Weathering and Global Denudation[1]

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ABSTRACT

A negative correlation between sediment yield and weathering history, as measured by the chemical alteration (CIA) of the suspended sediment, is observed for many of the world's major rivers and other regions of denudation. The weathering history is a first-order control on the sediment yield of such areas, termed *equilibrium denudation regions*. For other areas, data scatter with either apparent increases or decreases of sediment yield for given CIA values. These areas are termed *nonequilibrium denudation regions*. Low sediment yields can be attributed to moderated erosion (either natural or human induced) and/or the incorporation of unweathered glacial debris. Accelerated erosion, resulting in high sediment yield, is primarily human-induced and results from cultivation and other land use. Each of these effects has a profound influence on global sediment discharge from the continents. Pre-human suspended sediment discharge from the continents is estimated to be 12.6 $\times$ 10^{15} g/yr or about 0.6 the present discharge.

Introduction

Studies of erosion and denudation on a continental scale have long been central issues in the earth sciences. For example, Charles Darwin (1859) used denudation calculations for the Weald of southern England to demonstrate the great antiquity of the earth and accordingly provide sufficient time for evolution (these calculations were in fact highly controversial and were revised in later editions of his book). Understanding denudation is important for many questions of global significance, such as crustal evolution (e.g., McLennan and Taylor 1983), climate change (e.g., Donnelly 1982), soil erosion, uplift rates, and nutrient transfer to the oceans (e.g., Milliman 1991).

Most attempts to estimate denudation on a continental scale rely heavily on measurements of sediment yield from the rivers of the world. Considerable effort has been expended both to estimate sediment yield of the major rivers and to understand controls on sediment transfer within river systems. Efforts toward understanding the controls of continental denudation have emphasized topographical, lithological, and climatic factors, but attempts to model quantitatively sediment yield have met with mixed success. For example, Jansen and Painter (1974) modeled sediment yield using eight variables, including water discharge, basin area, altitude, relief, precipitation, temperature, vegetation, and lithology. Such an approach provided predictions of sediment yield reliable only to within about 2 orders of magnitude. More recently, Milliman and Syvitski (1992) have emphasized basin area and elevation as the primary controls on natural sediment flux.

Although the controls on sediment yield in rivers are no doubt complex in detail, it seems logical to suppose that a first-order relationship should exist between weathering history and erosion of a given area. The general relationship between continental freeboard and erosion rates is well documented, with continental-scale denudation correlating reasonably well with mean elevation above sea-level (Garrels and Mackenzie 1971; Milliman and Syvitski 1992). Intuitively, one would expect that sediment sources with high relief would erode quickly and have least time to be affected by chemical changes associated with weathering. At the other extreme, highly weathered terrains, such as those in Brazil, require time scales on the order of 10^7–10^8 yr for their formation (Kronberg 1985). Little mechanical erosion could be achieved from the

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inherently stable terrains that give rise to deeply weathered profiles. The purpose of this paper is to examine the relationship between continental scale denudation, as measured by sediment yield, and the weathering history experienced by major drainage basins, as measured by the chemical composition of suspended river sediment or other fine-grained erosional products.

Sediment Yield and Denudation

Measurements of suspended sediment discharge in the world's river systems, when divided by drainage area and corrected for dissolved load, bed load, and flood discharge, result in an estimate of regional denudation. Numerous problems are associated with such estimates, among the most important being that measurements commonly are based on "spot" sampling, difficulty in establishing stream equilibrium over the relevant time scales (Trimble 1977), the fact that many measurements are taken upstream from the mouth and accordingly do not account for sediment deposited in lower alluvial plains and deltas (Milliman and Meade 1983), and the difficulty in estimating bed load and flood discharge (Milliman and Meade 1983). The relative importance of sediment loads (physical denudation) and dissolved loads (chemical denudation) is also variable but is largely controlled by weathering processes (Martin and Meybeck 1979; Meybeck 1987).

In addition to these problems, human influence has resulted in dramatic changes in erosion and denudation rates. Intensive land use may result in a severe acceleration of local erosion rates (Judson 1968; Toy 1982; Milliman 1991). Dam reservoirs are sites of major sediment accumulation, resulting in huge decreases in sediment reaching the oceans, thus complicating estimates of continental scale denudation. Perhaps the best example of this is the Colorado River where dam construction has resulted in a decrease, by a factor of about 10^4, in the amount of sediment reaching the Gulf of California (Curtis et al. 1973). The Nile River is similarly affected, and sediment yield from the Indus River is likely to fall to zero in the near future (Milliman 1991).

In table 1, various estimates of sediment discharge and yield from some major rivers of the world are given. These rivers were selected solely because reasonable estimates can be made for the chemical composition of suspended sediment. Sediment yields of Milliman and Meade (1983) and Milliman and Syvitski (1992) are accepted as the most reliable values in all but a few areas. In the case of the Colorado, Columbia, Indus, Mississippi, and Nile Rivers, the very low sediment yields measured at or near the mouths are, to a large extent, a consequence of human interference (Milliman and Meade 1983). Higher values, based on historical records or estimates, are available and of interest, and are also provided in the footnotes of table 1.

Table 1. Suspended Sediment Yield of Some Major Rivers and Denudation Areas of the World

	Drainage Area (10^6km^2)	Sediment Discharge (10^6t/yr)	Sediment Yield (t/km^2/yr)
Rivers:			
Amazon	6.15	1,200	195
Colorado	.64	.01	.02
Columbia	.67	10	15
Congo (Zaire)	3.72	43	12
Danube	.81	67	83
Ganges/Brahmaputra	1.48	1,060	716
Huanghe	.75	1,050	1,400
Indus	.97	59	61
Mackenzie	1.81	42	23
Mekong	.79	160	202
Mississippi	3.27	210	64
Niger	1.21	40	33
Nile	3.03	0	0
Orinoco	.99	150	152
Parana	2.83	79	30
St. Lawrence	1.03	4	4
Denudation Areas:			
Western Europe	2.60	(36)	14
Alpine Europe	.55	(297)	540
Central America (incl. Mexico)	2.08	442	213
N.W. South America	.30	150	500
Ocean Islands (excl. New Zealand)	2.5	(7,175)	2,870
New Zealand (South Island)	.26	(442)	1,700
U.S. Atlantic Coast	.74	(26)	35

Note. Pre-dam yields (t/km^2/yr): Colorado—190; Columbia—70; Indus—258; Mississippi—200; Nile—40. Pre-dam yields based on oldest available measurements and estimates.
Data Sources: Adams (1980); Huang et al. (1992); Judson and Ritter (1964); Holeman (1968), Curtis et al. (1973); Milliman and Meade (1983); Milliman (1991); Milliman and Syvitski (1992).

Although the large rivers considered here represent a substantial amount of the continental surface, it is inadvisable to rely on these alone for a global view of denudation. Small rivers individually carry only a trivial fraction of the sediment discharge to the oceans; however sediment yield is commonly large, and cumulatively small rivers are very important (Milliman and Syvitski 1992). Development of large rivers is also tectonically controlled (Potter 1976) leading to a possible bias. In order to include the contributions of small rivers, a number of denudation regions (modified from Milliman and Meade 1983) were evaluated. Sedi-

Table 2. Estimates of the Major Element Composition of Suspended Sediment from Some Major Rivers of the World

	Amazon	Colora.	Columb.	Congo	Danube	Ganges	Huang.	Indus	Macken.	Mekong	Mississ.	Niger	Nile	Orinoco	Parana	St. Lawr.
SiO_2	60.2	79.9	64.1	58.0	64.9	66.8	59.4	56.3	67.4	61.9	76.3	51.7	53.0	69.5	64.7	60.0
TiO_2	1.23	.51	1.0	1.59	.71	.97	. . .	.81	.77	.63	.64	1.44	. . .	.97	1.64	1.44
Al_2O_3	22.9	8.28	16.9	25.1	12.1	16.0	17.3	15.4	15.7	22.3	11.5	30.9	18.8	17.3	20.9	16.3
FeO_T	7.45	3.01	6.1	10.3	7.19	5.22	6.2	6.25	5.02	7.57	3.40	12.4	14.1	6.07	6.46	6.91
MnO	.14	.06	.3	.21	.08	.14	.13	.14	.08	.13	.07	.09	. . .	.06	.04	.10
MgO	1.96	1.75	2.5	1.09	3.53	2.26	4.0	4.19	.70	2.36	1.54	1.09	3.12	1.28	1.89	4.50
CaO	2.36	4.85	3.3	1.34	6.39	4.07	6.62	12.5	5.35	.87	2.37	.48	5.68	.80	.87	3.57
Na_2O	1.11	.66	2.9	.32	2.38	1.58	1.05	1.48	.32	.74	1.36	.13	1.00	1.62	.94	3.73
K_2O	2.28	1.84	2.9	1.64	2.51	2.77	3.25	2.73	4.53	3.04	2.51	1.36	2.32	2.22	2.27	3.40
P_2O_5	.40	.13	. . .	.39	.16	.14	. . .	.23	. . .	.48	.20	.39	. . .	.15	.31	.06
Total	100.0	100.0	100.0	100.0	100.0	100.0	98.0	100.0	99.9	100.0	99.9	100.0	98.0	100.0	100.0	100.0
Moles:																
Al_2O_3	.225	.0812	.166	.246	.119	.157	.170	.151	.154	.219	.113	.303	.184	.170	.205	.160
CaO^*	.0179	.0106	.0468	.0052	.0384	.0255	.0169	.0239	.0052	.0042	.0163	.0000	.0161	.0107	.0082	.0602
Na_2O	.0179	.0106	.0468	.0052	.0384	.0255	.0169	.0239	.0052	.0119	.0219	.0021	.0161	.0261	.0152	.0602
K_2O	.0242	.0195	.0308	.0174	.0266	.0294	.0345	.0290	.0481	.0323	.0266	.0144	.0246	.0236	.0241	.0361
CIA	79	67	57	90	54	66	71	66	72	82	64	95	76	74	81	51

Data Sources. Amazon, Colorado, Congo, Danube, Ganges, Mackenzie, Mekong, Niger, Nile, Parana, and St. Lawrence Rivers: suspended river sediment (Martin and Meybeck 1979); Columbia River: average fine-grained bottom sediments from Grand Coulee and Ice Harbor reservoirs (Whetten et al. 1969); Huanghe (Yellow River): suspended river sediment taken near delta (average of samples J1 and J2) (Huang et al. 1992); Indus River: average of 14 Indus cone turbidite muds from DSDP Site 222 (Donnelly 1980); Mississippi River: composite of 235 delta muds. Analysis includes 1.40% CO_2 and CIA calculated assuming 1:1 proportions of calcite and dolomite; Na corrected for salt (Clarke 1924); Orinoco River: Boca Vagre Delta mud sample BV592 (Hirst 1962).

ment yields, also listed in table 1, were estimated by extrapolating measured yields from available small rivers in each of the areas (Milliman and Meade 1983; Milliman and Syvitski 1992).

Weathering and Sediment Composition

The chemical reactions and phase relationships of weathering of upper crustal material are understood in general (e.g., Garrels and Mackenzie 1971; Curtis 1976; Nesbitt and Young 1984). More recently, progress has been made toward the quantification of weathering intensity on a given rock (Nesbitt and Young 1982, 1984, 1989; Kronberg et al. 1986). Nesbitt and Young (1984, 1989) have noted that the chemistry of weathering typical upper crustal rocks can be approximated by the weathering of feldspar and volcanic glass, comprising some 75% of the labile material in the upper crust. Accordingly, much of the chemical variation resulting from weathering may be expressed in the system Al_2O_3 − (CaO^* − Na_2O) − K_2O, where CaO^* represents the Ca in the silicate fraction only. It is possible to derive an index of chemical alteration (CIA; Nesbitt and Young 1982), in molecular proportions:

$$CIA = [Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)]^* \, 100 \quad (1)$$

CIA values of about 45–55 indicate virtually no weathering (the average upper crust has a CIA value of about 47), whereas values of 100 indicate intense weathering with complete removal of the alkali and alkaline earth elements.

In such a formulation, it is necessary to make a correction to the measured CaO content for the presence of Ca in carbonates (calcite, dolomite) and phosphates (apatite). This is normally accomplished by calculating corrections from measured CO_2 and P_2O_5 contents. Where such data are not available (generally the case for CO_2), approximate corrections can be made by assuming reasonable Ca/Na ratios in silicate material. For this study, CaO was corrected for phosphate using P_2O_5, where available. If the remaining number of moles is less than that of Na_2O, this CaO value was adopted. If the number of moles is greater than Na_2O, CaO^* was assumed to be equivalent to Na_2O. Since Ca is typically lost more rapidly than Na during weathering, this is likely to yield minimum CIA values, by up to about 3 units. Discrepancies are likely to be greatest for intermediate CIA (60–80), since at low CIA this approach is generally valid, and at high CIA both Na and Ca concentrations are low and uncertainties have little effect on CIA. For examples containing halite, a comparable correction is necessary for Na_2O either using chlorine content (Donnelly 1980) or analyzing water-leached samples (McLennan et al. 1990).

Table 2 tabulates the chemical composition of suspended or fine-grained delta muds from the various rivers. Estimates of the average composition of fine-grained erosional products from the other denudation regions are given in table 3. CIA values vary from 51 for the St. Lawrence River, indicating virtually no weathering products, to 95 for the Ni-

Table 3. Estimates of the Major Element Composition of Erosional Products from Some Major Denudation Regions of the World

	Western Europe	Alpine Europe	Central America	Northwest South America	Ocean Islands (excl. N.Z.)	New Zealand (S. Island)	U.S. Atlantic Coast
SiO_2	61.9	53.9	62.5	67.1	67.8	62.6	61.2
TiO_2	.93	.56	.90	.66	.64	.67	.90
Al_2O_3	16.0	11.6	18.8	15.7	14.4	18.9	17.9
FeO_T	9.48	5.98	6.63	6.82	5.63	5.32	6.45
MnO	.45	.14	.09	.12	.085	.07	.20
MgO	2.01	2.25	2.70	2.57	2.99	2.38	3.12
CaO	4.71	21.2	2.86	1.91	2.36	3.38	3.12
Na_2O	.72	1.18	2.84	2.03	3.53	2.49	1.54
K_2O	2.53	2.46	2.68	2.82	2.41	3.52	3.42
P_2O_5	1.13	.64	...	.25	.13	.21	.21
Total	99.9	99.9	100.0	100.0	100.0	99.9	99.9
Moles:							
Al_2O_3	.157	.114	.184	.154	.141	.185	.176
CaO^*	.0116	.0190	.0458	.0282	.0390	.0402	.0248
Na_2O	.0116	.0190	.0458	.0328	.0570	.0402	.0248
K_2O	.0269	.0261	.0285	.0299	.0256	.0374	.0363
CIA	76	64	61	63	54	61	67

Note. Samples from DSDP were selected to eliminate ash-bearing samples and minimize carbonate-bearing samples.
Data Sources. Western Europe: average suspended sediment/delta mud from Ems, Garonne, Meuse, Loire, Rhine, Vistula Rivers (Clarke 1924; Martin and Meybeck 1978); Alpine Europe: suspended sediment from Rhone River (Martin and Meybeck 1978); Central America: average of three turbidite muds west of Central America, Na corrected for seawater salt (McLennan et al. 1990); northwest South America: average of four uppermost sediments DSDP Site 321 and turbidite mud off western South America; Na corrected for salt (Donnelly 1980; McLennan et al. 1990); Ocean Islands: average fine grained Japan Trench sediment (corrected for biogenic silica) derived from uppermost sediment at IPOD Sites 434, 435, 438, 439, 440; Na corrected for salt (Sugisaki 1980); South Island New Zealand: Average of three shelf muds (Stoffers et al. 1984); U.S. Atlantic Coast: average of 16 (13 for P_2O_5) muds from upper 1m at DSDP Sites 102, 104, 105, 106; Na corrected for salt (Donnelly 1980).

ger River, indicating derivation from intensely weathered sources. The data are plotted on the ternary diagram Al_2O_3 – (CaO^* + Na_2O) – K_2O in figure 1. Also plotted are major rock-forming minerals important in silicate rock weathering, average upper crust (Taylor and McLennan 1985), and typical natural waters (Nesbitt and Young 1984). The overall trend is consistent with increasing degrees of weathering affecting typical upper crustal compositions.

Sedimentary Recycling and Provenance Composition. Important variations in the composition of the provenance may exist, and it is important to distinguish these variations from those induced by weathering history. Average upper continental crust has a CIA value of about 47, and average island arc andesite has a value of about 46 (Taylor and McLennan 1985). Thus, variations of CIA among igneous source rocks are likely to be minimal. An important source of variability may result from a recycled sedimentary provenance where a weathering history may be inherited. Although the CIA in average shale is about 65–70, for average sediment it is somewhat lower, about 61 (McLennan 1993). CIA is plotted in figure 2 as a function of mixing between average upper continental crust and average sediment. The mixing relationship is non-linear due to different absolute abundances of major elements in the end members, and CIA becomes more sensitive to change with greater sediment. It is well established that the process of sedimentation is highly cannibalistic with the level of recycling being variable and related to tectonic setting (e.g., Veizer and Jansen 1985). For this work, we assume a provenance CIA value of 50 (figure 2). However, this variability is a source of uncertainty, and the provenance of individual regions may have average CIA anywhere in the range of 45–60.

Weathering and Sediment Yield

Milliman and Meade (1983), among others, have observed that rivers of the flat-lying arid regions of the Arctic have especially low sediment yields. To evaluate the relationship between weathering and sediment yield in these regions, additional geochemical data from Arctic rivers (notably Asian

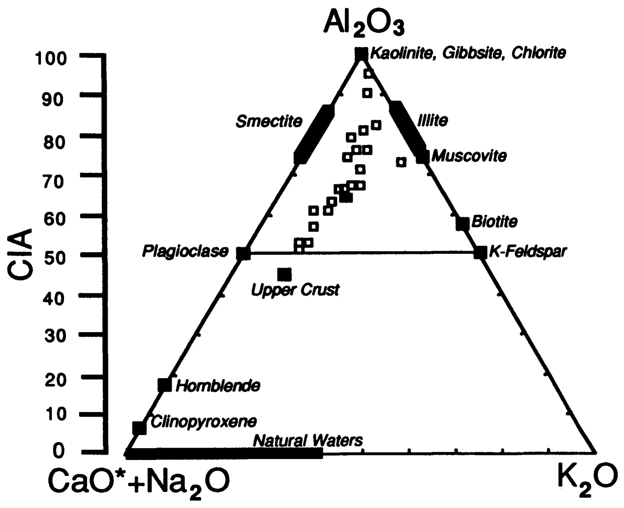

Figure 1. Ternary diagram of molecular proportions Al_2O_3 − (CaO^* + Na_2O) − K_2O. Plotted are estimates of suspended sediments from the major rivers and denudation areas considered in this study. Also plotted is the average upper continental crust (Taylor and McLennan 1985), as well as idealized mineral compositions. Shown at the side is the CIA scale. Sediments display a wide range of weathering effects, from only slightly evolved from unweathered upper crust to intensely weathered and plotting near the composition of pure aluminosilicate minerals.

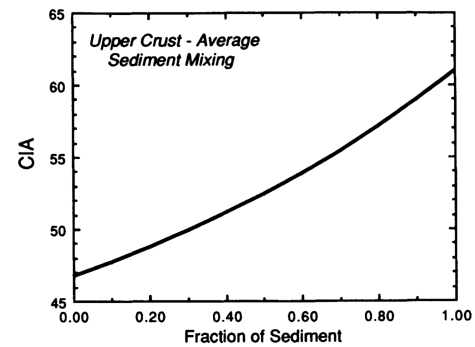

Figure 2. Plot illustrating how CIA changes for mixing of unweathered upper continental crust (Taylor and McLennan 1985) and average sediment (McLennan 1993). Since most sediments are derived in part from pre-existing sedimentary rocks, a weathering history may be inherited in the provenance. An average provenance CIA of 50 is adopted, but individual areas could vary considerably.

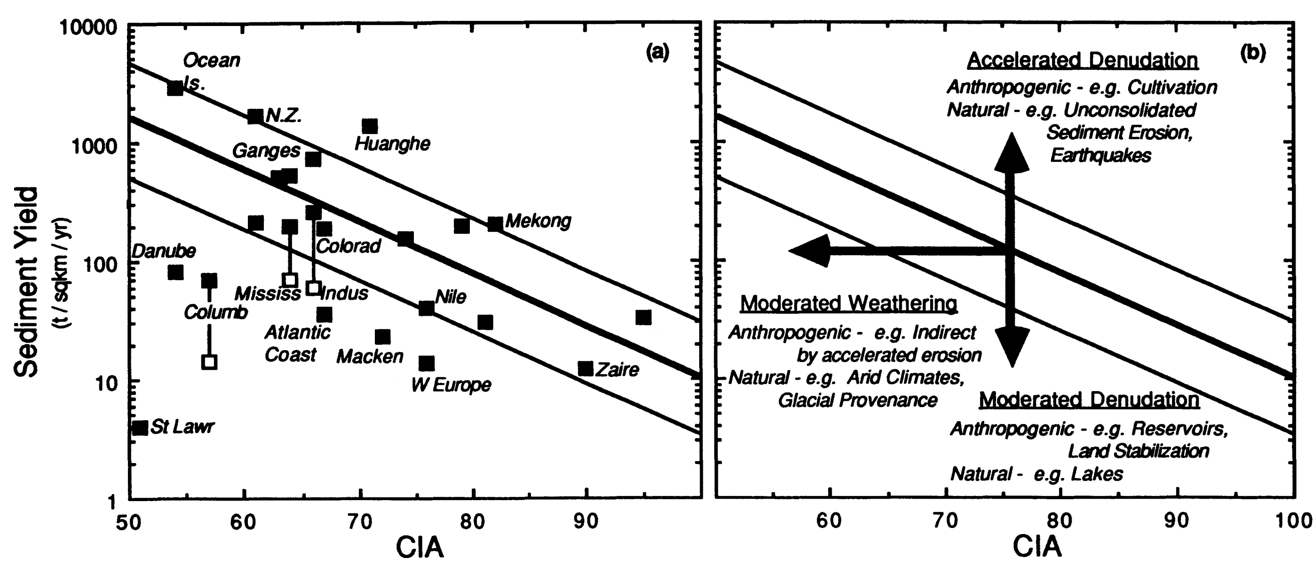

Figure 3. (*a*) Plot of Sediment Yield versus CIA of suspended sediment for various rivers and denudation regions. Pre-dam yields are plotted in solid symbols for the Colorado, Columbia, Indus, Mississippi, and Nile Rivers. Measured yields for these rivers are plotted as open symbols except for the Colorado and Nile, where current yields are essentially zero. Also shown is a simple model that relates sediment yield to CIA of suspended sediment, including a field representing a factor of 3 in sediment yield (see text). (*b*) Schematic diagram illustrating how various natural and human induced processes can affect sediment yield-weathering relationships.

rivers) are required. Thus, most Arctic regions of Asia and North American are excluded from this analysis.

Figure 3*a* displays a plot of sediment yield versus the estimated CIA values of fine-grained suspended sediment. Also shown is a simple model to explain the weathering-sediment yield relationship. Sediment yields from small rivers may reach in excess of 20,000 t/km^2/yr (Milliman and Syvitski 1992), but the upper limit for river basins >50,000 km^2 in size in areas relatively unaffected by human activities is about 1,500 t/km^2/yr. At the other extreme are the highly weathered terrains of the world. Sediment yields for large nonarid rivers, reported by Milliman and Syvitski (1992), are rarely below 10 t/km^2/yr. By assigning CIA values representative of unweathered (50) and extremely weathered (100) sources to extreme denudation values, a simple model to explain the relationship between weathering and denudation can be constructed (figure 3*a*):

$$\text{Sediment Yield}(t/km^2/yr) = (2.25 * 10^5)(10^{-0.0435[\text{CIA}]}) \quad (2)$$

Also shown on figure 3*a* is a field, selected arbitrarily, corresponding to a factor of ±3 uncertainty in sediment yield for a given CIA value.

The data may be divided into three groups. Many of the high-yield areas correspond to the negative sediment yield-weathering relationship and are consistent with weathering intensity, providing a first-order control on sediment yield. These areas are considered to have a sediment discharge that approaches an equilibrium with prevailing weathering conditions and accordingly are termed *equilibrium denudation regions* (EDR). Most of the other areas have sediment yield much lower than predicted from the relationship, and four areas (Huanghe, Mekong, New Zealand, Ocean Islands) are considered to have higher sediment yields. These areas are termed *nonequilibrium denudation regions* (NDR).

Equilibrium Denudation Regions. For rivers, the sizes of the EDR drainage basins cover the full range under consideration with the Colorado being the smallest and Amazon the largest. The majority of EDR's represent areas that are least affected by (or can be corrected for) human interference. Natural phenomena, apart from weathering, may also have an effect on some of these rivers. For example, the sediment yield of the Zaire may be lower because this river encounters lakes before reaching the Atlantic (Milliman and Meade 1983; see below), and that of the Ganges/Brahmaputra almost certainly has been accelerated due to land use practices (Milliman 1991). Thus, regions included as EDRs are not necessarily unaffected by secondary factors apart from weathering, but it appears that weathering history remains as a primary influence.

Other Controls on Sediment Yields. There are additional processes that can affect the EDR relationship shown on figure 3*a*, and some of these are shown schematically in figure 3*b*. The first is the lowering of sediment yield through moderating denudation rates. The low denudation rate observed in Arctic regions has already been cited as one example of this. Additional natural and human-induced mechanisms for lowering sediment yield are related to the presence of lakes or the construction of dam reservoirs that trap sediment.

It is also possible to accelerate erosion rates, thus raising sediment yields. The mass of sediment in rivers that pass through easily erodable material, such as loess, is known to increase dramatically (such as in the Huanghe; Long and Xiong 1981). In addition, many forms of cultivation and other land use are known to increase erosion rates dramatically (Toy 1982). However, it is less clear how local increases in sediment mass carried in the rivers influence overall sediment discharge. For example, the increased sediment mass in the Huanghe diminishes significantly over the alluvial plain near the delta and the sediment content of the river at the lowest gaging stations is only slightly greater than at gaging stations above the loess deposits (Long and Xiong 1981).

A third process is the erosion of material with abnormally low CIA values (moderated weathering). Again, in principle, this can be achieved by natural or human induced processes. The present surface of the earth has abundant glacial deposits, that are generally unconsolidated and easily eroded. The fine grain size of much of this material makes it easily transported in suspension. For example, loess deposits cover about 10% of the earth's surface. For the most part, glacial material forms from mechanical grinding and the derived sediment has not passed through the normal chemical processes of weathering, yet it is very easily eroded. This results in abnormally low CIA values (Taylor et al. 1983). Preferential incorporation of such material in the sediment load of a river would have the effect of giving an apparently low sediment yield for a given CIA value. Accelerated erosion, resulting from human activity, could also result in sediment that has had insufficient time to be influenced by weathering process normally expected for the given geological conditions. Moderated weathering competes with accelerated erosion in affecting the sediment yield-weathering relationships of figure 3, but in the case of the Huanghe, accelerated erosion clearly dominates.

Nonequilibrium Denudation Regions. Rivers with low sediment yields can be understood in terms of natural or human-induced influence on what may be considered the equilibrium (with respect to weathering history) denudation rates. In many cases, more than one factor is involved in controlling sediment yield.

The St. Lawrence River stands out as having its sediment yield drastically diminished by natural causes. The Great Lakes provide a large natural reservoir for trapping sediment. The CIA value of the St. Lawrence sediment is the lowest reported. An additional natural factor likely to have had a significant effect is the widespread occurrence of glacial material as a potential sediment source. Both the Mackenzie and Zaire Rivers constitute EDRs according to figure 3*a*. Nevertheless, it is likely that lakes have lowered the sediment yield of these rivers. In the case of the Mackenzie, the effect is likely to be small. Although the Great Bear and Great Slave Lakes are within the drainage basin, they would represent traps for sediment derived from the Canadian Shield, which is likely to be slight. Most of the sediment load in the Mackenzie is likely derived from highlands to the west and accordingly less diminished by trapping in lakes. The presence of permafrost and extended periods of freezing in the lower drainage areas are likely to further moderate sediment yields.

Erosion of glacial material is likely to have some effect on other NDRs, including the Huanghe (discussed above), Columbia, Danube, and possibly Mississippi Rivers. The Mississippi and Danube cut the loess fields of central North America and Europe, and the provenance of the upper reaches of the Columbia is substantially glacial (Whetten et al. 1969). In each of these cases, the sediment yields are so far from equilibrium and the potential or documented role of human-induced change is so great, it is likely that more than one factor is playing a role.

The major human-induced factors that result in low sediment yield are the construction of reservoirs and land stabilization. In the case of the Colorado, Columbia, Danube, Mississippi, and Nile Rivers, as well as the regions of the U.S. Atlantic Coast and Western Europe, this is likely a dominant factor. Sediment yields are lower than equilibrium values by factors ranging from about 3 for the Mississippi (Kesel et al. 1992) to in excess of 10^4 for the Colorado (Curtis et al. 1973). Along the U.S. Atlantic Coast and in Western Europe, cultivation historically resulted in increased erosion rates (e.g., Meade 1982). It appears that, more recently, the building of dams and land stabilization programs have resulted in moderated denudation. Rivers where dams may seriously affect sediment yields in the future include the Indus, where major dams have been built, and the Amazon, where dams are planned.

Both the Huanghe and Mekong Rivers lie above the trend for EDRs. In both cases, it is likely that cultivation and associated deforestation has greatly accelerated erosion and denudation. The region of Pacific Ocean Islands has also suffered significant accelerated erosion due to cultivation (Milliman 1991). The south island of New Zealand lies above the EDR trend, but it is unlikely that anthropogenic effects have been large. Adams (1980) has noted that nearly 60% of the sediment load in New Zealand south island rivers results from earthquake activity, providing an additional natural process of accelerated denudation.

Human Impact on Denudation

It is not the purpose of this study to provide a means to predict the sediment yield of individual rivers or regions where data are unavailable. Uncertainties are too great. Rather, this approach is more useful in evaluating the various controls on denudation. If errors in such estimates are essentially random, it may also be possible to provide constraints on the overall human influence over global denudation rates using the sediment yield-CIA relationship. Human interference provides two competing effects: accelerating denudation due to land use and moderating denudation due to dam construction. The magnitude of each may be estimated.

The global suspended sediment discharge to the oceans, prior to human interference, was estimated as follows. Measured sediment discharge from equilibrium denudation regions was accepted, except for those areas clearly suffering significant human impact. Sediment yields from regions suffering accelerated denudation, including the Ganges/Brahmaputra, Huanghe, Mekong, and Pacific Islands were corrected using the sediment yield-CIA model, and sediment discharge was calculated from the known basin areas (table 1). Areas suffering moderated erosion, including the Danube, Western Europe, and U.S. Atlantic Coast, were similarly corrected, only in this case to higher sediment yields (and assuming average shale CIA of 65 for the Danube). In the case of the Colorado,

Table 4. Estimates of Pre-human Continental Sediment Discharge

Reference	Sediment Discharge (10^{15} g/yr)	Method of Estimate
This study	14[a]	Sediment yield/ weathering relationship.
Judson 1968	9.3	Global extrapolation of erosion rates in areas unaffected by humans.
Gregor 1970	10.5	Na mass balance in oceans.
Wold & Hay 1990	10.9	1.6–10.6 Ma sediment flux based on mass-age distribution of sediments.

[a] Includes 1.5×10^{15} g/yr to account for bedload and flood discharge.

Columbia, Indus, Mississippi, and Nile rivers, historical records were used (see footnote of table 1). For the regions considered in table 1, this leads to a pre-human sediment discharge of 8.0×10^{15}g/yr compared to the current value of 12.7×10^{15} g/yr. or 0.62 of the current value. If we further assume that these regions are representative of non-Arctic regions it leads to an estimate of pre-human suspended sediment discharge of 12.6×10^{15} g/yr compared to the current value of 20×10^{15} g/yr (Milliman and Syvitski 1992). This estimate, although somewhat higher, compares favorably with others derived from completely independent approaches (table 4).

The impact of human interference has been profound. The estimate of the component of accelerated denudation amounts to 10.2×10^{15} g/yr or about 80% of the pre-human rate, whereas that of moderated denudation is 2.6×10^{15} g/yr or about 20% of the pre-human rate. With increased construction of dams and improved land stabilization techniques, it is likely that sediment discharge to the oceans will fall dramatically over the coming decades. Trapping sediment from the Amazon river alone will account for a further 6% drop in global sediment discharge.

Conclusions

The major conclusion of this study is that there is a general relationship between the sediment yield of major denudation regions and the history of weathering as recorded in the major element composition of suspended sediment. The denudation of areas that deviate substantially from this relationship primarily can be understood in terms of natural and anthropogenic processes that accelerate or moderate erosion rates and provenance from easily eroded glacial debris that has not experienced a normal weathering history. Estimates of pre-human sediment yields are nearly a factor of two lower than currently measured yields.

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