of the Andes and the Caribbean Marginal Mountains located along the western and northern margins of the basin, and the Llanos, a region of alluvial plains within the foreland basin that is located between the shield and mountain belts. The Guayana Shield can be subdivided into an extremely flat region in the southwestern part of its extent within the Orinoco River basin and a region of hilly to mountainous topography in the northern and eastern part of its extent within the basin. Rivers in the Llanos can be differentiated into those that have their headwaters in the mountain belts and their foothills, and those that drain only the Llanos.

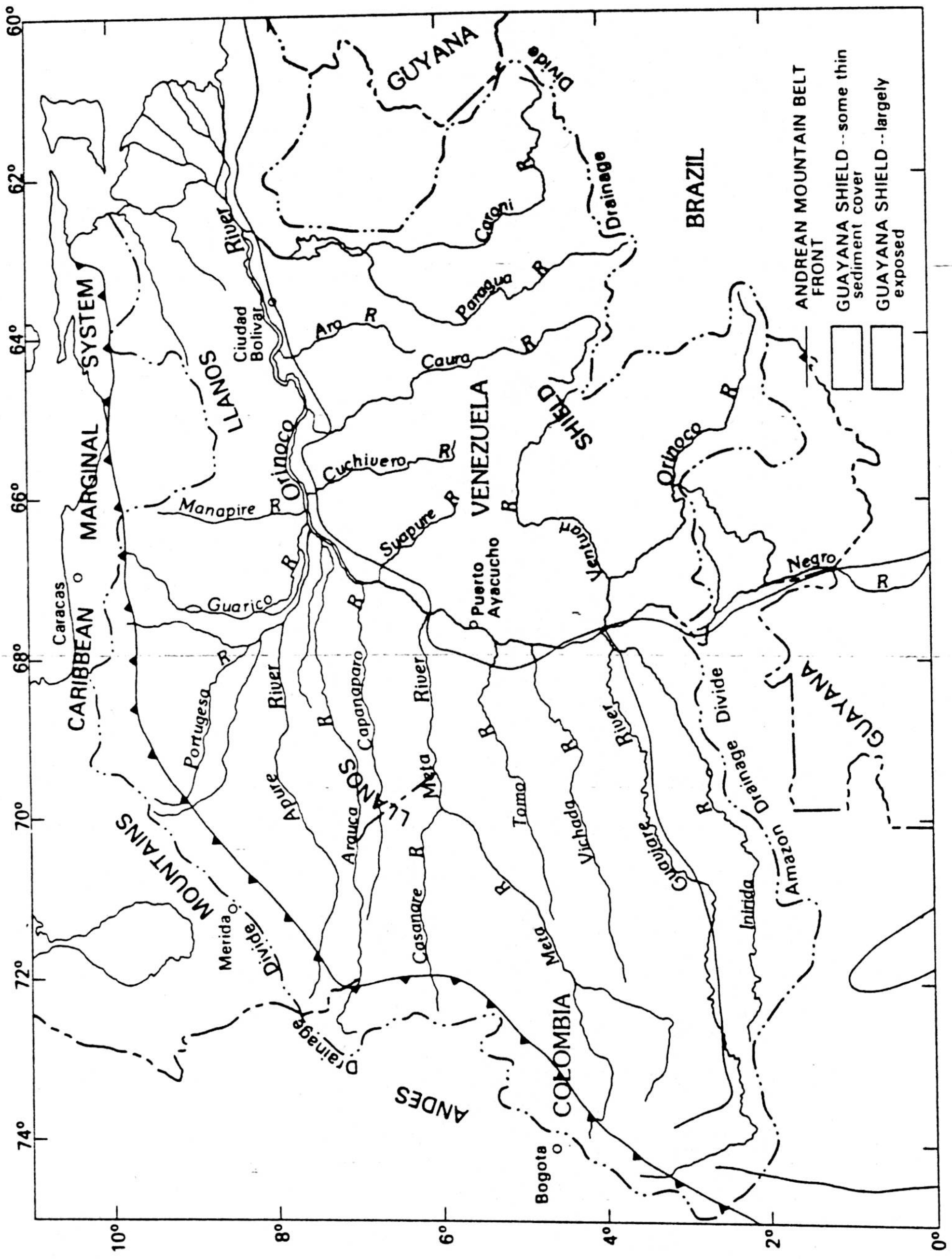

Fig. A.1.—Tectonic and drainage features of the Orinoco River basin.

The Samples

Samples of river-bed sand have been collected from throughout the Orinoco River basin. Three major approaches used to study these samples are: (1) systematic description of fluvial sand throughout the Orinoco River basin; (2) characterization of chemical processes that affect sand composition by studying the formation of quartz arenites (Johnsson *et al.*, 1988); and (3) utilization of mixing models to calculate the relative contributions of sand from different parts of the Orinoco River basin to the mainstem bedload. Laboratory work involves petrographic and major/minor element analyses of the sand and of particle coatings. The modal compositions of more than 200 samples of bed material collected from the mainstem and from tributaries from throughout the basin were determined by point counting.

Samples of suspended sediment and overbank muds, collected from throughout the Orinoco River basin, are separated into size-fraction classes that are analyzed chemically and mineralogically. Techniques for rapidly size-fractionating large quantities of fine material were developed by using a slightly modified version of a tangential-flow filtration system to concentrate suspensions of material coarser than a molecular weight of 100,000 daltons (virtually all geologic materials) (Koehnken Hernández and Stallard, 1988). The procedure is used in the field and in the laboratory, is rapid, and is almost 100 % efficient. Six size fractions of silt and clay (<0.2 μm, 0.2 to 0.63 μm, 0.63 to 2.0 μm, 2.0 to 6.3 μm, 6.3 to 20.0 μm, and 20 to 63 μm) are being analyzed for major, minor, and trace elements, and for mineral composition. Bulk < 63 μm overbank samples from throughout the Orinoco River basin have been chemically analyzed. Suspended-solid, overbank-mud, and bed-material samples were collected from the Apure River system, and four size fractions (<0.2 μm, 0.2 to 0.6 μm, 0.6 to 2.0 μm, < 63 μm) have been chemically analyzed for major crustal elements and for mineral composition. Water samples that correspond to most of the sediment samples have been collected throughout much of the basin; these samples have been analyzed for major dissolved components. In this paper, we include water-composition data from the Amazon River basin (Stallard and Edmond, 1983) to extend coverage into important geologic environments that were not adequately sampled in the Orinoco River system.

TECTONISM AND EROSION IN THE HUMID TROPICS

For a given climate, the distribution of landforms relates closely to tectonic setting and bedrock lithology. The geologic configuration of the Orinoco River basin provides the opportunity to compare river-load composition, erosional processes, and landforms between the two important continental terrains: areas with extremely active tectonic processes—the fold and thrust terrains, and areas with little tectonic activity—the cratons. Tectonic processes are typically fast at

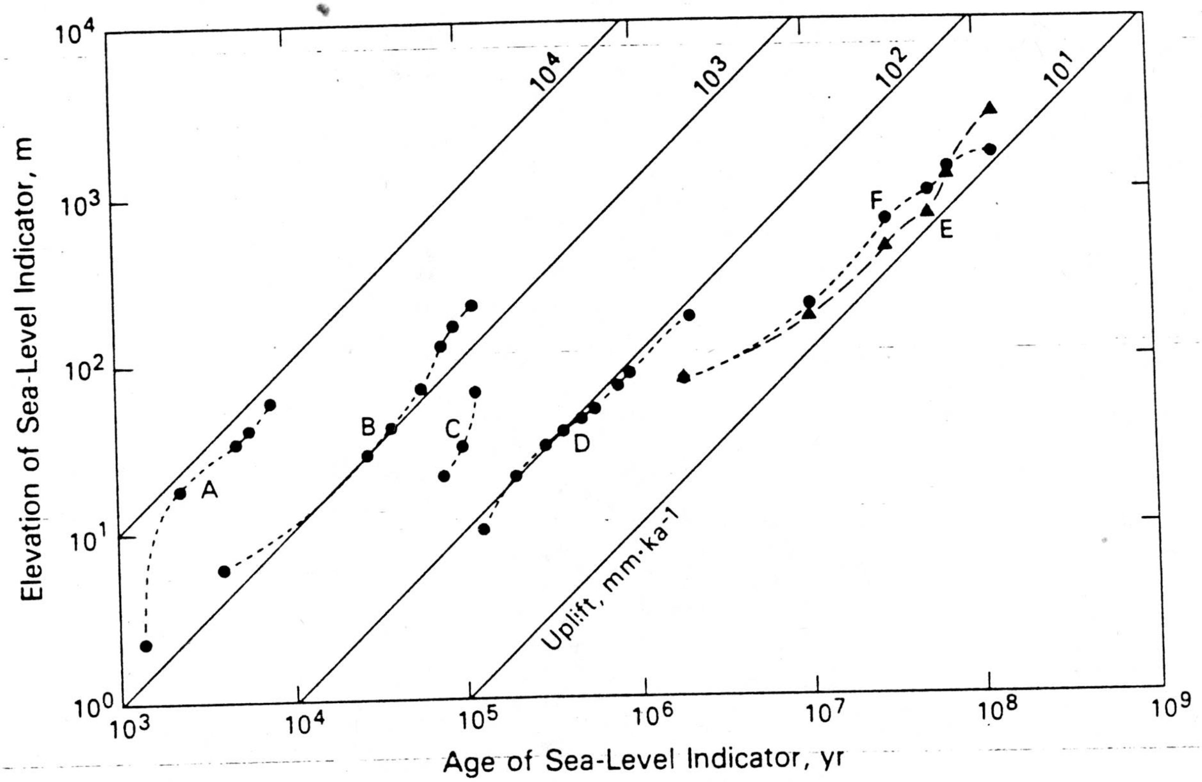

Fig. A.2.—The elevation of terraces and other sea-level indicators compared to their age for several locations (Stallard, 1988). To derive actual uplift rates, one needs to know the age of the terrace and the eustatic sea level at that time. A: Elevation data from the Hengchun Peninsula, Tainan, and Eastern Coast Range of Taiwan, corrected for glacial-eustatic effects and grouped by intervals of about 1,500 years. Uplift seems to have been discontinuous, but has averaged about 5,000 m/Ma (Pęng *et al.*, 1977). B: Calculated composite terrace elevations for the Huon Peninsula, New Guinea, using data from Bloom *et al.* (1974). Uplift has been continuous and has ranged from 940 to 2,560 m/Ma-; the calculation used 1,620 m/Ma. C: Terrace elevations for the Island of Barbados (Clermont traverse) from Matthews (1973); uplift rate has been about 400 m/Ma. D: Depositional terraces in the Amazon Trough from Klammer (1984). Ages are estimated from those of interglacials on the standard oxygen-isotope curve. Uplift is calculated to have been about 80 m/Ma. Klammer argues that the apparent change in elevation has been caused by drop in sea level since the Pliocene rather than by uplift. E and F: Erosion surfaces from the Guayana and Brazilian Shields, respectively (King, 1957; McConnell, 1968; Aleva, 1984).

plate boundaries and slow in plate interiors. Collisional plate boundaries are of greatest interest for they are the sites the intense folding, thrust faulting, and volcanism associated with the development of the great mountain belts of the world.

The term "craton" generally is used to refer to tectonically quiet or stable continental areas. Major subdivisions include "shields" where long-term erosion has exposed extensive areas of the crystalline basement; "platforms" where a flat-lying sedimentary veneer overlies the basement; "intracratonic basins" where slow, long-term subsidence has resulted in the deposition of thick, sedimentary deposits on the craton; and "passive continental margins" where the continental crust has rifted, separated, cooled, and subsided. Between cratons and mountain belts there is commonly a "foreland basin" where the basement has slowly subsided because of loading by sediments derived from the mountain belts and tectonic downwarping.

Uplift curves that represent the elevation of various sea level indicators compared to time for tectonically active (a–c) and quiet (d–f) regions are shown in Figure A.2 (Stallard, 1988). If the hypsographic curve for a region is assumed to have remained fixed through time (geomorphic steady-state), then uplift rate equates with denudation rate. Because many of the climatic and the tectonic processes that affect landform development do not operate constantly, current denudation rates may differ substantially from these values.

Dissolved-solids (dissolved phases derived from the weathering of bedrock) concentrations can be used to estimate ranges of denudation rates for the main types of terrain within the Orinoco River and Amazon River basins (Fig. A.3). The approximate denudation scale is calculated as the product of dissolved-solids concentrations, mean annual runoff (1 m/yr), and a correction factor to account for large ratios of suspended load to dissolved load in rivers that drain mountain belts and for the greater than average annual precipitation in the lowlands close to the equator. The correction factor was treated as a linear function of dissolved solids and ranged from 2 for the most dilute rivers (dissolved solids less than 10 mg/L) to 4 for rivers most concentrated rivers (dissolved solids more than 1000 mg/L). Bedrock density is assumed to be 2.65 g/cm^3. These denudation rates are in general agreement with more rigorous estimates (Gibbs, 1967; Stallard, 1980; Paolini, 1986; Lewis *et al.*, 1987). Comparison with Figure A.2 shows a reasonable match between denudation rates and uplift rates for a particular type of terrain. The most concentrated water samples and most rapid denudation rates are for river basins draining tectonically active areas.

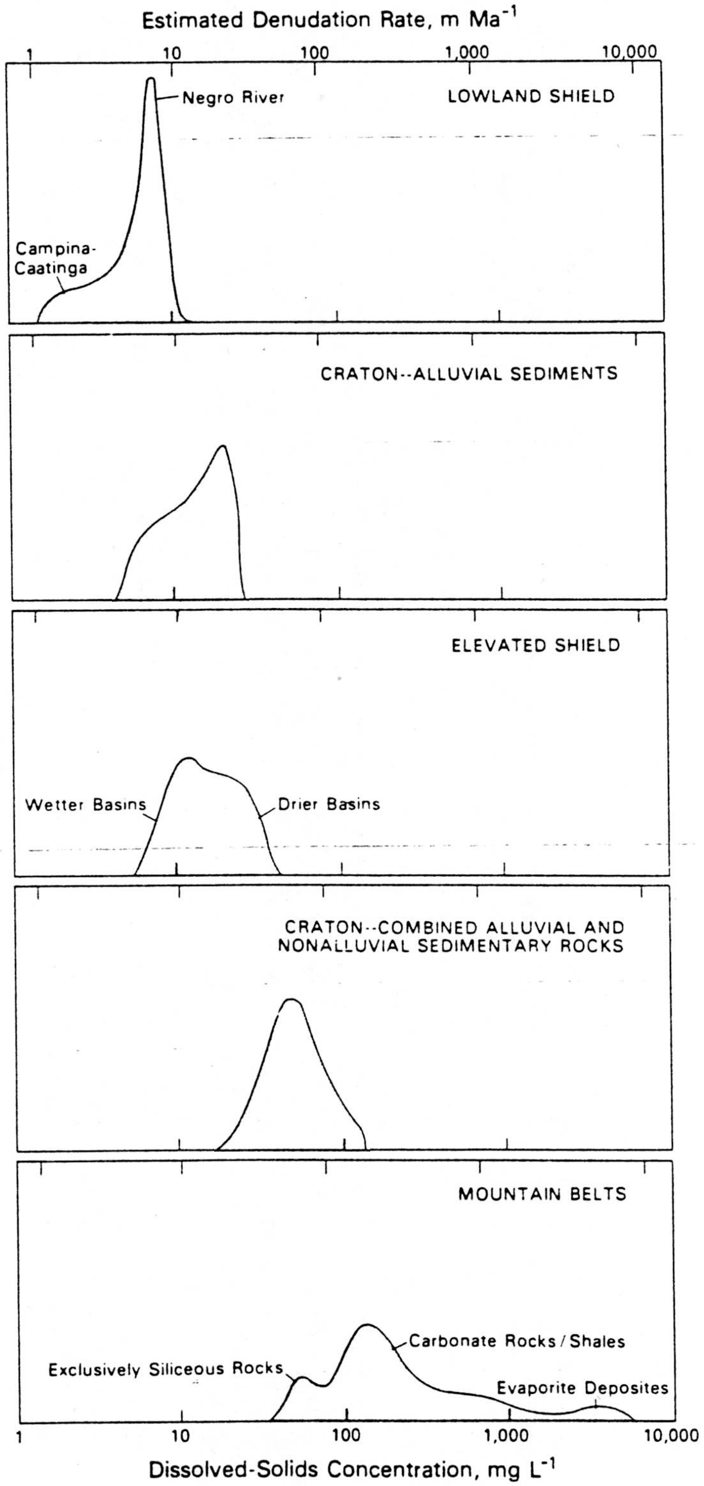

Fig. A.3.—Histogram of dissolved solids concentrations of samples from the Orinoco and Amazon River basins and corresponding denudation rates for morpho-tectonic regions in the humid tropics of South America (Stallard, 1985).

CHEMICAL PARTITIONING AND THE EROSION PROCESS

The most important sources of river-borne materials are weathering, atmospheric deposition, and fixation of elements from atmospheric gases. Of the elements studied, the main source of Al, Ca, Cl, Fe, K, Mg, Na, P, S, Si, Sr, Ti, and Zr is usually bedrock weathering. Sea salt blown inland (cyclic salts) sometimes makes substantial contributions of Cl, Mg, Na, and S. Weathering, biological, and atmospheric chemical processes cause substantial exchange of C, N, and S with the atmosphere usually resulting in a net transfer from the atmosphere to river catchments. The following elements—Al, Fe, Si, Ti, and Zr—are transported mostly in the solid load either as unweathered primary (bedrock) minerals or as secondary (weathering-produced) minerals. Si, as $Si(OH)_4$, is the most soluble of these elements; Al and Fe are slightly soluble under acidic conditions and in the presence of organic chelators; and Ti and Zr are the least soluble. Several major and minor dissolved species are important to the transport of some of the elements. These species include the "soluble cations" (K^+, Na^+, Mg^{2+}, Ca^{2+}, Sr^{2+}), the "soluble anions" (HCO^{3-}, CO_3^{2-}, Cl^-, NO_3^-, SO_4^{2-}), and important neutral species (H_2CO_3, $Si(OH)_4$). Elements such as C, N, P, S, K, Mg, and Ca, are important nutrient elements that are stored by plants, and large proportions of river-borne C, N, and P may be incorporated into dissolved and solid organic phases, including living organisms. Dissolved organic materials include ionized and neutral components. Organic anions contribute substantially to the acidity of some dilute waters and to the solubilization of metals as complexes. Silica is important to diatoms, and when these are especially active, much of the $Si(OH)_4$ can be converted into opal.

Weathering typically is the dominant source of river-borne materials, so to a first approximation, the composition of rivers is controlled by the selective partitioning of elements among dissolved and solid phases during weathering. This partitioning occurs because the proportions of elements in weathering products do not match those in the bedrock. There are two ways for this to happen. One way is by the preferential weathering of certain primary minerals. The other way is by the formation of secondary phases that are enriched or depleted in certain elements relative to bedrock. Aggradation or degradation of the biomass or soil reservoirs may cause what seems to be partitioning between dissolved and solid phases. This apparent partitioning is because the elemental ratios in the biomass or soil reservoirs can be different from those of bedrock. In nonevaporative settings, soil ratios are so similar to those in river-borne sediment that it would be difficult to determine the effects of soil aggradation or degradation, except perhaps under certain circumstances (rapid erosion after deforestation, changes in erosion regime after climate change, or the weathering of alluvial soils). Sufficiently rapid and large changes in the biomass reservoir are sometimes evident in river chemistry (Likens *et al.*, 1977).

Mass-balance models involving the relative concentrations of dissolved $Si(OH)_4$, K^+, Na^+, and Cl^- in stream waters can be used to study the weathering of silicate rocks (Stallard, 1985, 1988; Stallard and Edmond, 1987). Silicon is derived exclusively from the weathering of silicate rocks. Two important additional sources of Na^+ and K^+ are cyclic salts and the weathering of evaporite minerals (mostly halite); Cl^- is used to correct these two sources. A "*" superscript in the following discussion indicates that concentrations have been corrected for cyclic-salt contributions as described by Stallard and Edmond (1983). Cl^* is then subtracted from Na^* to correct for halite weathering. Because the cyclic contribution of K^+ is so much smaller than that of Na^+, when adequate information about cyclic Cl^- is lacking, the simplest correction is to subtract Cl^- from Na^+. The cations—Mg^{2+} and Ca^{2+}—cannot easily be used in mass-balance studies of silicate weathering, because the weathering of carbonate minerals is commonly such a dominant source of these cations.

Erosion Regime and Landforms

Weathering, atmospheric deposition, and atmospheric–gas exchange are areal sources which affect the entire surface of the river basin. During downslope transport towards a river channel, material derived from these sources commonly interacts with soil and vegetation. Weathered material is stored in soil and colluvium. Because of these interactions and storage, hillslope processes are particularly important in determining the composition of dissolved and solid weathering products delivered to rivers.

It is very difficult to directly characterize the effects of hillslope erosion processes on the composition of erosion products. The time scale of human observation is inadequate to directly determine the rates or net effects of many phenomena. For example, some phenomena often are episodic and infrequent, such as flash floods, landslides, and glaciations. Other phenomena, such as mountain building and soil formation, involve time scales that exceed those of major climatic fluctuations. Human activities such as lumbering and agriculture further complicate the interpretation based on direct observation. The effects of episodic and continuous processes related to tectonism, geology, climate, soils, and vegetation are integrated over considerable periods of time to produce characteristic landforms. Direct observation provides a general description of the processes, whereas geomorphic syntheses describe the integrated effects.

Erosion on slopes can be envisioned as a continuum between being weathering limited and transport limited (Carson and Kirkby, 1972; Stallard, 1980, 1985; Stallard and Edmond, 1983). Erosion is transport limited when the rate of supply of material by weathering exceeds the capacity of transport processes to remove the material; whereas, erosion is weathering limited when the capacity of the transport process exceeds the rate at which material is generated by weathering.

In weathering-limited situations, erosion rate is controlled by the susceptibility of bedrock to weathering, the rate at which chemical and physical weathering can supply loose particulate or dissolved material. Soils are thin, because any loose material moves downslope. Processes that are characteristic of weathering-limited erosion include rock-falls, landslides, or anything that tends to maintain a fresh or slightly weathered rock surface. These processes typically operate optimally where slope angles are steeper than a critical threshold. Consequently, slopes that are undergoing weathering-limited erosion are commonly long and straight.

Under transport-limited conditions, weathering rates ultimately are limited by the formation of soils that are sufficiently thick or so impermeable that free access by water to unweathered material is restricted. Erosion is slow, and soils and solid weathering products are cation deficient. Thick soils and slight convexo-concave slopes are typical of a region dominated by transport-limited erosion. With time, slopes become flatter. Soil creep is a process typical of such settings. Most soil mass movement and wash processes vary between being weathering limited and transport limited in character.

Erosion Regime and Elemental Partitioning

Different styles of erosion are associated with different degrees of partitioning of elements between dissolved and solid phases. As rocks weather chemically, they lose their structural integrity, often before primary minerals are completely decomposed chemically. Consequently, during weathering-limited erosion, much of the loose material that is transported downslope is only partially weathered. For example, in moist vegetated areas on crystalline rocks or indurated sediments, solifluction, soil avalanching, and sheet runoff remove weakly cohesive material (solum and soft saprolite); a cohesive hard saprolite is left behind (Stallard, 1980, 1985; Stallard and Edmond, 1983).

When primarily kaolinite or gibbsite or other cation-deficient phases are forming, which often occurs during transport-limited erosion, the ratios of dissolved soluble cations should match those of the bedrock. The samples indicated by open symbols in Figure A.4 are from rivers that drain flat and elevated shield terrains and flat sedimentary terrains. These samples plot within the bedrock compositional fields indicating that major soluble cations in these rivers are in bedrock proportions.

In rivers that drain regions where erosion is weathering limited, several important minerals that commonly occur in the solid load, including potassium feldspars, micas, and 2:1 clays, contain tightly bound K and Mg. Presumably, these minerals are derived from the physical erosion of par-

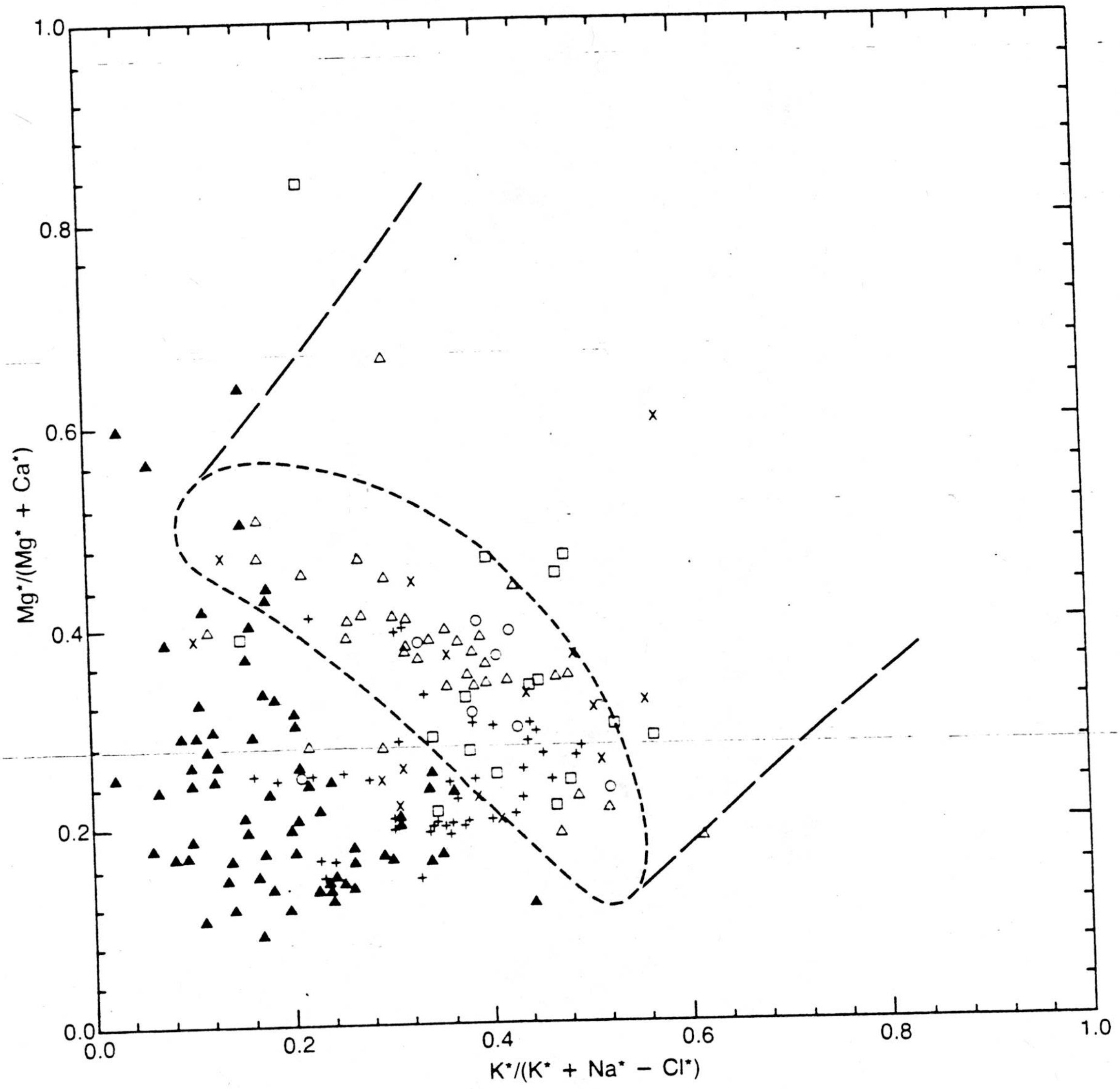

Fig. A.4.—Relation of Mg*/(Mg*+Ca*) to K*/(K*+Na*-Cl*) for dissolved material in surface waters of the Orinoco River and Amazon River basins and for rock types representative of bedrock in these basins. Symbols: ▲—samples from rivers that drain mostly mountain belts; **+**—samples from rivers that originate in mountain belts, but that drain large areas of craton; **x**—rivers that drain alluvial and nonalluvial sedimentary rocks in foreland and intracratonic basins; ☐—rivers that drain only alluvial sediments in foreland and intracratonic basins; △—rivers that drain hilly to mountainous shield; ○—rivers that drain peneplaned shield. The dashed oval represents the range of analyses for common igneous rocks; the dashed lines that extend away from the igneous-rock field represent the composition field for common sedimentary rocks.

tially weathered bedrock. A similar abundance of Na- and Ca-bearing minerals is lacking; thus, when compared to bedrock proportions, K is enriched relative to Na and Mg relative to Ca in solid erosion products. Likewise, Na^+ and Ca2$^+$ are enriched in solution relative to K^+ and Mg^{2+}. Water samples plotted as solid triangles in Figure A.4 are from rivers that drain mountain belts. These samples plot below (Ca^{2+} enriched) and to the left (Na^+ enriched) of compositional fields that correspond to common igneous and sedimentary rocks.

Weathering products and soil solutions evolve as they flow downslope. Contact with bedrock and soil is prolonged, and with increasing reaction time, the concentrations of soluble weathering products increase. Evapotranspiration can further concentrate soil solutions. As these solutions become more concentrated, the suite of secondary minerals thermodynamically favored by weathering reactions can vary. This variation can cause the compositional changes of soil mineral suites along hillslopes with the formation of more cation-rich 2:1 clays being favored downslope (Tardy *et al.*, 1973). Solids can continue to chemically weather when they accumulate at the base of slopes or during temporary storage in alluvial deposits; the soluble products of such weathering become part of the dissolved load.

Elemental Partitioning and 2:1 Clay Formation

The 2:1 clays have an especially important effect on in the budgets of soluble cations and Si. This group of clays has high Si:Al ratios in lattice sites when compared to secondary Al-bearing minerals characteristic of intensely leached soils, such as kaolinite (a 1:1 clay) and gibbsite. The substitution of Mg and Fe for Al, which is what normally occurs, is an important factor in this enrichment (see analyses given by Tardy and Fritz, 1981; Garrels, 1984; May *et al.*, 1986). The 2:1 clays also have substantial interlayer ion-exchange capacities. In the smectites (beidellite and montmorillonite are the most aluminous common varieties) and vermiculites, the interlayer cations are in a hydrated form and are readily exchanged (MacEwan and Wilson, 1980). In the illites, the interlayer ions are retained in a nonhydrated form and K^+ is strongly preferred to other cations (Eberl, 1980).

In most soils, Al is insoluble and tends to remain in the soil. Consequently, the retention of Si, K, and Mg in soils is enhanced when either 2:1 clays are forming or are failing to weather completely. A possible exception to this generality occurs during rapid weathering in moist acid environments, when especially aluminous 2:1 clays form because of the retention of Al^{3+} or $Al(OH)_3$ in the interlayer. These phases are not well-characterized and have been given many names including dioctahedral vermiculite and Al-chlorite. These phases seem to form at the exclusion of gibbsite in a phenomenon that Jackson (1963) has named the "antigibbsite effect."

Because of the retention of Si and Mg in the lattice, reactions tending to form or preserve 2:1 clays would be favored in weathering environments where high concentrations of $Si(OH)_4$ and Mg^{2+} are present. High concentrations of $Si(OH)_4$ and Mg^{2+} can result from the weathering of volcanic glass or mafic rocks (see analyses published by Hay and Jones, 1972; Meybeck, 1987). In most crystalline rocks, much of the $Si(OH)_4$ is bound up in quartz, which weathers very slowly. Quartz is, at best, a minor phase in volcanic glass and mafic rocks; consequently, greater concentrations of $Si(OH)_4$ build up in solutions within soils developed on these rock types. The weathering of carbonate rocks contributes to high concentrations of Mg^{2+} in soil solutions, and smectites are important minerals in soils developed on limestones in the tropics (see analyses published by Isphording, 1979; Irion and Petr, 1983). Cyclic wetting and drying also causes high solution concentrations in soils (Drever and Smith, 1978), as does the flow of soil waters down long slopes, described above. Such high concentrations may cause the formation of smectites (Drever and Smith, 1978) or illites (Eberl *et al.*, 1986).

Mass-balance models that use the relative concentrations of $Si(OH)_4$, K^+, Na^+, and Cl^- in stream water can be used to ascertain whether 2:1 clays might be forming in soils within their catchments. Suites of primary minerals decompose during weathering to form suites of secondary minerals. Normally, one does not know the exact composition of either suite of minerals. Consequently, to study silicate weathering by using mass balances, it is necessary to examine the extreme situation that involves those reactions that release the smallest quantity of $Si(OH)_4$ for the quantity of K^+ or Na^+ released.

Consider the set of all possible silicate weathering reactions that produce a given secondary mineral from common primary minerals. Assume that Al is immobile. There exists some combination of common primary minerals that, during weathering, produces the smallest possible ratio of dissolved $Si(OH)_4:(K^*+Na^*)$. This reaction is the "reference reaction." The weathering of any other combination of common primary silicate minerals to the given secondary mineral produces a larger $Si(OH)_4:(K^*+Na^*)$ ratio. Thus, if the $Si(OH)_4:(K^*+Na^*)$ ratio of a water sample has a ratio that is less than the theoretical minimum ratio, then a different secondary mineral must be forming. This other secondary mineral must retain more Si relative to Al than the secondary mineral produced in the reference reaction. The common primary minerals that yield the smallest $Si(OH)_4:(K^*+Na^*)$ ratios during weathering are sodium-feldspar and muscovite.

The relative concentrations of $Si(OH)_4$, K^*, and (Na^*-Cl^*) in river samples from the Orinoco River and Amazon River basins indicate that weathering produces abundant 2:1 clays within the mountain belts and adjacent foothills (solid triangles in figures) but not in shield or flat sedimentary terrains (open symbols in figures). Relative proportions of $Si(OH)_4:K^*:(Na^*-Cl^*)$ are compared in Figure A.5 along with trend lines corresponding to various reference weathering reactions. Of these reactions, the weathering of an arbitrary mixture of sodium-feldspar and muscovite to kaol-

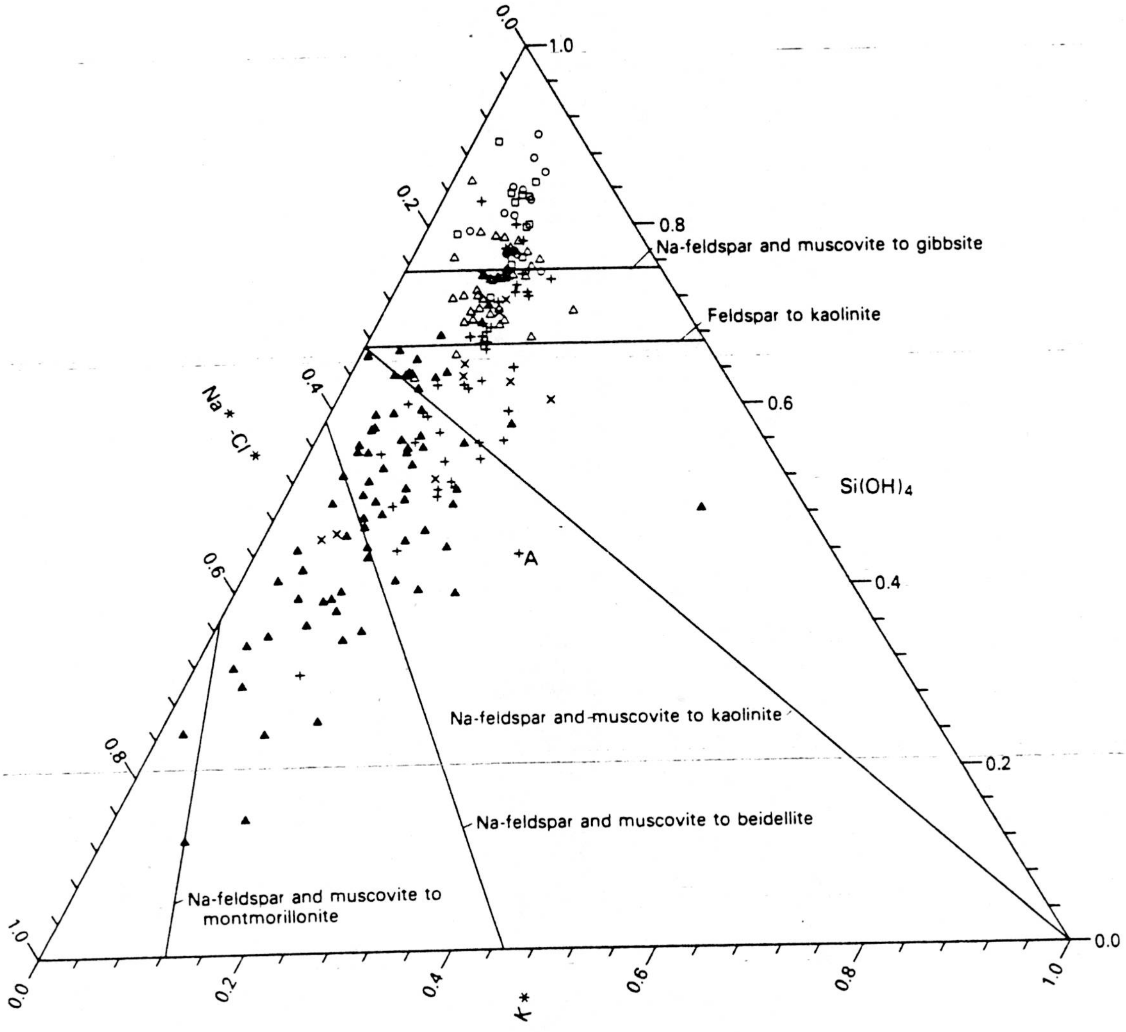

Fig. A.5.—Ternary diagram showing proportions of dissolved $Si(OH)_4$, K*, and (Na*-Cl*) in the Orinoco River and Amazon River basins. $Si(OH)_4$, K*, and (Na*-Cl*) presumably are derived from silicate-mineral weathering. The lines correspond to various reference weathering reactions, chosen to have the smallest $Si(OH)_4$:(K*+Na*-Cl*) ratio for reactions that start with common minerals and produce a particular secondary mineral. The weathering of bedrock to produce the secondary mineral associated with a particular trend line is sufficient to explain the $Si(OH)_4$, Na*-Cl*, and K* concentrations of all samples that plot on the high-$Si(OH)_4$:(K*+Na*-Cl*) side (above) of that trend line. The point labeled "A", for example, is consistent with the formation of beidellite or montmorillonite, perhaps in combination with kaolinite; it is not consistent with the formation of kaolinite or gibbsite without the simultaneous formation of 2:1 clays. Symbols are defined in Figure A.4.

inite is particularly important. Assuming that only common bedrock and soil minerals are involved, the formation of 2:1 clays is required to explain the composition of any sample plotting on the low $Si(OH)_4$:(K*+Na*-Cl*) side of the line corresponding to this reaction. This is the situation for most samples from rivers that drain mountain belts and their foot hills (solid symbols in Figure A.5). Kaolinite or gibbsite or both also could be forming at the same time.

The formation of 2:1 clays seems to limit the release of $Si(OH)_4$ during weathering. The weathering of an arbitrary mixture of sodium-feldspar and muscovite to kaolinite, just mentioned, corresponds to the trend line $Si(OH)_4$=2x(Na*-Cl*) in Figure A.6, a graph of $Si(OH)_4$ concentration compared to that of (Na*-Cl*). A zone is indicated in Figure A.6 for the complete loss of Si and Na from common igneous rocks during weathering. The concentrations of $Si(OH)_4$ that correspond to the dissolution of quartz and to kaolinite/gibbsite equilibrium are plotted as horizontal dashed lines. Sample $Si(OH)_4$ concentrations tend to increase with increasing Na*-Cl* until the trend line is crossed, beyond which there is little correlation between the two constituents. This indicates that the formation of 2:1 clays may enhance the retention of Si in bulk soil, and thereby, limit the release of $Si(OH)_4$ into rivers. Quartz instability is indicated by the many samples with a $Si(OH)_4$ concentration less than 100 µmol/L, and kaolinite instability is indicated in only a few samples with a $Si(OH)_4$ concentration less than 35 µmol/L. In the samples with the least Na*-Cl*, $Si(OH)_4$, and Na^+ are being mobilized in bedrock proportions even though kaolinite is thermodynamically stable in most samples.

EROSION AND THE COMPOSITION OF RIVER-BORNE MATERIALS IN MOUNTAIN BELTS

The fold and thrust terrains consist of the Caribbean Marginal Mountains in the north, and the Andes (Mérida Andes of Venezuela and Cordillera Oriental of Colombia) to the west. These terrains are dominated by youthful mountains with steep slopes and sharp summits; maximum relief is nearly 5,000 m. Current uplift rates probably exceed 800 m/Ma and may be as much as 5,000 m/Ma (Giegengack, 1984; Kohn *et al.,* 1984). Although mountains are sculpted by erosion, first-order topography is under tectonic control. The two mountain systems differ in tectonic history and in the dominant rock types exposed at the land surface. Interpretation of the tectonic history of the Caribbean Marginal Mountains is controversial (see articles in the volume edited by Bonini *et al.*, 1984). Pelitic schists and phyllites of greenschist facies, metavolcanic rocks, mafic to granitic plutons, and minor carbonates seem to have been transported southward on large-scale thrust faults. There is little evidence of extensive thrust faulting in the Mérida Andes. Uplift has exposed abundant granitic plutons, gneissic basement, unmetamorphosed to slightly metamorphosed shallow-marine shales, sandstones, and conglomerates (Shagam, 1972; Bellizzia G. *et*

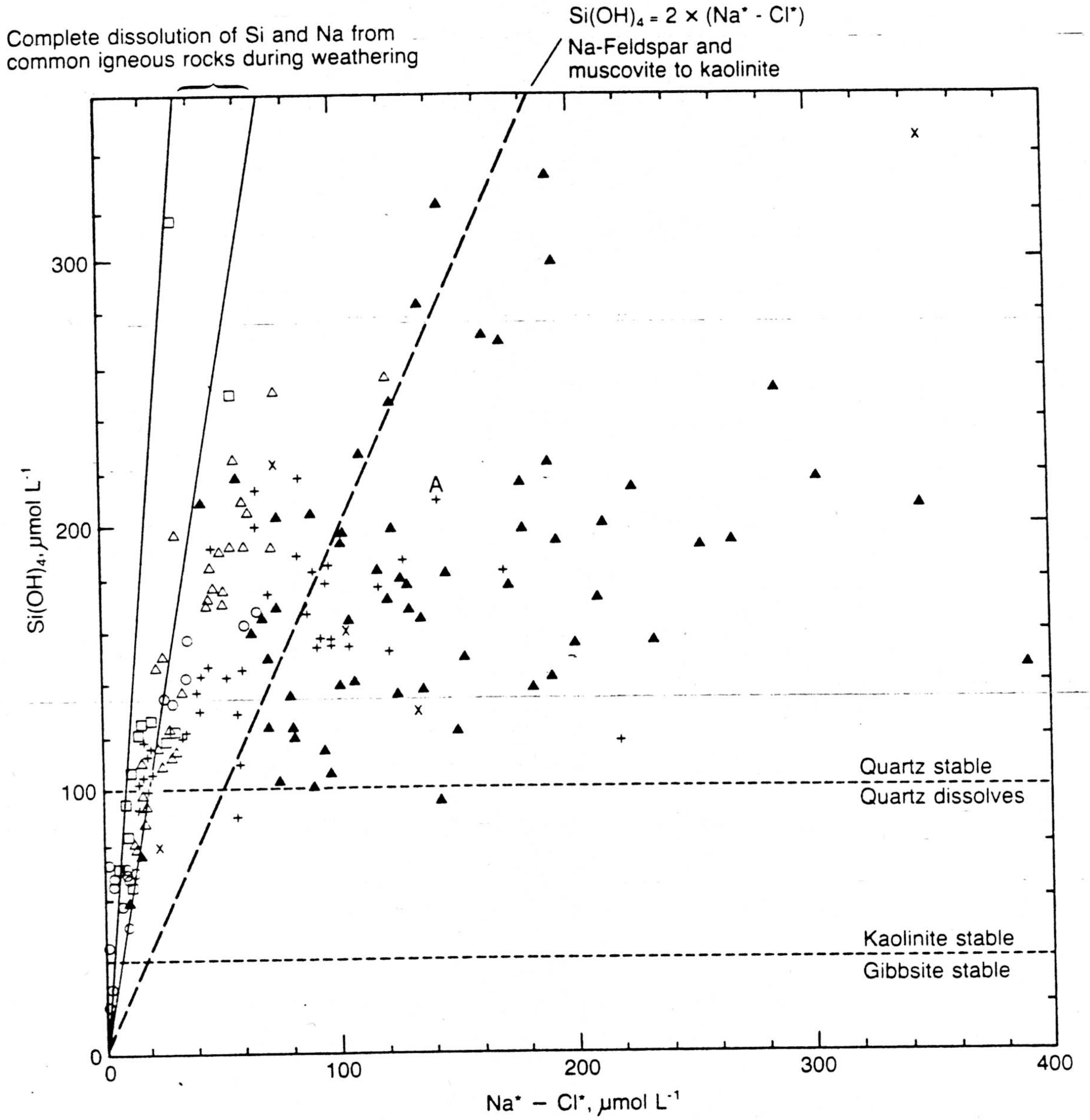

Fig. A.6.—Concentration of $Si(OH)_4$ compared to that of (Na*-Cl*) for surface waters of Orinoco River and Amazon River basins. The horizontal dashed lines correspond to thermodynamic equilibria: quartz stable/quartz dissolves (thermodynamic data from Brantley *et al.*, 1986) and kaolinite stable/gibbsite stable. Estimates for the $Si(OH)_4$ concentration for the gibbsite/kaolinite equilibrium vary considerably, from 7 to 70 μmol/L $Si(OH)_4$, and an intermediate value of 35 μmol/L was chosen. Symbols are defined in Figure A.4.

al., 1976). The Cordillera Oriental consists of Precambrian and Paleozoic metamorphic rocks overlain by marine clastic strata similar to those of the Mérida Andes. In addition, there are Paleozoic sedimentary rocks, Mesozoic red beds, volcanic rocks, and evaporite deposits. The range has undergone extensive thrust faulting (Case *et al.,* 1984). Minor volcanism occurred throughout the Cenozoic in all the mountain belts, but active Quaternary volcanism is restricted to regions west of the Orinoco River basin in Colombia. Vegetation is markedly zoned by elevation (MARNR, 1983). Rain forests (now extensively removed) and savannas in the foothills grade into temperate and cloud forests at higher elevations, then into páramo grasslands, and finally into tundra. There are small glaciers on some of the highest peaks.

A variety of factors related to tectonism contribute to rapid denudation in mountain belts. Both rapid uplift and volcanism maintain a supply of fresh bedrock despite intense erosion. Some freshly exposed rocks, such as carbonate rocks, evaporite deposits, and glassy lavas, are especially vulnerable to chemical weathering. Faulting and folding involve brittle deformation in which basement rock often becomes extensively fractured (Davis *et al.,* 1983). Volcanic rocks are commonly fragmented, because lavas cool rapidly and are often gaseous and released explosively. Fractured and fragmented bedrock is easily penetrated by meteoric waters, a process that enhances chemical weathering. The most fragmented bedrock does not seem to form long, oversteepened (near-vertical) slopes that are stable for long periods.

The composition of river-borne material correlates with basement lithology and its susceptibility to erosion, and is accordingly consistent with weathering-limited erosion. Rivers that drain evaporite deposits (rarer in the Orinoco River basin than the Amazon River basin) have the greatest total cation concentration, followed by those draining carbonate rocks, and finally by those that drain only siliceous rocks. This trend is illustrated by the trimodal nature of the histogram (Fig. A.2) of dissolved solids in rivers that drain mountain belts, and by the ternary diagram (Fig. A.7). In Figure A.7, ($Cl^*+SO_4^*$), alkalinity, and $Si(OH)_4$ are used as source indicators for the respective lithologies, bearing in mind that alkalinity also is produced by silicate weathering and sulfate by pyrite weathering. Total cations increase systematically from $Si(OH)_4$ to alkalinity, then to ($Cl^*+SO_4^*$). Many rivers within the mountain belts are slightly supersaturated with respect to calcite, an indication that calcite saturation ultimately limits the supply of alkalinity to rivers (Fig. A.8). Dissolved $Si(OH)_4$ concentrations may be limited by the formation of 2:1 clays (Fig. A.6). Similar limits do not apply to K^+, Na^+, Ca^{2+}, and Mg^{2+} because of additional inputs from the weathering of silicate and evaporite minerals. As in the Amazon River basin, within the Meta River subbasin of the Orinoco River basin, considerable evaporite dissolution is sustained by actively extruding salt diapirs (Benavides, 1968; Stallard, 1980). Erosional contributions by carbonate rocks and especially by evaporite deposits greatly exceed those expected if inputs are assumed to be proportional to the fraction of the catchment area that is encompassed by these lithologies.

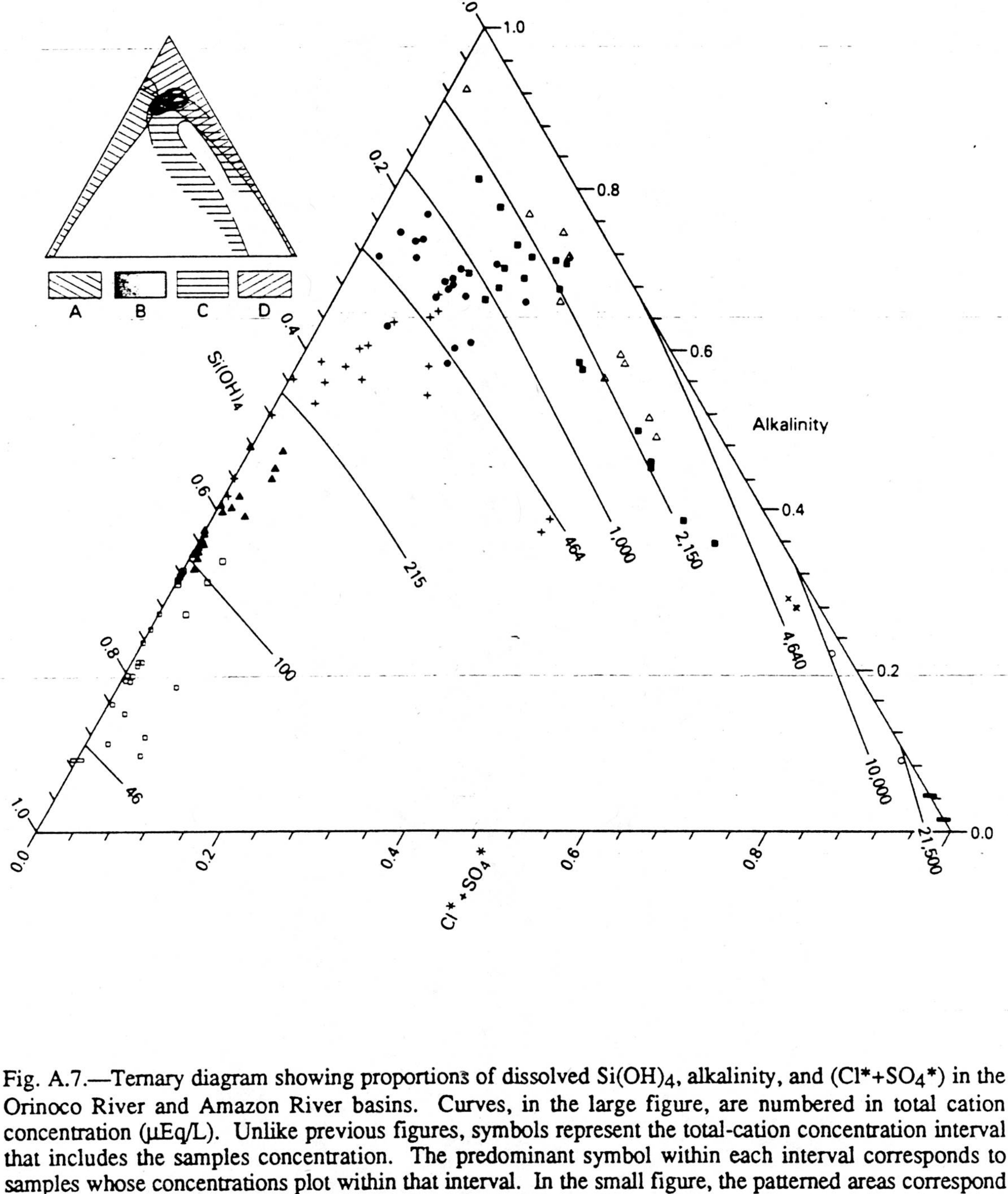

Fig. A.7.—Ternary diagram showing proportions of dissolved $Si(OH)_4$, alkalinity, and ($Cl^* + SO_4^*$) in the Orinoco River and Amazon River basins. Curves, in the large figure, are numbered in total cation concentration (µEq/L). Unlike previous figures, symbols represent the total-cation concentration interval that includes the samples concentration. The predominant symbol within each interval corresponds to samples whose concentrations plot within that interval. In the small figure, the patterned areas correspond to the predominant source of samples whose concentrations plot within the areas: A, streams that drain cratonic areas; B, streams that originate in mountain belts, but that drain large areas craton; C, streams that drain mountain belts with extensive black shales; D, streams that drain mountain belts with extensive carbonate rocks and evaporite deposits.

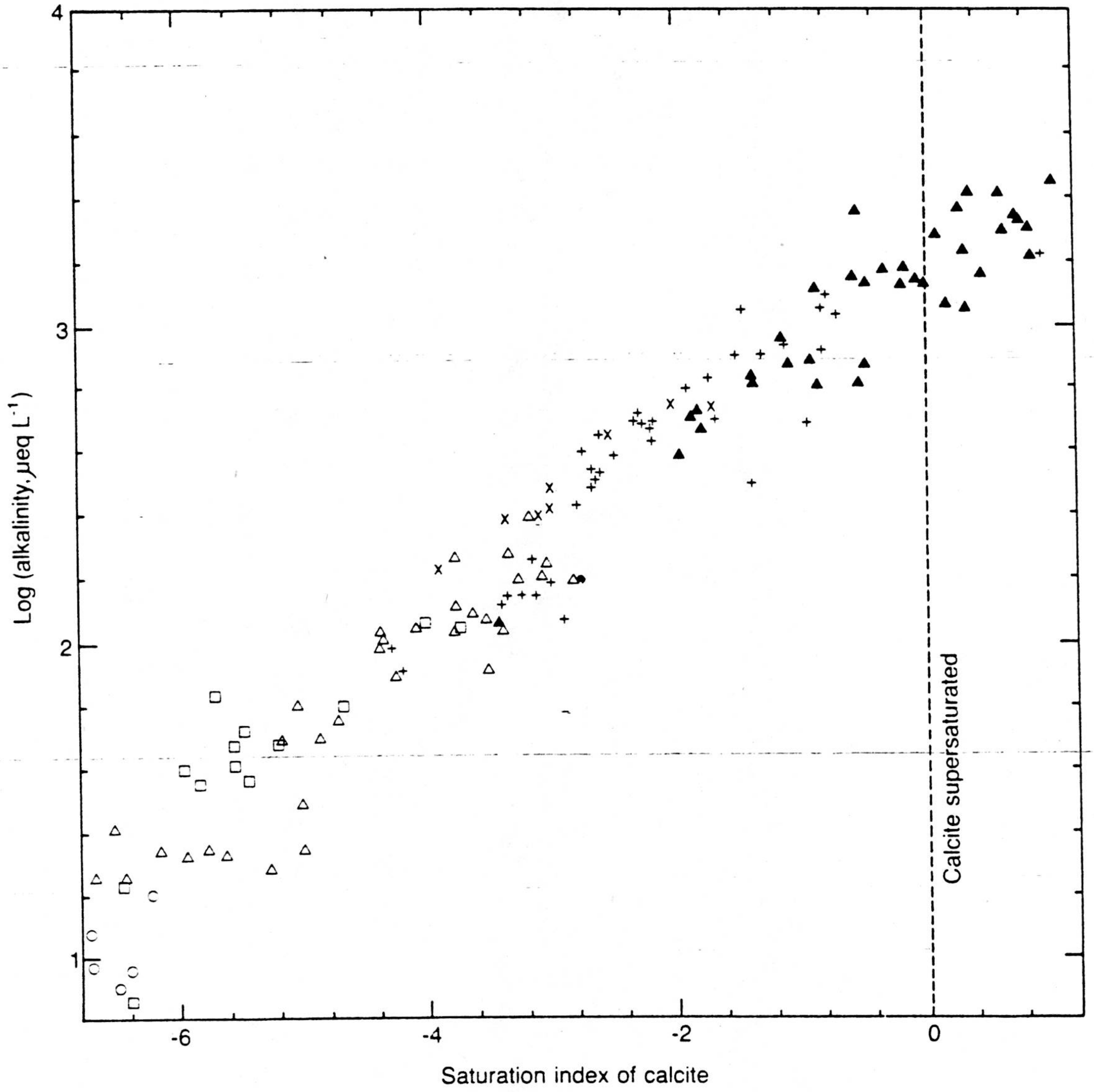

Fig. A.8.—Relation between alkalinity and the saturation index for calcite. A saturation index greater than zero indicates supersaturation. Symbols are defined in Figure A.4.

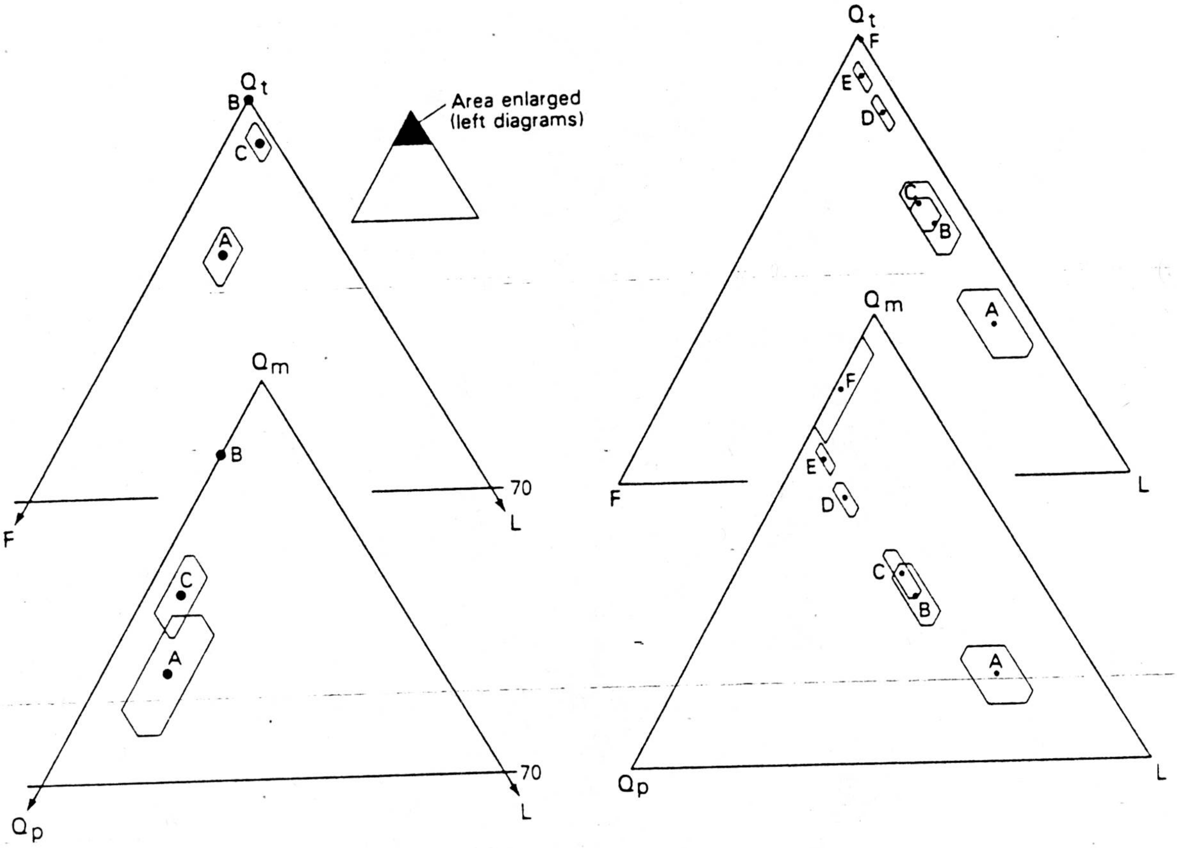

Fig. A.9.—Composition diagrams for total quartz (Q_t), feldspar (F), and lithic fragments (L)—top—and of monocrystalline quartz (Q_m), polycrystalline quartz (Q_p), and lithic fragments (L)—bottom—for samples from the Guayana Shield (left) and the Apure River basin (right). Note that for the shield (left), only the upper part (> 70 %) of each diagram is plotted. For the shield, suite means are plotted for samples collected from: A, parts of the elevated shield not having abundant platform cover; B, from the lowland shield; and C, from parts of the elevated shield with abundant platform cover (Proterozoic metaquartzites). The regions enclosed by error polygons correspond to two standard errors of the mean (~ 95% confidence interval). Error polygons around B are smaller than the size of the symbol. For the Apure River basin (right), suite means are plotted for samples collected from: A, the fold and thrust terrains; B, along the Andean front; C, within 100 km of the Andean front; D, 100 to 200 km from the Andean front; and E, 200 to 300 km from the Andean front. Samples from rivers that have catchments entirely within parts of the Llanos well away from mountain belts are plotted in F. Q-F-L diagrams are discussed by Dickinson (1985).

The great abundance of unstable and cation-rich minerals in suspended-sediment and bed-material samples of rivers that drain the mountain belts is consistent with extraordinarily rapid erosion. Tributaries that have their headwaters in the mountain belts transport litharenites (Fig. A.9). Especially unstable minerals such as calcite, amphiboles, and pyroxenes are present in samples from some of these rivers. The fine-grained fraction is rich in micas and 2:1 clays, including illites, vermiculites, and smectites. Chlorites (2:1:1 clays) are also common. Pyrophyllite is present in some rivers, notably the Guaviare River. When compared to average igneous rocks, fine-grained sediments typically are enriched in Al relative to soluble cations (Fig. A.10), in Mg relative to Ca, and in K relative to Na (Fig. A.11).

Vermiculites and chlorites seem to be a complex mixture of 14 Å phases. Two distinct vermiculitic phases have been identified, a 14 Å trioctahedral type that expands to as much as 16.5 Å when glycolated and a 14 Å dioctahedral type that does not expand. Both types collapse to 10 Å when heated to 400 °C. Much of the chlorite appears to be a degraded form, perhaps with a Fe-rich octahedral sheet, that collapses when heated to 550 °C. Either the dioctahedral vermiculite or the degraded chlorite or both may be transitional with a berthierine-like phase (Koehnken and Stallard, 1988).

EROSION AND SEDIMENTATION IN THE LLANOS

The Llanos is a region of alluvial plains within the foreland basin. The region is currently receiving sediments from the actively uplifting mountain belts to the north and west. The western part of the region is actively subsiding and is veneered by Holocene fluvial and lacustrine mud, sand, and gravel derived from the mountains. Much of the tropical savanna covering the region is inundated during the rainy season. The eastern part of region is being slightly uplifted, which exposes similar sediments of Tertiary age (Bellizzia G. *et al.,* 1976). Maximum relief on the Llanos is less than 200 m. Extensive fluvial reworking of alluvium is indicated by complex meander plains and very unstable interconnected channel systems. Eolian activity also is important in the redistribution of sands on the Llanos, particularly in the region between the Apure and Meta Rivers.

Sediment is stored on the alluvial plains of the Llanos for a sufficiently long time that chemical weathering can decompose unstable sedimentary grains. This weathering causes an increase in chemical maturity as the alluvial sediments are reworked. Tributaries that have catchments entirely within the Llanos transport sand of quartz-arenite composition (Fig. A.9). This intensely weathered sand is reincorporated into river bedload during channel migration. The result is a net dilution and replacement of newly eroded sand by older and compositionally more mature sand. This process is indicated in channel-sand composition by a marked decrease in the fraction

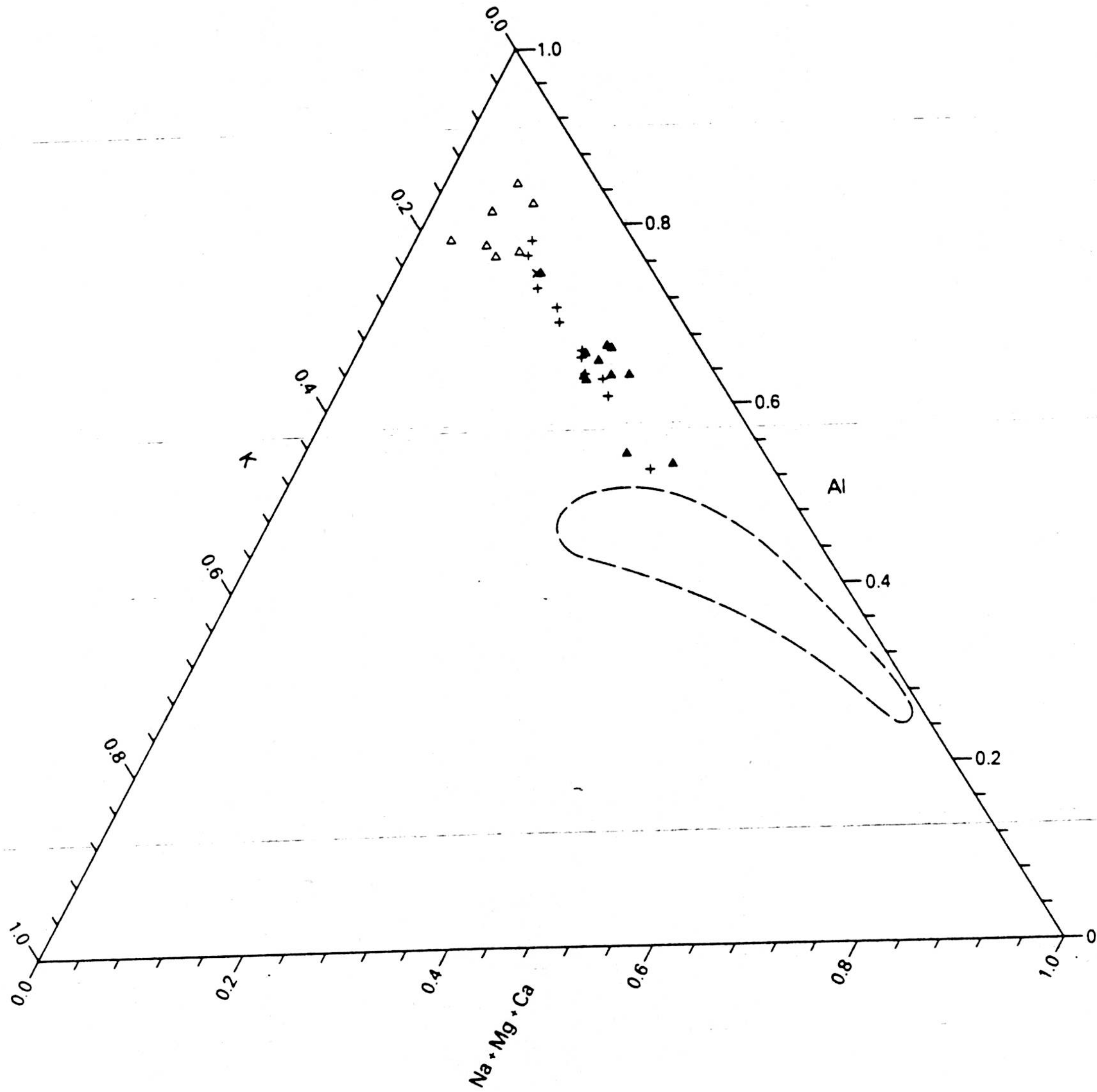

Fig. A.10.—Comparison of the proportions of Al, K, and (Na+Mg+Ca) for the < 63-µm fraction in overbank-material samples collected throughout the Orinoco River basin and for igneous-rock types representative of bedrock in the basin. Al is in moles; soluble cations are in equivalents. Symbols are defined in Figure A.4. The dashed oval represents the range of analyses for common igneous rocks. The distance from the Al vertex is a measure of the proportions of Al to total soluble cations. Note that sediments from rivers that drain the Guayana Shield are particularly K rich.

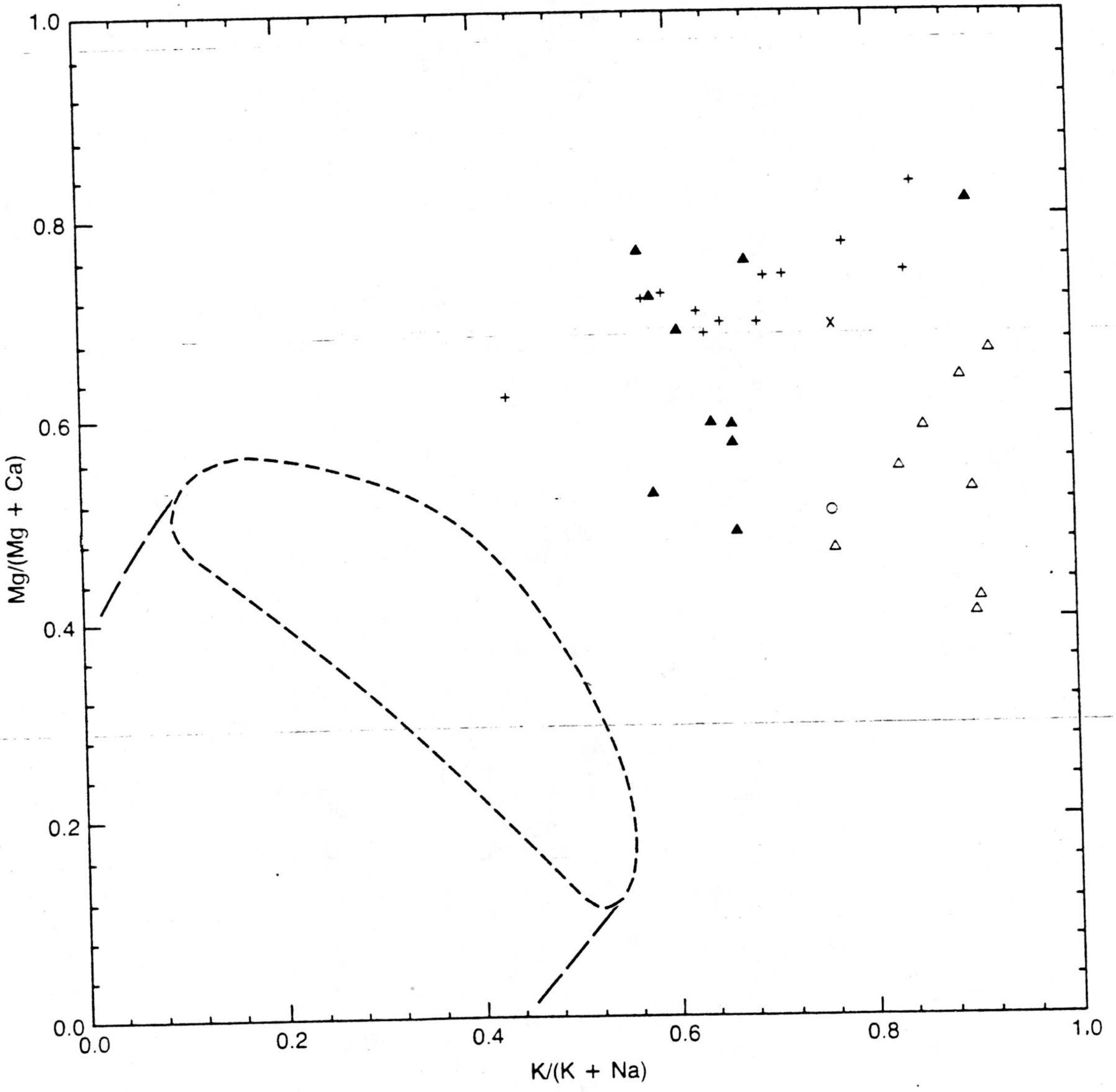

Fig. A.11.—Mg/(Mg+Ca) compared to K/(K+Na) for the < 63-µm fraction in overbank-material samples collected throughout the Orinoco basin and for igneous-rock types representative of bedrock in the basin. Symbols are defined in Figure A.4. The dashed oval represents the range of analyses for common igneous rocks; the dashed lines that extend away from the igneous field represent the composition field of rivers that drain the mountain belts plotted in Figure A.4. Note that when compared to igneous rocks, the sediments are enriched in Mg relative to Ca and K relative to Na. This tendency is opposite to that for rivers that drain rapidly eroding mountain belts.

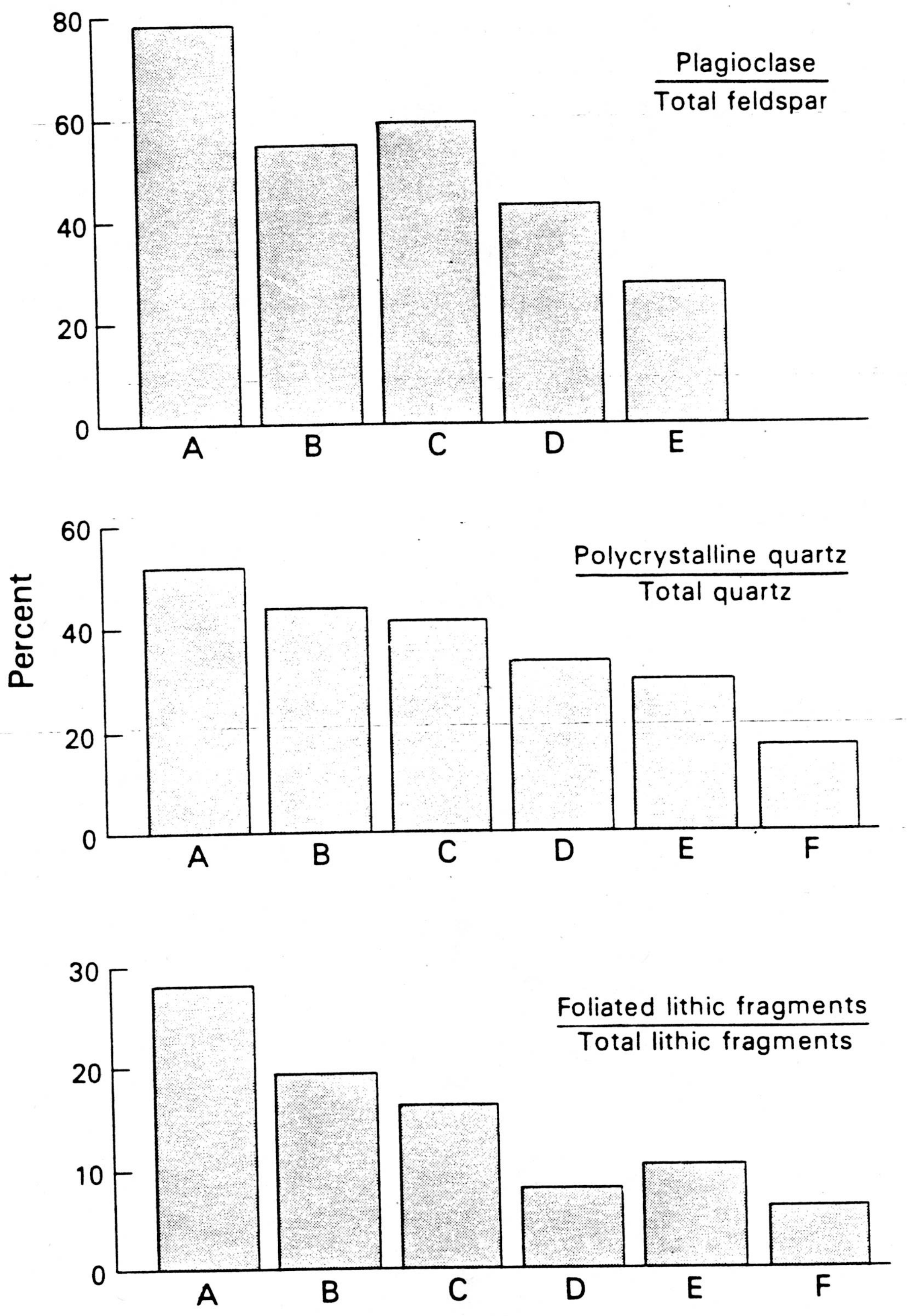

Fig. A.12.—Histograms showing mean ratios of plagioclase to total feldspar (top), polycrystalline quartz to total quartz (middle), and foliated lithic fragments (including polycrystalline quartz) to total lithic fragments (bottom) for each of the groupings of Andean-derived sands from the Apure River drainage described in the caption of Figure A.9.

of less stable mineral and lithic components with increasing distance from the mountain front (Fig. A.12).

For fine (< 63 μm) sediments, the contrast of compositions between the mountain belts and the Llanos is not pronounced as it is with the sand. The most cation-rich sediments are present in rivers that have their headwaters within the mountain belts. When cation to Al ratios are plotted, there is not a wide range of ratios (Fig. A.10), nor is there any clear downstream trend. The most cation-deficient sediments, composed of kaolinite and minor 2:1 clays, are present in rivers that have catchments entirely within the Llanos, well away from the mountain front. X-ray diffraction data indicate that weathering within the Llanos region is dominated by the degradation of mica/illite and formation of dioctahedral vermiculites along with kaolinite and gibbsite. The lack of an unambiguous decrease in cation to Al ratios with increasing distance from the mountain fronts indicates that the quantity of degraded fine-grained material contributed to the suspended load by the reworking of weathered alluvial sediments is probably not substantial.

THE GUAYANA SHIELD

Long-term sea-level fluctuations seem to be a major factor in the erosion of cratons. If the local sea level is stable for several million years, usually near times of minima or maxima, much of the landscape is eroded down to this level and an erosion (planation) surface forms. Major episodes of erosion occur when sea level drops below the altitude of this surface. With the passage of time, and repeated rises and falls of sea level, new surfaces may develop before remnants of old surfaces are completely eroded. Isostatic uplift seems to contribute to raising the remnants formed during sea-level maxima to elevations above those of later sea level maxima. The repetition of erosion and uplift causes stacked erosion surfaces, commonly separated by steep escarpments. In a sense, these surfaces are rather like super terraces; for a particular region, there is a limited range of elevations for each surface. Surfaces nearest sea level are well defined and undissected, whereas the most elevated usually are remnants of small extent or are simply delineated by numerous hills of similar height commonly topped by deeply weathered soils. In South America and other tropical cratonic regions, at least five major levels seem to be identifiable. King (1967) argued that, to a first approximation, the surfaces are globally synchronous (within about 10 Ma) and that the oldest ones are of great age, perhaps predating the rifting of the South Atlantic Ocean (Late Jurassic to Early Cretaceous). Subsequent geomorphic studies have produced a better dating (Fig. A.2) and descriptions of relations among erosion surfaces in South America (McConnell, 1968; Aleva, 1978, 1984; Krook, 1979; Menendez and Sarmentero, 1984; Shubert *et al.*, 1986). Aleva (1984) notes that the major surfaces seem to coincide with major high stands on the late Mesozoic–Cenozoic sea-level curve.

The Guayana Shield is among the best exposures of crystalline basement in the humid tropics. The bedrock consists primarily of Proterozoic felsic to intermediate plutonic rocks and gneisses, and a discontinuous orthoquartzite platform cover containing minor mafic volcanic rocks (Bellizzia G. *et al.*, 1976; Gibbs and Barron, 1983 and references therein). Mafic and ultramafic gneisses of Archean age are exposed in the northeastern part of the shield within the Orinoco River basin. The topography of the Guayana Shield has primarily resulted from the development of a series of stacked erosion surfaces. Landforms can be spectacular with steep slopes, either of bare rock or thinly vegetated, commonly topped by high plateaus, some of which are quite expansive. Soils on the plateaus are composed of kaolinite, Fe/Al-sesquioxides, and quartz. These soils are commonly more than 10 m thick and are of great age. The highest elevations, 2,000 to 3,000 m, are large table-like mountains or "tepuys," topped by thick, often nearly flat-lying orthoquartzites. Karst-like features developed on quartzite, gneiss, and granite are widely distributed (Szczerban, 1976; Blancaneaux and Pouyllau, 1977; Chalcraft and Pye, 1984; Urbani, 1986). Inselbergs are locally common. Aerial photographs and radar images indicate that all but the youngest surfaces are dissected to various degrees, and that this dissection is controlled by geologic structure. Many rivers seem to follow fault systems and dike swarms (see maps by Shubert *et al.*, 1986). The fact that lithology is a major factor in landscape morphology indicates that erosion is weathering limited. Within the Orinoco River basin, much of the Shield is elevated. Vegetation is primarily tropical rain forests and savanna, with the latter being more common in the drier areas, at higher elevation, and in the north.

The youngest major erosion surface, of late Neogene age, forms an extensive area of low relief on the Guayana Shield and the Llanos. On the Shield, the erosion surface encompasses the region south of the Orinoco and the Guaviare Rivers. The surface extends over much of the western Llanos, including most of the areas drained by rivers that do not have their headwaters in the mountain belts. The lowland areas are characterized by black-water rivers and associated campina-caatinga vegetation.

Denudation in shield terrains is much slower than in active mountain belts such as the Andes, even though elevations in the Guayana Shield are as high as 3,000 m. Both lithology and basement structure seem to contribute to the slow denudation. Uplift is slow (Fig. A.2, d–e) and seems to involve more plastic deformation and less faulting or folding than in the mountain belts. Consequently, the bedrock is not so fragmented nor as permeable to water as in tectonically active regions, and great cliffs and near-vertical slopes are common. Rocks typically are composed of more stable minerals like quartz, potassium- and sodium-feldspars, and micas. Because uplift is slow, there is no rapid resupply of easily weathered material during erosion, and a long history of weathering removes all unstable rock types. In contrast, platform and basin sedimentary deposits on cratons generally are unconsolidated or poorly cemented. When exposed on hillslopes, such

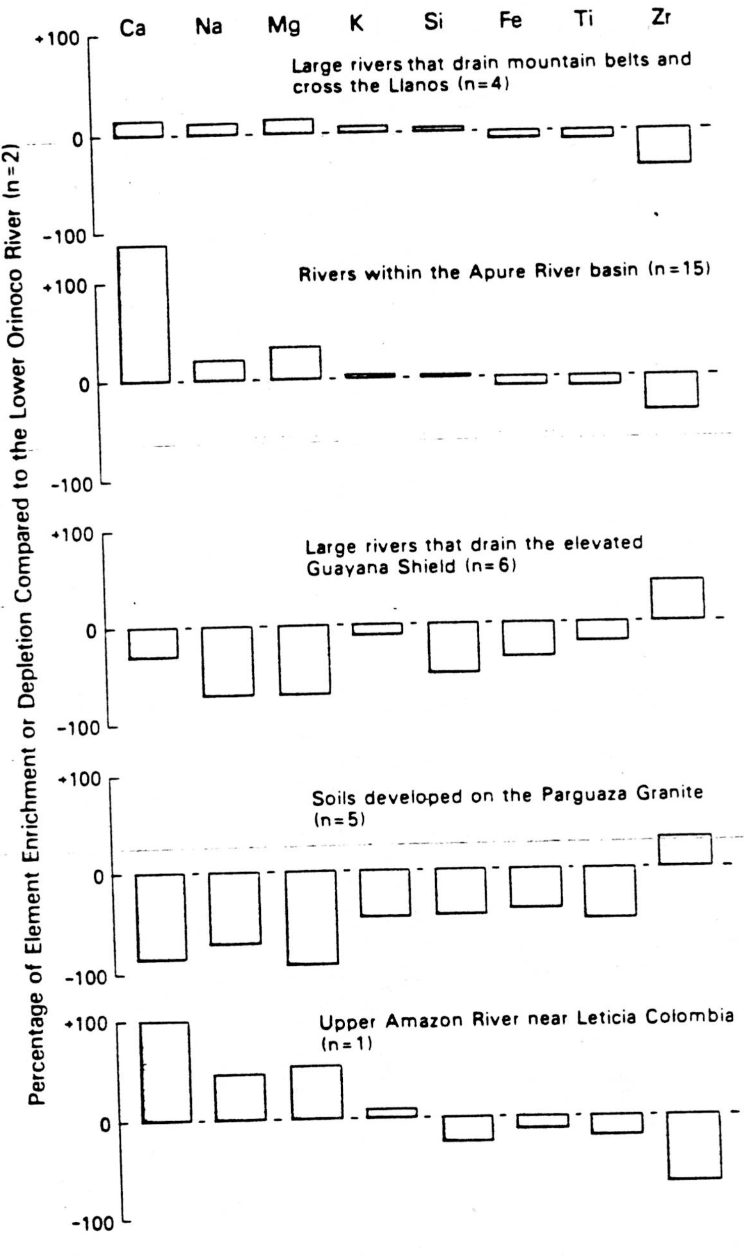

Fig. A.13.—Comparison of the elemental compositions of fresh < 63-µm overbank material from rivers that drain different regions of the Orinoco River basin and from the upper Amazon River. The elemental concentrations in the sample were normalized to the Al concentration; the data for each region were averaged, then average element-to-Al ratio for each element was normalized to the ratio for that element in samples from the lower Orinoco River. Results are expressed as a percentage of elemental enrichment or depletion relative to the lower Orinoco River samples. Note that average values for samples from the mouths of big rivers that drain mountain belts and cross the Llanos are about zero, and therefore, similar to those of the lower Orinoco River. The elements that are enriched in these samples are depleted in samples from rivers that drain the Guayana Shield. The reverse is true for Zr. This indicates that the fine sediment in the lower Orinoco River is a mixture of sediment from rivers that cross the Llanos and those that originate on the Shield. Note also that the composition of sediment from rivers originating on the Shield is similar to the average composition of soil from a profile developed on the Parguaza Granite described by Stallard (1985, samples OR-4 to OR-8). The Proterozoic Parguaza Granite is especially deficient in Mg, hence the pronounced Mg depletion. The sample from the upper Amazon River near Leticia, Colombia, is included for comparison.

deposits erode rapidly. These rock types, however, occur in only the flattest areas and undergo transport-limited erosion.

Weathering-Limited Erosion on The Elevated Shield

Rivers originating on the elevated Guayana Shield typically transport little dissolved or solid load (Paolini, 1986; Lewis *et al.*, 1987; Meade *et al.*,, in press), and the solids tend to be more resistant mineral phases. Tributaries transport micaceous, subarkosic sand. As might be expected if weathering-limited erosion is occurring on the steep slopes, river sand includes more potassic feldspars. Iron-sesquioxide coatings are normal. In rivers on the elevated Shield, fine-grained suspended sediment is cation-depleted; the smallest size fraction (<0.2 µm) consists solely of kaolinite and minor quantities of gibbsite. With increasing grain size, mica/illite (0.6 to 2.0 µm), quartz (2.0 to 6.3 µm), and feldspars (>6.3 µm) also are present. Potassium is particularly abundant compared to other cations (Figs. A.10, A.11), in agreement with the abundance of mica/illite. The mineral and chemical compositions of fine-grained suspended sediment are very similar to surface layers of soils developed on the shield (Fig. A.13). The micas and vermiculite that are present in the deeper parts of soil profiles are not abundant. This observation indicates that fine-grained sediments primarily may be accounted for by surficial erosion processes, such as sheet wash. The great enrichment in Zr (as much as eightfold) in the fine-grained fraction illustrates the intensity of chemical weathering. Compared to the mountain belts, sediments derived from elevated parts of the Guayana Shield are more mature. The composition of the dissolved load is consistent with thermodynamic calculations and mass-balance calculations for the weathering of common igneous rocks to kaolinite and, depending on the situation, with or without quartz (Figs. A.4–A.6).

Transport-Limited Erosion on the Lowlands

Vast tracts of the South American lowlands that encompass the late Neogene erosion surface can be characterized as having dominantly transport-limited erosion regimes (Stallard, 1980, 1985; Stallard and Edmond, 1983). Soil compositions and river loads are chemically similar in the shield and in sedimentary terrains not receiving sediment from mountain belts. Soils are rich in quartz, kaolinite, and Fe/Al-sesquioxides, all of which are cation-depleted phases. In low swampy areas, tropical podzols are common. Rivers are characterized by little turbidity, black water, and beds of extremely white quartzose sand (Fig. A.9). There is a near absence of very fine-grained weathering products in the suspended load. If present, weathering products are limited to kaolinite and Fe/Al-sesquioxides, with the latter being less common. Dissolved-solids concen-

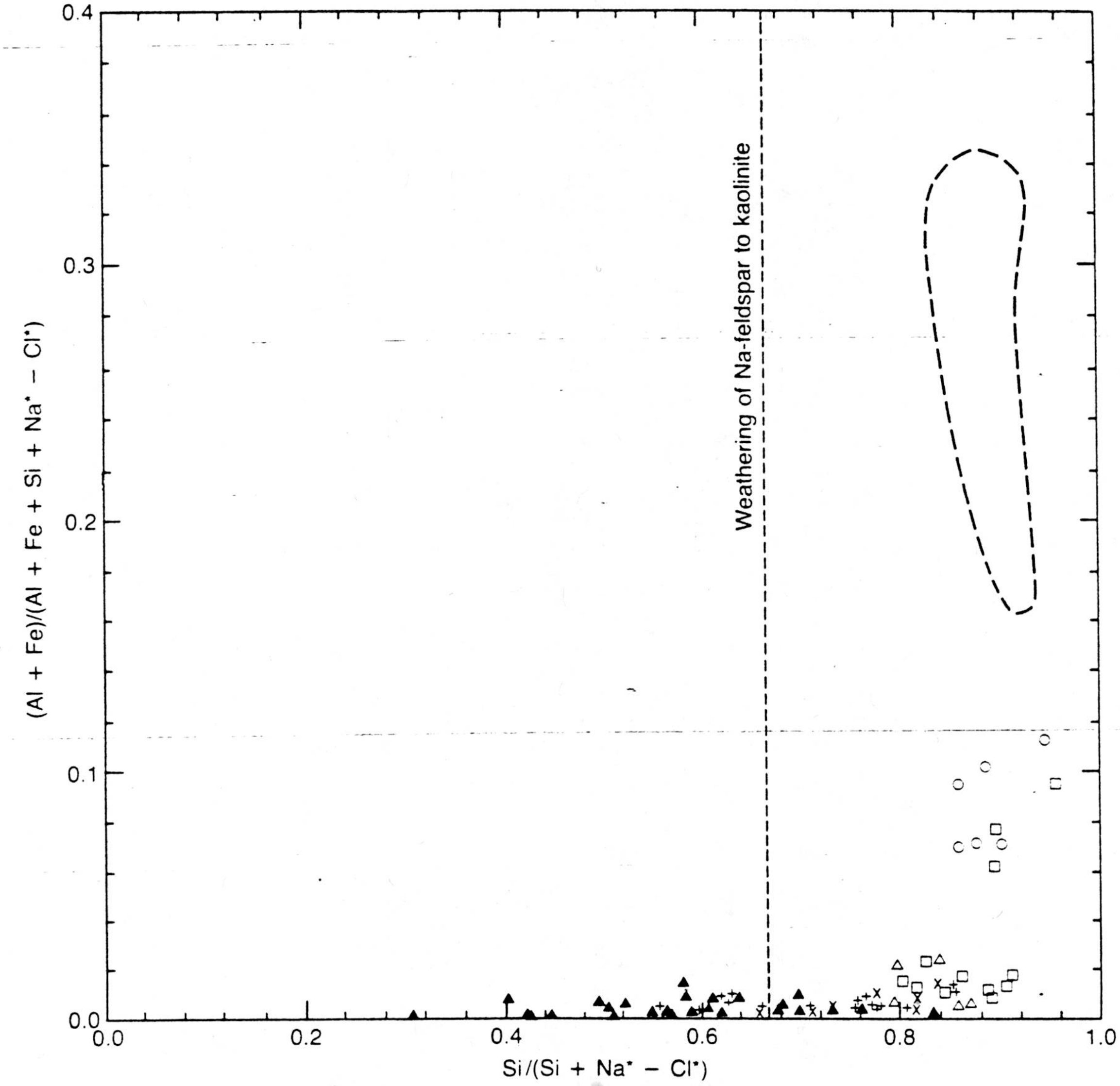

Fig. A.14.—Comparison of the proportions of dissolved (Al+Fe), $Si(OH)_4$, and (Na*-Cl*) in surface water of the Amazon River basin, and for rock types representative of bedrock in this basin. Symbols are given in Figure A.4. The dashed oval represents the range of analyses for common igneous rocks.

vated parts of the shield contains minor quantities of K-rich minerals (mica/illite and potassium-feldspar) which probably are derived from erosion on steep slopes. Dissolution is most pronounced in the flat late Neogene erosion surfaces, where substantial quantities of Al and Fe are transported in solution.

Data from water chemistry and surveys of suspended sediment and bed sand indicate that compositionally very mature sediments including modern first-cycle quartz arenites are being formed in the Orinoco River basin by at least two independent mechanisms. In the Llanos, extended time is provided by temporary storage of orogenically derived sediments on extensive alluvial plains. In the lowland part of the Guayana Shield, exceedingly slow erosion and transport rates cause soil-mineral residence times to be long, reflecting the low relief and tectonic quiescence that characterize this regions. Common to both mechanisms is an environment of intense chemical weathering and extended time during which weathering can occur.

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