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Natural controls of fluvial denudation rates in major world drainage basins

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Abstract. We present a new compilation of estimates of modern rates of mechanical and chemical denudation for externally drained basins exceeding 5 x 10^5 km^2 in area. These estimates are based on sediment and solute load data selected in order to represent natural rates as far as possible. Chemical denudation rates have been calculated by deducting the nondenudational component of solute load. Mechanical denudation rates range from 1 mm kyr^{-1} for the St. Lawrence and Dnepr basins to 670 mm kyr^{-1} for the Brahmaputra basin. Chemical denudation rates vary from 1 mm kyr^{-1} (Kolyma, Niger, Nile and Rio Grande basins) to 27 mm kyr^{-1} (Chiang Jiang basin). The Kolyma basin has the lowest (4 mm kyr^{-1}), and the Brahmaputra basin the highest, overall rate of denudation (688 mm kyr^{-1}). Relationships between denudation rates and a range of morphometric, hydrologic, and climatic variables are investigated through correlation and regression analysis. Morphometric variables, such as mean local relief, are accurately calculated for large basins for the first time by using the National Geophysical Data Center 10-minute topographic database. Variables expressing basin relief characteristics and runoff are found to be most strongly associated with both mechanical and chemical denudation rates, with more than 60% of the variance in total denudation being accounted for by basin relief ratio and runoff. Basin area, runoff variability, and mean temperature, however, are only weakly associated with rates of denudation. Although direct comparisons cannot be made, it appears that rates of basin denudation derived from present-day mass flux estimates are not, overall, significantly different from estimates of long-term rates based on sediment volume and thermochronologic data. It therefore appears that the key factors identified as controlling denudation rates here are also applicable to the geological time spans relevant to the interaction between tectonic and denudational processes.

Introduction

A knowledge of rates of denudation and an understanding of the factors that control them are important for a number of reasons. Quantitative models of landscape evolution [*Ahnert*, 1987] depend on estimates of the rates at which landscape change occurs, while those interested in the interaction between tectonic and subaerial processes, both in orogenic [*Molnar and England*, 1990; *Beaumont* et al., 1992] and cratonic [*Gilchrist and Summerfield*, 1990; *Bishop and Brown*, 1992] terrains need to apply realistic denudation rates in the calibration of their models. Estimates of long-term denudation rates are a vital component of both geochemical [*Berner*, 1991] and sediment [*Leeder*, 1991] mass balance studies, while the importance of understanding the factors that control spatial and temporal variations in sediment supply to sedimentary basins is now becoming more widely appreciated [*Cross*, 1990; *Sinclair and Allen*, 1992]. Recently, the suggestion that the creation of topography associated with orogenesis can significantly affect rates of chemical denudation and thereby perturb the global carbon budget and consequently global climate [*Raymo et al.*, 1988; *Raymo and Ruddiman*, 1992] has further reinforced the need for a clear understanding of the factors controlling denudation rates.

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Although a range of approaches, most notably thermochronology and calculations of offshore sediment volumes, can provide estimates of long-term denudation rates, only data on present-day rates derived from sediment and solute discharges of rivers generally provide the most viable basis for linking variations in denudation rates to specific controlling variables. A number of studies using this approach have focused on the role of climate, or vegetation as mediated by climate, as the key variable determining rates of denudation [*Langbein and Schumm*, 1958; *Fournier*, 1960; *Corbel*, 1964; *Douglas*, 1967; *Wilson*, 1973; *Jansen and Painter*, 1974; *Jansson*, 1982, 1988; *Ohmori*, 1983]. Although some of these analyses also considered topographic controls on denudation rates, the role of elevation and relief has been emphasized in relatively few studies [*Ahnert*, 1970; *Pinet and Souriau*, 1988; *Einsele*, 1992; *Milliman and Syvitski*, 1992].

The aim here is to present a new compilation of estimates of rates of denudation for the world's major drainage basins and to provide an initial assessment of the main controls of denudation rates at the regional to subcontinental scale relevant to the geological time spans appropriate for modeling the interactions between tectonic and denudational processes. In order to produce estimates of denudation rates which are more appropriate to modeling over geological timescales we have attempted to exclude, as far as possible, anthropogenic effects through careful assessment of the available sediment and solute discharge data. In doing this we are aiming to provide estimates of "natural" rates of denudation and to assess the major "natural" controls that determine them. All externally drained basins with an area of more than 5 x 10^5 km^2 are included, although comprehensive data are not available for all of these (Figure 1). Together these 33 basins cover an area of 5.28 x 10^7 km^2, representing over 35% of the Earth's land area. Three internal basins above the area threshold (the Okavango, the Volga, and the Chari) have been excluded from the analysis as they do not contribute to an overall reduction of continental elevation. Our reason for focusing on the very largest basins is that we are interested at this stage in establishing first-order effects rather than examining small-scale controls on denudation rates.

The main constraints on our analysis are the quality of available sediment and solute load data, the extent to which appropriate allowances can be made for anthropogenic impacts, and the accuracy with which likely controlling variables can be characterized. In order to minimize these potential limitations, sediment and solute load data have been carefully selected so as to represent, as far as possible, conditions prior to major human modification of the basins concerned. We have also been careful in our estimation of chemical denudation rates to make an adjustment for the nondenudational component of solute load introduced by atmospheric inputs. The data set we present is our best estimate, within the limitations of the available data, of natural rates of mechanical and chemical denudation under prevailing basin conditions of topography, climate, vegetation, and lithology. This data set in turn provides the basis for our exploratory analysis of the main factors determining worldwide variations in denudation rates for very large basins.

In addition to our new estimates of natural denudation rates for major drainage basins, another novel component of this analysis is our use of National Geophysical Data Center (NGDC) 10-minute digital topographic data (see *Cuming and Hawkins* [1980] for full documentation of this database) to calculate accurately for the first time a range of morphometric variables for these basins. In particular, we produce the first calculations of mean local relief for large drainage basins.

Data Sources and Quality

Potential Controlling Variables

Data are presented for 11 potential controlling variables for which measurement is possible at the interval or ratio scale (Tables 1 and 2). (Full documentation of data sources is available on request from the authors.) Variable selection was aimed at including those factors thought most likely to play an important role in controlling denudation rates and for which data of adequate quality are available. In order to use the NGDC digital topographic database for the calculation of morphometric variables, all basin perimeters were digitized. Where the location of basin perimeters is unambiguous our basin area estimates are within 5% of those given in existing published sources. Mean local relief for large basins has previously been estimated from

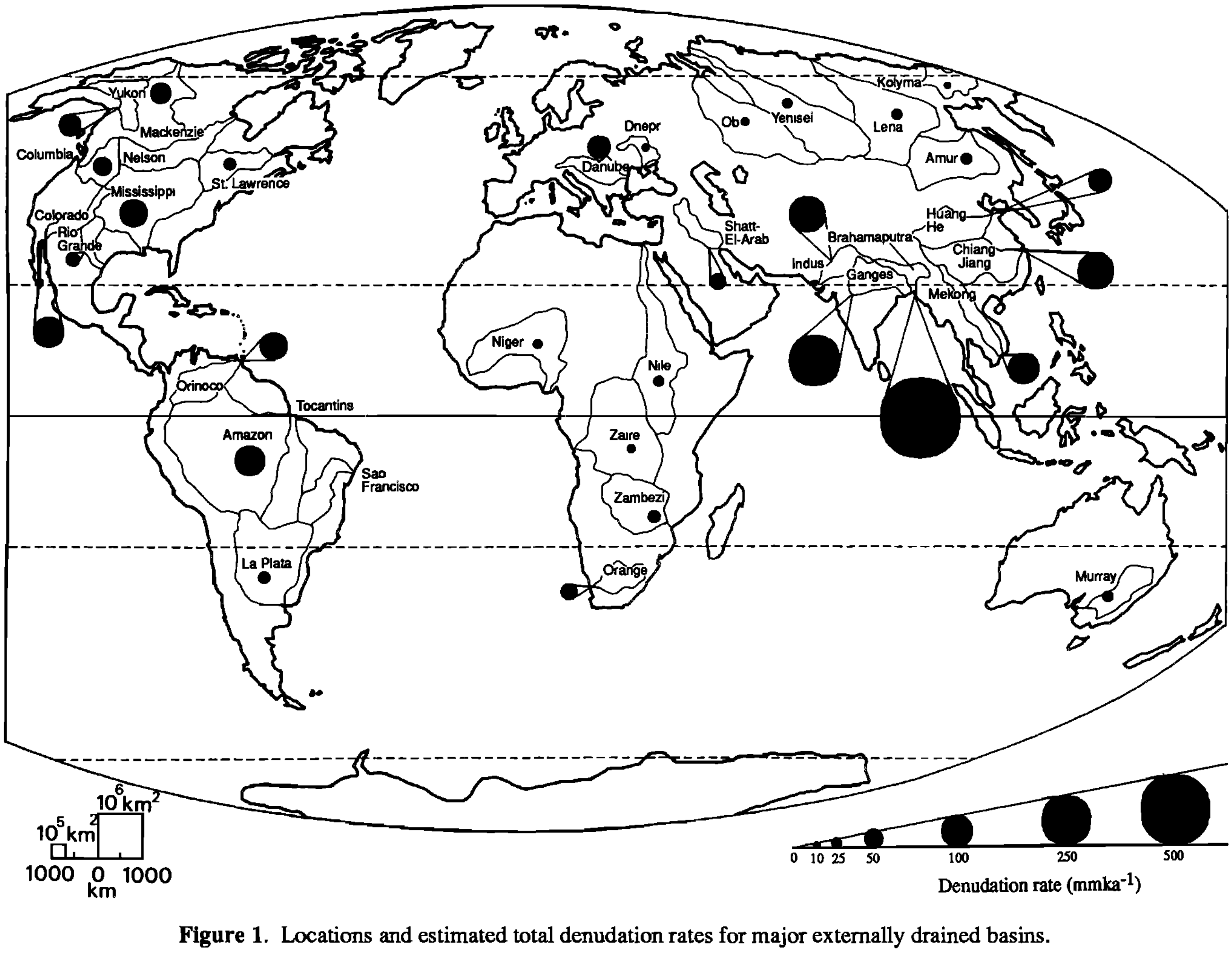

Figure 1. Locations and estimated total denudation rates for major externally drained basins.

Table 1. Definition and Calculation of Potential Controlling Variables

Variable	Definition/Comments
	Morphometric Variables
Basin area	Calculated from digitized basin perimeters estimated from drainage lines and interfluve contour forms.
Mean trunk channel gradient	Calculated from elevation of source of longest channel and channel lengths estimated from *Times Atlas* [1968] (Brahmaputra, Ganges, Tocantins) and *UNESCO* [1978] (all other basins).
Basin relief	Defined as maximum-minimum basin elevation; derived from maximum modal elevation values from 10-minute topographic database
Relief ratio	Defined as basin relief/basin length; basin length defined as straight-line distance from basin mouth to most distant point on basin perimeter.
Mean modal elevation	Defined as mean of modal elevation of each 10-minute grid cell with area weighting in proportion to variation with latitude.
Mean local relief	Defined as mean of maximum-minimum elevation within each 10-minute grid cell.
Hypsometric integral	Calculated from modal elevation values from 10-minute topographic database.
	Hydrologic Variables
Mean annual runoff	Derived from basin area as defined above and discharge data from following sources: Brahmaputra, Dnepr, Ganges, Nelson, Nile, Orange, Rio Grande, and Tocantins [*Meybeck* 1976]; Colorado [*Meade and Parker*, 1985]; Mississippi [*Coleman*, 1988]; Orinoco [*Paolini et al.*, 1987]; Zaire [*Probst and Tardy*, 1987]; all other basins [*Milliman and Meade*, 1983].
Runoff variability	Defined as percentage of total mean annual runoff represented by the three months of maximum runoff; calculated from following sources: Amazon, Columbia, Danube, Dnepr, Kolyma, Mackenzie, Mississippi, Murray, Nelson, Orinoco, La Plata (Parana), Rio Grande, St. Lawrence, São Francisco, Shatt-el-Arab (for Tigris at Baghdad), Tocantins and Yukon [*Korzoun et al.*, 1977]; Zaire [*Nkounkou and Probst*, 1987]; all other basins [*UNESCO*, 1978].
	Climatic Variables
Mean annual temperature	Sources: Dnepr, Nelson, Rio Grande and Tocantins [*USSR Academy of Sciences*, 1964]; all other basins [*Pinet and Souriau*, 1988].
Mean annual precipitation	Sources: as for mean annual temperature.

sample areas using topographic maps [*Ahnert*, 1970]. Although this method poses difficulties when large areas or numerous basins are considered [*Milliman and Syvitski*, 1992], mean local relief can be readily derived from the maximum and minimum elevation values contained in the 10-minute resolution NGDC database. The only limitation of this approach is that the use of 10-minute grid units, as opposed to the equidimensional cells used by *Ahnert* [1970], results in some variation in cell dimensions with latitude. This ranges from 18.5 x 18.5 km in the tropics to 16 x 18.5 km at latitude 30° and 9.3 x 18.5 km at latitude 60°. Nevertheless, these grid dimensions are still comparable to the 20 x 20 km cells used by *Ahnert* [1970].

The quality of the hydrologic data is highly variable, and the extent to which recent discharge records are representative of longer term averages is, of course, uncertain. Discharges prior to dam closure and abstraction for irrigation have been used rather than recent data for anthropogenically modified basins. Uncertainty also pertains to the climatic variables which have an additional possible error associated with the estimate of a mean value for temperature and precipitation over very extensive areas. Although the reliability of the hydrologic and climatic data is, therefore, not high we regard it as acceptable for a study attempting to identify first-order effects.

Denudation Variables

Estimates of denudation rates have been derived from solid and solute load data (Table 3). Where available data are for suspended load only, it has been assumed that bed load contributes an additional 10% to total solid load, an estimate compatible with those of *Milliman and Meade* [1983] and *Walling and Webb* [1987]. Sediment load data have been selected so as to represent, as far as possible, conditions unperturbed by anthropogenic impacts. Where applicable, predam closure sediment discharge estimates have been used rather than simple longterm means. In the case of the Huang He an estimate of "natural" sediment discharge has been made on the basis of calculations by *Milliman et al.* [1987] of the volume of Holocene sediment deposited by the river. This is an order of magnitude less than the present value (1080 Mt yr^{-1} [*Milliman and Meade*, 1983]) which is inflated through the effects of intensive agricultural activity, dating back to around 2300 years ago, on the loess plateau within the basin.

Estimates of mean annual solute load (Table 3) have been derived mainly from the concentrations of total dissolved solids (TDS) given by *Meybeck* [1979] using the mean discharge data employed in this study, although more recent solute load data have been used where available. Meybeck's data exclude, at least

Table 2. Morphometric, Hydrologic, and Climatic Data

Basin	Area, 10^6 km^2	Mean Trunk Channel Gradient, m km^{-1}	Basin Relief, m	Relief Ratio	Mean Modal Elevation, m	Mean Local Relief, m	Hypsometric Integral, %	Mean Annual Runoff, mm	Runoff Variability, %	Mean Annual Temperature, °C	Mean Annual Precipitation, mm
Amazon	5.98	0.78	5486	0.00178	426	215	7	1211	43	26	2030
Amur	2.04	0.67	2133	0.00090	571	249	24	159	51	-1	380
Brahmaputra	0.64	2.18	6705	0.00554	2734	992	42	951	52	15	2030
Chiang Jiang	1.73	0.89	6400	0.00228	1688	667	28	520	42	15	1270
Colorado	0.70	1.65	3749	0.00266	1652	520	44	32	49	15	250
Columbia	0.67	1.69	2987	0.00264	1329	832	45	377	66	10	640
Danube	0.79	0.38	3048	0.00181	501	303	15	259	33	10	760
Dnepr	0.54	0.27	304	0.00039	152	30	39	99	72	7	660
Ganges	0.98	2.39	7010	0.00449	890	438	13	373	70	21	2030
Huang He	0.79	1.13	5486	0.00213	1885	461	34	64	49	13	760
Indus	0.93	1.64	7833	0.00475	1855	785	23	254	68	24	380
Kolyma	0.65	1.17	1828	0.00156	564	306	29	112	81	-10	130
La Plata (Parana)	2.86	0.23	5486	0.00247	562	211	10	164	30	21	1140
Lena	2.45	0.25	2529	0.00122	602	294	22	210	72	-10	250
Mackenzie	1.77	0.42	2743	0.00139	634	272	23	173	38	-4	380
Mekong	0.76	1.11	6096	0.00218	1062	563	17	618	61	21	1270
Mississippi	3.20	0.45	3688	0.00127	656	173	17	152	38	13	760
Murray	1.14	0.26	1524	0.00099	266	109	16	19	44	18	760
Nelson	1.24	1.04	2895	0.00190	544	99	19	89	31	-1	400
Niger	2.16	0.22	2133	0.00101	429	143	20	89	42	29	1140
Nile	3.63	0.28	3779	0.00097	662	205	21	24	63	26	510
Ob	2.98	0.84	3657	0.00159	301	115	7	129	56	-1	380
Orange	0.89	1.77	3048	0.00222	1241	190	41	103	53	15	380
Orinoco	0.92	1.50	4572	0.00299	456	347	10	1244	44	24	1400
Rio Grande	0.63	1.25	4175	0.00253	1279	413	31	5	57	14	400
São Francisco	0.62	0.39	1371	0.00097	609	191	45	158	41	24	1020
Shatt-El-Arab	0.89	1.12	2956	0.00202	669	281	22	53	54	21	250
St. Lawrence	1.05	0.15	1066	0.00065	265	132	25	426	27	5	890
Tocantins	0.76	0.40	1127	0.00062	390	134	33	456	68	24	1700
Yenisei	2.55	0.49	3352	0.00127	749	330	21	220	63	-6	380
Yukon	0.84	0.60	4267	0.00262	741	504	18	233	59	-4	380
Zaire	3.63	0.37	2712	0.00117	740	166	26	357	36	24	1520
Zambezi	1.41	0.41	2438	0.00116	1033	232	42	159	51	21	1020

Table 3. Solid Load, Solute Load and Denudation Rate Data

Basin	Mean Annual Solid Load Mt yr^{-1}	Mean Annual Specifc Load t km^{-2}yr^{-1}	Mechanical Denudation Rate mm kyr^{-1}	Mean Annual Solute Load Mt yr^{-1}	Mean Annual Denudational Solute Load Mt yr^{-1}	Mean Annual Specific Denudational Solute Load t km^{-2} yr^{-1}	Chemical Denudation Rate mm kyr^{-1}	Total Denudation Rate mm kyr^{-1}	Chemical Denudation as Proportion of Total %
Amazon	1320(1)	221	82	275(17)	171	29	11	93	11.6
Amur	57(2)	28	10	22(6)	12	6	2	12	17.6
Brahmaputra	1157(3)	1808	670	51(18)	31	49	18	688	2.6
Chiang Jiang	468(4)	281	104	226(19)	124	72	27	131	20.4
Colorado	167(5)	239	89	16(20)	13	19	7	96	7.4
Columbia	32(6)	48	18	33(20)	21	32	12	30	40.0
Danube	74(7)	94	35	63(20)	35	45	17	52	32.4
Dnepr	1(6)	2	1	11(6)	7	12	4	5	85.7
Ganges	680(3)	694	257	75(21)	41	42	16	273	5.7
Huang He	100(3)	127	47	22(20)	14	18	7	54	12.4
Indus	300(3)	323	120	62(6)	38	42	16	136	11.5
Kolyma	6(9)	9	3	4(22)	2	4	1	4	30.8
La Plata (Parana)	87(10)	30	11	38(10)	25	9	3	14	23.1
Lena	17(9)	7	3	88(6)	55	22	8	11	75.9
Mackenzie	110(3)	62	23	65(20)	40	23	9	32	27.1
Mekong	176(3)	232	86	47(20)	27	36	13	99	13.4
Mississippi	605(11)	189	70	105(20)	64	20	7	77	9.6
Murray	33(2)	30	11	8(20)	6	6	2	13	9.7
Nelson	-	-	-	31(6)	20	16	6	-	-
Niger	40(3)	19	7	13(20)	8	4	1	8	17.4
Nile	100(3)	28	10	20(20)	11	3	1	11	9.7
Ob	18(9)	6	2	50(6)	31	11	4	6	64.7
Orange	58(12)	65	24	17(20)	10	11	4	28	14.5
Orinico	165(13)	179	66	29(23)	21	23	9	75	11.4
Rio Grande	30(11)	48	18	3(24)	2	4	1	19	7.7
São Francisco	7(14)	11	4	-	-	-	-	-	-
Shatt-El-Arab	50(3)	56	21	19(20)	13	14	5	26	20.0
St Lawrence	2(11	2	1	60(20)	35	34	13	14	94.4
Tocantins	-	-	-	-	-	-	-	-	-
Yenisei	14(9)	5	2	73(6)	45	18	7	9	78.3
Yukon	79(15)	94	35	34(20)	19	23	9	44	19.7
Zaire	51(16)	14	5	37(16)	23	6	2	7	30.0
Zambezi	48(3)	34	13	13(20)	9	6	2	15	15.0

Sources: 1, *Meade et al.* [1985]; 2, *Jansen et al.*(1979]; 3, derived from *Milliman and Meade* [1983]; 4, *Wang et al* .[1986]; 5, derived from *Meade and Parker* [1985]; 6, *Meybeck* [1976]; 7, *Milliman and Meade* [1983]; 8, *Milliman et al* .[1987]; 9, *Lisitzin* [1972]; 10, *Depetris and Cascante* [1987]; 11, *Meade and Parker* [1985]; 12, derived from *Rooseboom and Harmse* [1979]; 13, *Meade et al.* **[1994]**; 14, *Milliman* [1975]; 15, *Brunskill et al.* [1975] cited by *Meybeck* [1976]; 16, *Nkounkou and Probst* [1987]; 17, Stallard [1980] cited by *Berner and Berner* [1987]; 18, *Sarin and Krishnaswami* [1984]; 19, Hu *et al.* [1982]; 20, *Meybeck* [1979]; 21, Mean of estimates by *Abbas and Subramanian* [1984] and *Sarin and Krishnaswami* [1984]; 22, *Strakhov* [1967]; 23, *Paolini et al.* [1987]; 24, *Livingstone* [1963].

partially, the effects of pollution by not incorporating recent analyses from industrialized catchments. They do, however, include atmospheric and recycled components. Previous estimates of chemical denudation have generally been based directly on this raw data, but in order to assess correctly the contribution of dissolved load to denudation (as opposed to total solute transport) it is necessary to deduct these components. Detailed mass balance studies are not available for large drainage basins, so we have assumed, on the basis of the global mean estimates of *Berner and Berner* [1987], that 4.5% of TDS is contributed by precipitation and that 64% of HCO_3^- originates from atmospheric CO_2. Values for HCO_3^- and TDS have been derived from *Meybeck* [1979], except for the Amazon [*Berner and Berner*, 1987], *Chiang Jiang* [*Hu et al.*, 1982] and Rio Grande [*Livingstone*, 1963]. For basins for which no data on HCO_3^- are available we have estimated that bicarbonate constitutes 52% of (unpolluted) TDS (global mean value according to *Meybeck* [1979]). Where not directly available, TDS values have been calculated from dissolved load data. The denudational component for the Zaire Basin is a specific estimate by *Nkounkou and Probst* [1987].

Mean annual specific solid load and mean annual specific denudational dissolved load were derived for each basin using our digitized drainage areas. In all cases the lowest point in the basin for which solid and solute load data are available have been used, although this is not always at the basin outlet. However, the discrepancies between the upstream area from these measurement points and the digitized basin areas are small. Rates of mechanical, chemical, and total denudation were calculated assuming a mean rock density of 2700 kg m^{-3} (Table 3). It is important to note, however, that calculations of denudation rates from mass transport data involve assumptions about the density changes that occur during rock weathering prior to the removal of solid and dissolved material from a drainage basin [*Summerfield*, 1991a]. In using bedrock density as the volumetric conversion factor we are assuming a steady state regolith thickness.

Results and Analysis

The data for potential controlling variables generally show at least an order of magnitude variation (Table 2). For instance, maximum values for relief ratio and mean local relief attained by the Brahmaputra basin (0.00554 and 992 m, respectively) can be compared with the minimum values for the Dnepr basin (0.00039 and 30 m). Mean annual runoff is similarly variable, ranging from 5 mm for the Rio Grande to 1244 mm for the Orinico. The Brahmaputra basin has the highest rates of both mechanical (670 mm kyr^{-1}) and total denudation (688 mm kyr^{-1}) (Table 3 and Figure 1), although a recent sediment discharge estimate of 540 Mt yr^{-1} cited from unpublished data by *Milliman and Syvitski* [1992] indicates that our estimate may be too high. The Brahmaputra comes only second, however, in chemical denudation, being exceeded by the Chiang Jiang basin with a rate of 27 mm kyr^{-1}. The Dnepr and St. Lawrence basins have the lowest rates of mechanical denudation at 1mm kyr^{-1}, while four basins share the minimum chemical denudation rate of 1mm kyr^{-1} - the Kolyma, Niger, Nile and Rio Grande. The Kolyma also has the lowest rate of total denudation at 4 mm kyr^{-1}. As found in previous studies, the proportion of total denudation contributed by chemical denudation decreases as total denudation increases (Figure 2). This means that in basins experiencing very high total denudation rates chemical denudation is high in absolute terms, but low in relative terms. In basins with very low overall denudation rates, such as those of the major Siberian rivers, chemical denudation can account for more than 50% of the total (Table 3).

In order to explore the relationships both between denudational and potential controlling variables, and among the controlling variables themselves, scatter plots were produced for all variable pairings. In addition, Pearsonian correlation coefficients were calculated for all variable pairings for Y = mX + c, and for selected variable pairings for log Y = mX + c and log Y = mlog X + c. Partial and multiple correlation coefficients were

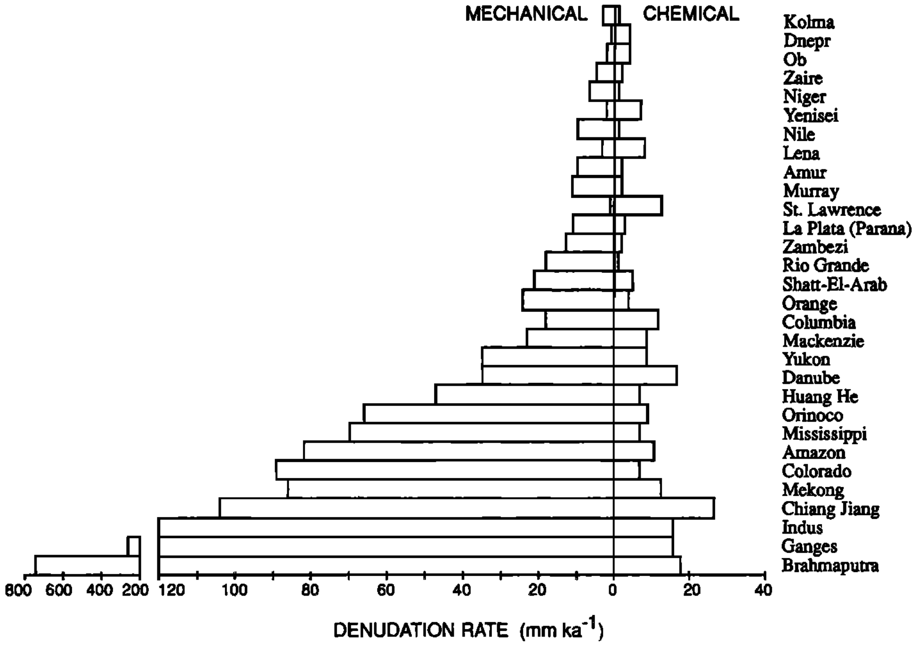

Figure 2. Histograms comparing mechanical and chemical denudation rates for major externally drained basins.

also calculated for selected variable pairings. Unlike in the recent analysis of *Milliman and Syvitski* [1992], all data points were included in the calculation of correlation coefficients and regression equations since using an arbitrary cutoff point in terms of standard deviation would have masked the real degree of scatter in the data.

For most variable pairings this degree of scatter was high, an unsurprising finding given the wide range of factors likely to control rates of mechanical and chemical denudation. However, an important additional reason for high data scatter is probably low data quality, since there is no reason to suspect that inaccuracies in the data would be systematically biased so as to enhance any correlations between controlling and denudation variables. On the contrary, data errors are likely to be approximately random, and therefore the true strength of statistical associations between controlling and denudation variables determined from the data presented here is likely to be underestimated. In other words, our interpretations of the strength of associations between controlling and denudational variables are inherently conservative.

The relatively low amount of variance accounted for among most of the pair-wise associations mean that a range of best fit regression relationships describe them about equally well. Nevertheless, close examination of the data indicates that associations between the potential controlling variables are best described in terms of linear relationships (Table 4), whereas associations between denudation rates and basin variables are more adequately described by the form log Y = mX + c (Table 5). Among the potential controlling variables there is a relatively high degree of correlation between those expressing various aspects of topography, that is, mean trunk channel gradient, basin relief, relief ratio, mean local relief, and mean modal elevation (Table 4). However, basin hypsometry, as represented by the hypsometric integral, is weakly correlated with the other basin variables except for basin area and mean modal elevation where there is a moderate degree of association. None of the climatic variables (including runoff and runoff variability) is strongly associated with the other basin variables.

Table 5 and Figure 3 illustrate the relatively strong correlation between the topographic variables, excepting basin hypsometry, and rates of both mechanical and total denudation. Of considerable interest is the fact that mean local relief appears to be no better as a predictor of denudation rate than basin relief ratio, in spite of the former providing a much more detailed representation of average basin relief and slope characteristics. Given that mean local relief is a time-consuming variable to quantify, this is a helpful finding for those requiring a simple but effective means of characterizing basin relief in modeling studies. However, this result may be scale-specific and does not necessarily mean that relief ratio provides an equally appropriate representation of basin relief characteristics for smaller basins than those considered here. Chemical denudation rates are more weakly associated with these topographic variables than mechanical denudation rates. Interestingly, given the findings of some other studies [*Milliman and Syvitski*, 1992], only an extremely weak negative correlation was found between basin area and denudation rates. In terms of the "climatic" variables only mean annual runoff and to a lesser extent mean annual precipitation are at all strongly associated with denudation rates (Figure 3). Runoff variability, at least as defined in this study, shows no association with denudation rates.

Table 4. Pearsonian Correlation Matrix for Morphometric, Hydrologic, and Climatic Variables

	Mean Trunk Channel Gradient	Basin Relief	Relief Ratio	Mean Modal Elevation	Mean Local Relief	Hypsometric Integral	Mean Annual Runoff	Runoff Variability	Mean Annual Temperature	Mean Annual Precipitation
Area	-0.38	0.11	-0.27	-0.30	-0.33	-0.51	0.21	-0.16	0.10	0.21
Mean trunk channel gradient		0.60	0.84	0.66	0.67	0.22	0.29	0.24	0.13	0.16
Basin relief			0.82	0.64	0.68	-0.27	0.40	0.02	0.29	0.35
Relief ratio				0.73	0.80	0.01	0.36	0.11	0.19	0.28
Mean modal elevation					0.85	0.49	0.14	0.05	0.16	0.12
Mean local relief						0.29	0.33	0.22	0.05	0.14
Hypsometric integral							-0.22	0.15	0.04	-0.12
Mean annual runoff								-0.01	0.26	0.71
Runoff variability									-0.24	-0.11
Mean annual temperature										0.58

Table 5. Pearsonian Correlation Matrix for Denudational Versus Morphometric, Hydrologic, and Climatic Variables

	Log. Mechanical Denudation Rate	Log. Chemical Denudation Rate	Log.Total Denudation Rate
Area	-0.11	-0.16	-0.18
Mean trunk channel gradient	0.67	0.36	0.66
Basin relief	0.80	0.51	0.79
Relief ratio	0.78	0.50	0.79
Mean modal elevation	0.66	0.36	0.66
Mean local relief	0.68	0.54	0.71
Hypsometric integral	-0.03	-0.06	0.03
Mean annual runoff	0.45	0.52	0.54
Runoff variability	-0.04	0.08	-0.05
Mean annual temperature	0.41	0.09	0.34
Mean annual precipitation	0.42	0.32	0.52

Interpretation and Discussion

Mechanical Denudation Rates

The importance of basin topography, and to a lesser extent runoff, in influencing rates of mechanical denudation is supported by the relatively strong statistical association between these variables. On the other hand, the very weak correlation between mechanical denudation rate and runoff variability does not support the importance of "storminess" in influencing denudation rates [*Molnar and England*, 1990] for the scale of basins considered here. The strong statistical association between relief and mechanical denudation rate may, itself, be partly a function of other factors related to relief, such as high levels of seismicity and the prevalence of fractured rock in high-relief orogenic terrains [*Milliman and Syvitski*, 1992].

The significant data scatter, even in the relationships between mechanical denudation rate and relief and runoff, could be due to a number of factors in addition to errors in specific sediment yield and water discharge estimates. One is the lack of any direct assessment of variations in erodibility, such as those associated with lithology, but for very large basins erodibility variations might be expected to average out and thus not play a major role in contolling basin-wide denudation rates. A second factor which is potentially more significant, especially for the very large basins considered here, is variable storage effects. In very large basins sediment may be "temporarily" stored in floodplains for thousands of years or more. Clearly, for such river systems, sediment sampling at the basin mouth, even over several decades, may provide an unrepresentative snapshot of the long-term mean sediment flux. Given these effects, it is perhaps surprising that the data do not, in fact, show an even greater degree of scatter.

The very weak negative correlation between mechanical denudation rate and basin area observed here contrasts with findings in a number of previous studies, most recently that of *Milliman and Syvitski* [1992]. This may be because only a relatively small size range of basins was considered, spanning only about one order of magnitude. However, basin area itself can have no causal link with denudation rates since area itself cannot be a determining factor. The association identified in previous studies, therefore, probably arises from the fact that basin area is negatively correlated with other potential causal variables, such as relief ratio and mean local relief (Table 4). This is a complex issue, however, as demonstrated by data from western Canada which shows that denudation rates are lowest in the smallest basins (<100 km^2) and highest in intermediate sized catchments (1000-100,000 km^2) [*Slaymaker*, 1987]. The largest basins (>100,000 km^2) were found to have intermediate denudation rates.

The idea that mechanical, and indeed total, denudation rates vary as a function of mean elevation would appear to be supported by the data presented here (Table 5). This association has been applied in a number of studies modeling interactions between tectonics and denudation [*Lambeck and Stephenson*, 1986; *Slingerland and Furlong*, 1989; *Pitman and Golovchenko*, 1991; *Lorenzo and Vera*, 1992] either through a misunderstanding of the studies by *Ahnert* [1970] and *Ruxton and McDougall* [1967] (which demonstrated a relationship with local relief rather than elevation), for mathematical convenience, or from an assumed causal link between elevation and denudation rate. But clearly, as with basin area, elevation itself cannot be a direct determinant of denudation rate. The flux of sediment at a specific location will be a function of the gradient at that point, irrespective of its elevation above mean sea level [*Summerfield*, 1991b].

The reason why mean basin elevation is strongly associated with denudation rate is that elevation is itself strongly correlated with other topographic factors which are causally related to specific sediment yield. This is evident from Table 4 where it can be seen that trunk channel gradient, relief, relief ratio, and mean local relief are all either moderately or strongly related to mean modal elevation. These relationships, however, must be examined with care. Although there is a clear relationship between mean modal elevation and mean local relief for basins as a whole (Figure 4), when intrabasin patterns are examined important differences emerge. For a number of basins, such as the Yukon, the intrabasin pattern replicates the interbasin association between elevation and local relief (Figure 5). But for basins such as the Ganges the data points cluster around a distinct curvilinear trend caused by a decline in local relief at high elevations (>3500 m). This kind of pattern is also found in other basins, such as the Indus, Brahmaputra, and La Plata

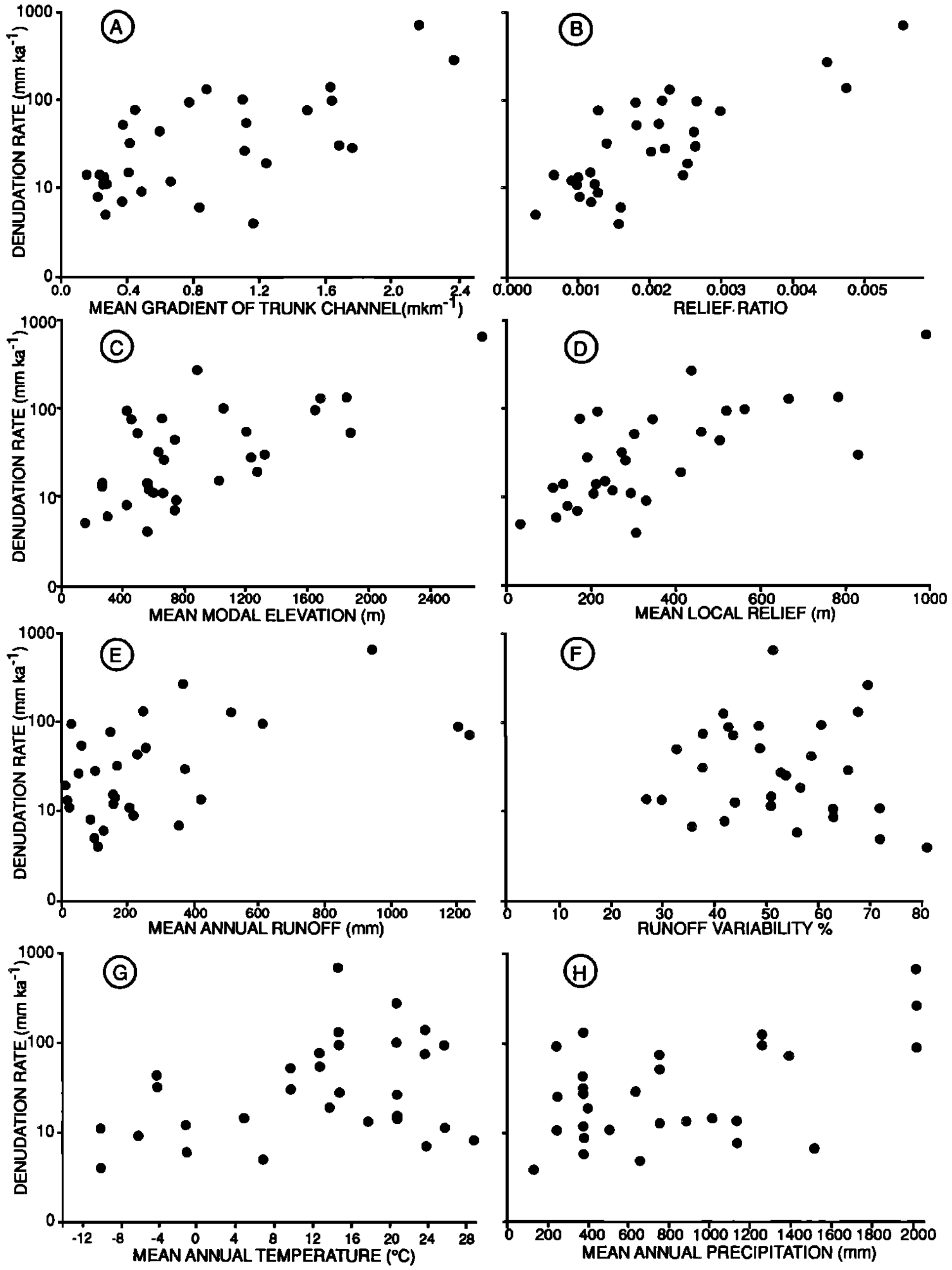

Figure 3. Scatter plots of total denudation rates versus various morphometric, hydrologic and climatic variables.

(Parana), which have part of their upper catchments in high mountain plateaus. Another kind of intrabasin pattern is characteristic of basins which drain to high elevation passive margins, such as the Orange and Zambezi. Here there is a clustering of very low local relief values at moderate elevations of around 1000 m. This pattern is also suggested by the high hypsometric integrals for these basins (Table 2). The significance of these contrasting relationships is that local relief is strongly correlated with local slope gradients [*Ahnert*, 1970], so such intrabasin variations in local relief are likely to be mirrored by contrasts in denudation rates [*Summerfield*, 1991b]. In basins where there is a very low correlation between elevation and local relief, such as the Orange and Zambezi (Figure 5), elevation may provide a very poor basis for predicting denudation rates.

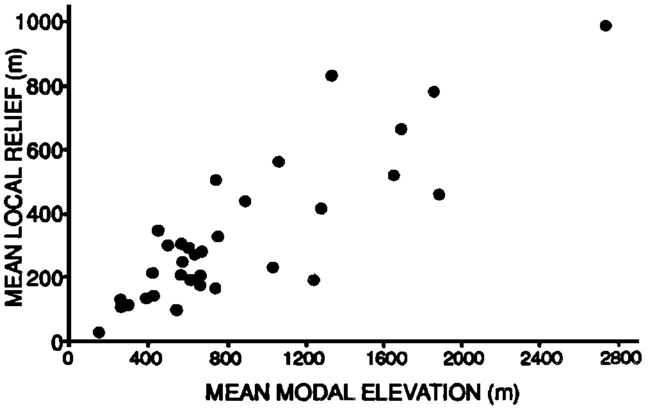

Figure 4. Scatter plot of mean modal elevation versus mean local relief.

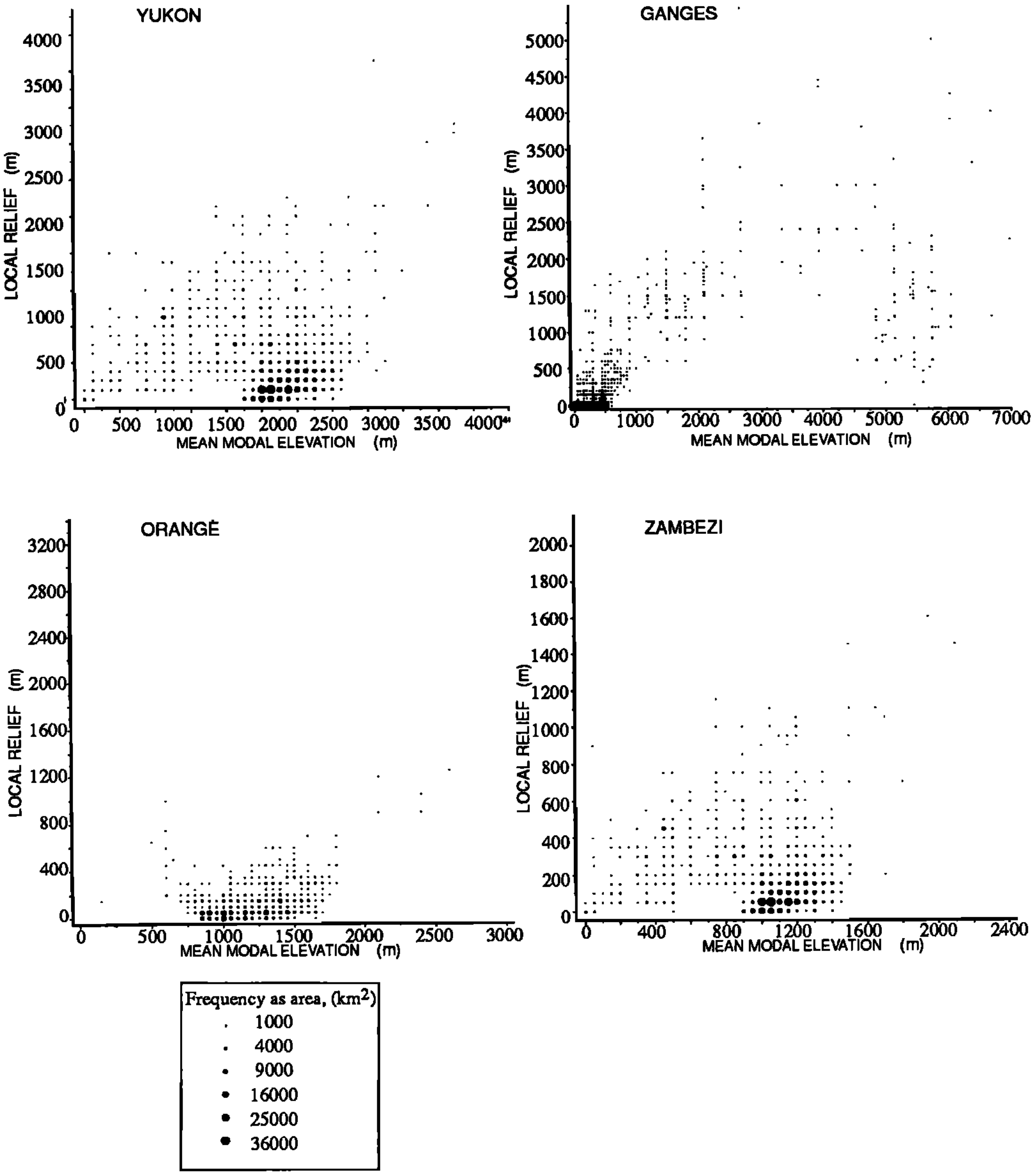

Figure 5. Scatter plot of intrabasin variations of local relief and area frequency mean modal elevation for the Yukon, Ganges, Orange, and Zambezi basins.

Chemical Denudation Rates

The statistical associations recorded in Table 5 support the conclusion that chemical denudation rates, like those for mechanical denudation, are more strongly influenced by relief factors than by climatic controls [*Summerfield*, 1991a; *Raymo and Ruddiman*, 1992]. In particular, at the scale of this study, temperature appears to play no role in controlling rates of chemical denudation. This supports the idea that the efficient removal of weathered regolith and the resulting continuous advection of bedrock into the weathering zone is the critical determinant of the rate of chemical weathering. In fact, our data suggest that chemical denudation rates are more clearly influenced by relief variables than (indirectly) by elevation. Thick weathering mantles developed in areas of minimal local relief are likely to be inimical to high rates of chemical denudation, irrespective of elevation. The correlation of chemical denudation rates with runoff suggests that maximum rates will occur where high runoff is coupled with high relief, a conclusion supported by the rates observed in basins draining orogenic belts.

A factor not considered in the correlation and regression analysis presented here is that of the lithologic control of chemical denudation rates. A detailed study of very small (median area 7.8 km²) unpolluted catchments of uniform lithology by *Meybeck* [1987] has demonstrated significant variations in chemical denudation rate as a function of rock type. It is probable that the otherwise anomolously high chemical denduation rate for the Chiang Jiang (Table 3) can be explained by the extensive outcrop of carbonate rocks within its catchment area. The potential role of lithology raises the question of the extent to which high rates of chemical denudation in orogenic belts are a function of the exposure of readily weathered sedimentary strata rather than relief itself [*Berner and Berner*, 1987, pp. 225-226; *Raymo and Ruddiman*, 1992].

Irrespective of the specific controls on chemical denudation rates it is clear that for basins with high overall denudation rates chemical denudation constitutes only a small proportion of the total (Figure 2 and Table 3). Both mechanical and chemical denudation rates are positively associated with relief variables, but the former is somewhat more sensitive to variations in topography. This is dramatically illustrated by comparing the Brahmaputra and Ob basins. Although chemical denudation accounts for only 2.6% of the total in the former basin, the absolute rate of 18 mm kyr^{-1} is the second highest in the basins considered here. Nearly 65% of the denudation in the Ob basin, however, is attributable to solute loss, but the absolute rate is less than a quarter of that of the Brahmaputra.

Interaction of Relief and Runoff

The individual role of two, at least partly, independent factors (relief and runoff) in influencing denudation rates raises the question as to how strongly their combined effect controls denudation rates. Taking relief ratio to characterize basin topography, the linear partial correlation coefficient for denudation rate and relief ratio keeping runoff constant is 0.732. This is only slightly lower than the correlation coefficient for relief ratio and denudation rate ($r = 0.757$) indicating that the latter relationship is not significantly inflated by the impact of interbasin differences in runoff. The joint effect of relief and runoff can be clearly seen through the linear multiple correlation coefficient for denudation rate against the relief ratio and runoff ($r = 0.792$). Thus these two variables alone account for over 62% of the variance in denudation rate. This is a remarkably high amount of explained variance given the low data quality and the fact that only erosivity variables are included.

Implications

The data presented above indicate the degree of variability of denudation rates for very large drainage basins and the major factors that appear to control such variations. A critical question, however, is to what extent these rates, and the interpretation of the factors that control them, can be extrapolated to the geological timescales relevant to the interaction of denudation and tectonics. A common view is that modern denudation rates have limited applicability to these long timescales because sediment yields since the beginning of farming are probably far in excess of preagriculture rates (see *Milliman and Syvitski* [1992] for discussion). Although this is undeniably true in specific instances, it is less certain that such a generalisation is valid at the global scale. Our reason for suggesting this is that present denudation rates for major basins are in some cases comparable to long-term rates estimated from sediment volume and thermochronologic data. For instance, preliminary calculations for the Orange basin from offshore sediment volumes indicate rates of denudation since the formation of the South Atlantic ranging from 7 to 114 mm kyr^{-1} (depending on assumptions made about changes in drainage area through time) [*Rust and Summerfield*, 1990]. These rates, which have varied both temporally and spatially, are compatible with estimates of post-rifting depths of denudation of up to 3-4 km from apatite fission track analysis [*Brown et al.*, 1990], but they are also comparable to the modern estimate of 28 mm kyr^{-1} for the Orange basin. The great extent of the basins considered in this study precludes direct comparisons with thermochronologic data which provide denudation estimates for limited areas. Nevertheless, available data certainly indicate denudation rates which are at least of the same order of magnitude as modern rates. For instance, thermochronologic data from the Alps and Himalayas indicate denudation rates ranging up to 1000mm kyr^{-1} and more over the past few million years [*Brown et al.*, 1994; *Clark and Jäger*, 1969; *Hurford*, 1991].

A more specific comparison can be made for the Ganges and Brahmaputra basins since the accumulation of sediment in the Himalayan molasse foredeep and alluvial plains, the subaerial part of the Ganges Delta and the Bengal Fan can be used to estimate catchment mechanical denudation rates over the past 20 m.y. Assuming no change in catchment boundaries, this indicates a mean combined denudation rate for these two basins of 435 mm kyr^{-1} from 20 to 7.7 Myr ago, and 300 mm kyr^{-1} from 7.7 Myr ago to the present [*Einsele*, 1992]. These figures compare with the present combined rate estimated here for the Brahmaputra and Ganges of 420 mm kyr^{-1}. The data of *Milliman and Syvitski* [1992] yield a similarly comparable figure of 242 mm kyr^{-1}.

If the gross variations demonstrated here at the regional to subcontinental scale between denudation rates in drainage basins of contrasting relief and runoff characteristics are accepted as broadly valid over geological timescales, then present-day denudation rates and the factors that appear to control them can be used as a basis for modeling interactions between tectonics and denudation. The careful application of such data should greatly improve the calibration of tectonic models incorporating the effects of subaerial processes, although the scale dependence of the factors controlling denudation must be considered.

Two main avenues of future research are indicated by the conclusions from this preliminary survey of the world's major drainage basins. One is the need for an application of the kinds of morphometric data presented here. In particular, it would be interesting to see to what extent variations in denudation rates in smaller basins could be "predicted" from a combination of basin morphometry and runoff data. The other potentially fruitful line of enquiry would be a more detailed comparison of modern denudation rates with estimates of long-term rates culled from thermochronologic and sediment volume data.

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