What controls erosion rates?

We saw last time that there are extremely significant world-wide variations in erosion rate

Summarized in Table 5.2 & Figure 5.1 (Berner & Berner)

Recall $100 \frac{\text{tons sed}}{\text{km}^2\ \text{yr}} = 0.04 \frac{\text{km}}{\text{Myr}}$ erosion rate

region	erosion rate $\dot{e}$ (km/Myr)
world-wide average	0.1
Arctic	0.003
New Zealand, etc.	1.2
Taiwan	5.5
S. Alps NZ	~ 9

(world-wide average through Taiwan: more than 3 orders of magnitude variation)

NAM 0.03 km/Myr lower 48 US states ~ same

WHY? What are the factors that control the rate of erosion

- climate (& vegetation)
- rock type
- relief

Let's discuss each of these in turn. Because they are all three important, it is not easy to isolate them.

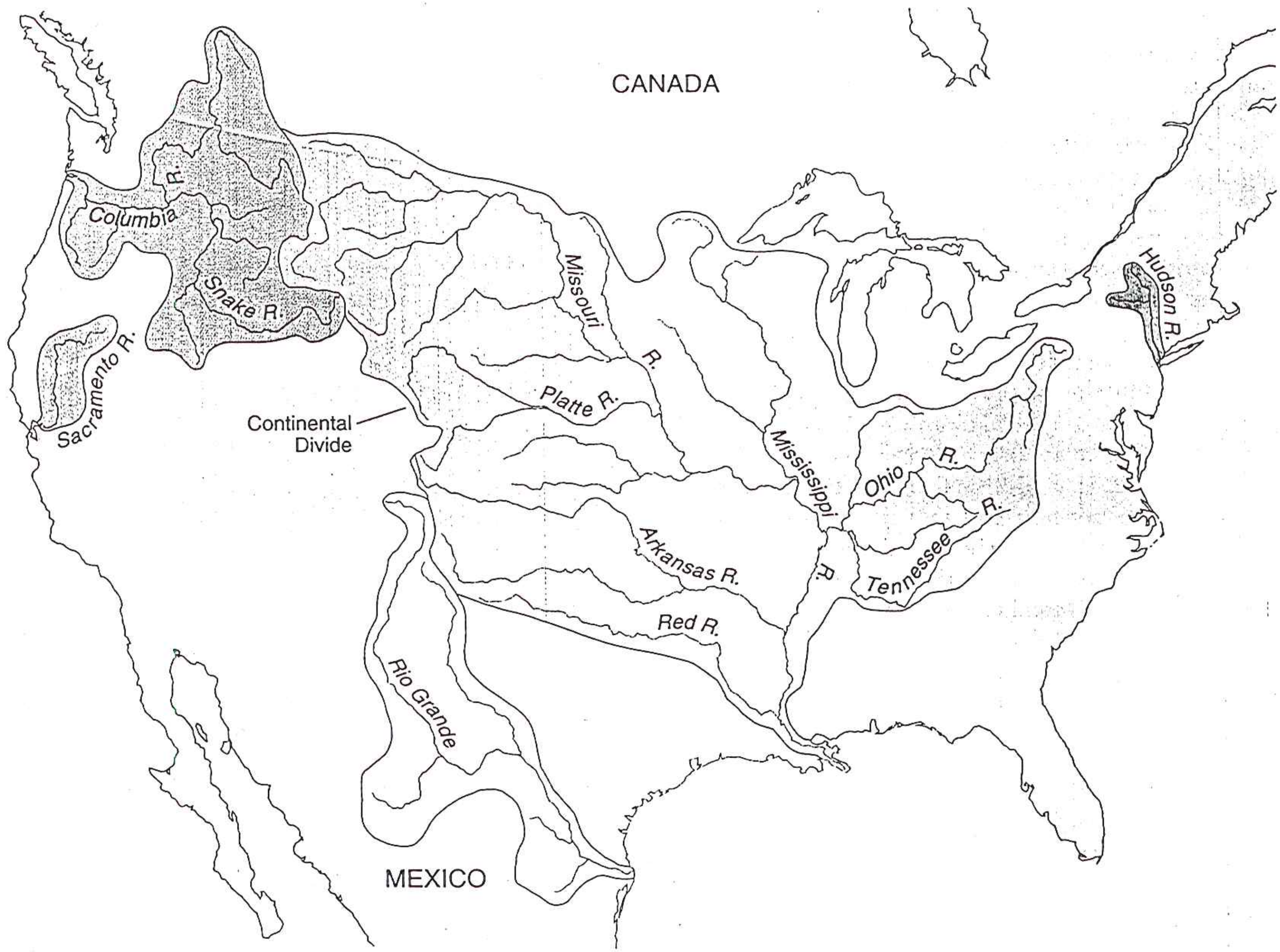


FIGURE 14.19 The stream's drainage basin is the area from which the stream and its tributaries receive water. Some well-known drainage basins in North America are shown here.

TABLE 5.2 Suspended Sediment Carried by Rivers to the Ocean (in Metric Tons)

Continent	Drainage Area Contributing Sediment to Ocean (10^6 km^2)	Sediment Discharge (10^6 tons/yr)	Sediment Yield (tons/km^2/yr)	Mean Continental Elevation (km)
North America	15.4	1020	66	0.72
Central America[a]	2.1	442	210	—
South America	17.9	1788	97	0.59
Europe	4.61	230	50	0.34
Eurasian Arctic	11.17	84	8	~0.2
Asia	16.88	6349	380	0.96
Africa	15.34	530	35	0.75
Australia	2.2	62	28	0.34
Pacific & Indian Ocean Islands[b]	3.0	9000[c]	3000[c]	~1.0
World total	88.6	20,000[d]	226[d]	

[a] Includes Mexico.

[b] Japan, Indonesia, Taiwan, Phillipines, New Guinea, and New Zealand (Oceania).

[c] From Milliman and Syvitski (1992).

[d] From Milliman and Syvitski (1992). Data reflect greater sediment discharge from South America, the Alps-Caucusus Mountains, and northwest Africa, in addition to Oceania.

Sources: After Milliman and Meade (1983) and Milliman and Syvitski (1992), elevations from Fairbridge (1968).

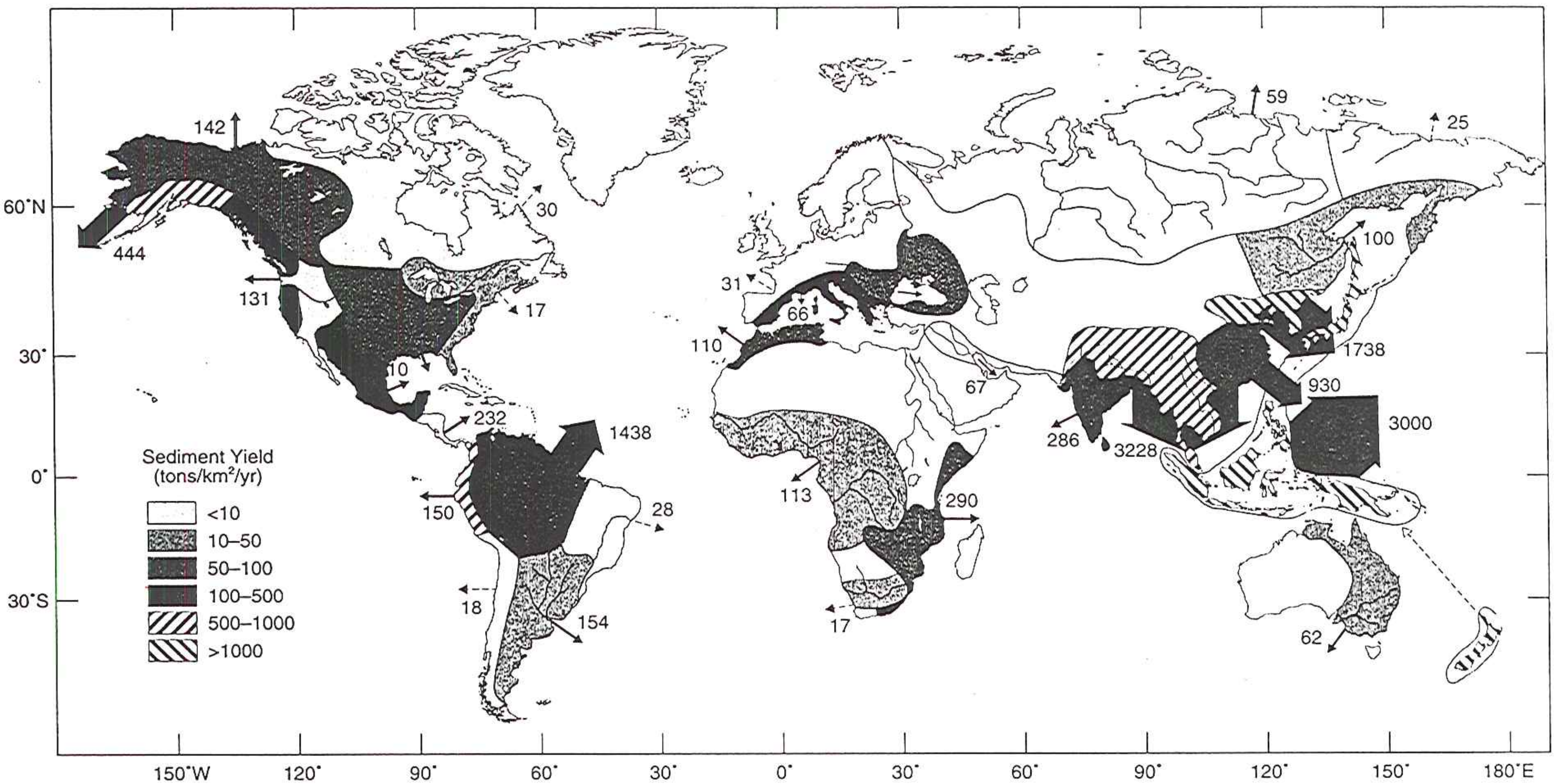


Figure 5.1. Discharge of suspended sediment from world drainage basins (in 10^6 tons/yr) as indicated by arrows. Sediment yield (tons/km^2/yr) for various drainage basins is also shown by appropriate pattern (see legend). Open pattern indicates essentially no sediment discharges to the oceans. [After J. D. Milliman and R. H. Meade. "World-Wide Delivery of River Sediment to the Oceans," *Journal of Geology* 91(1): 16. Copyright © 1983 by The University of Chicago Press, reprinted by permission of the publisher.]

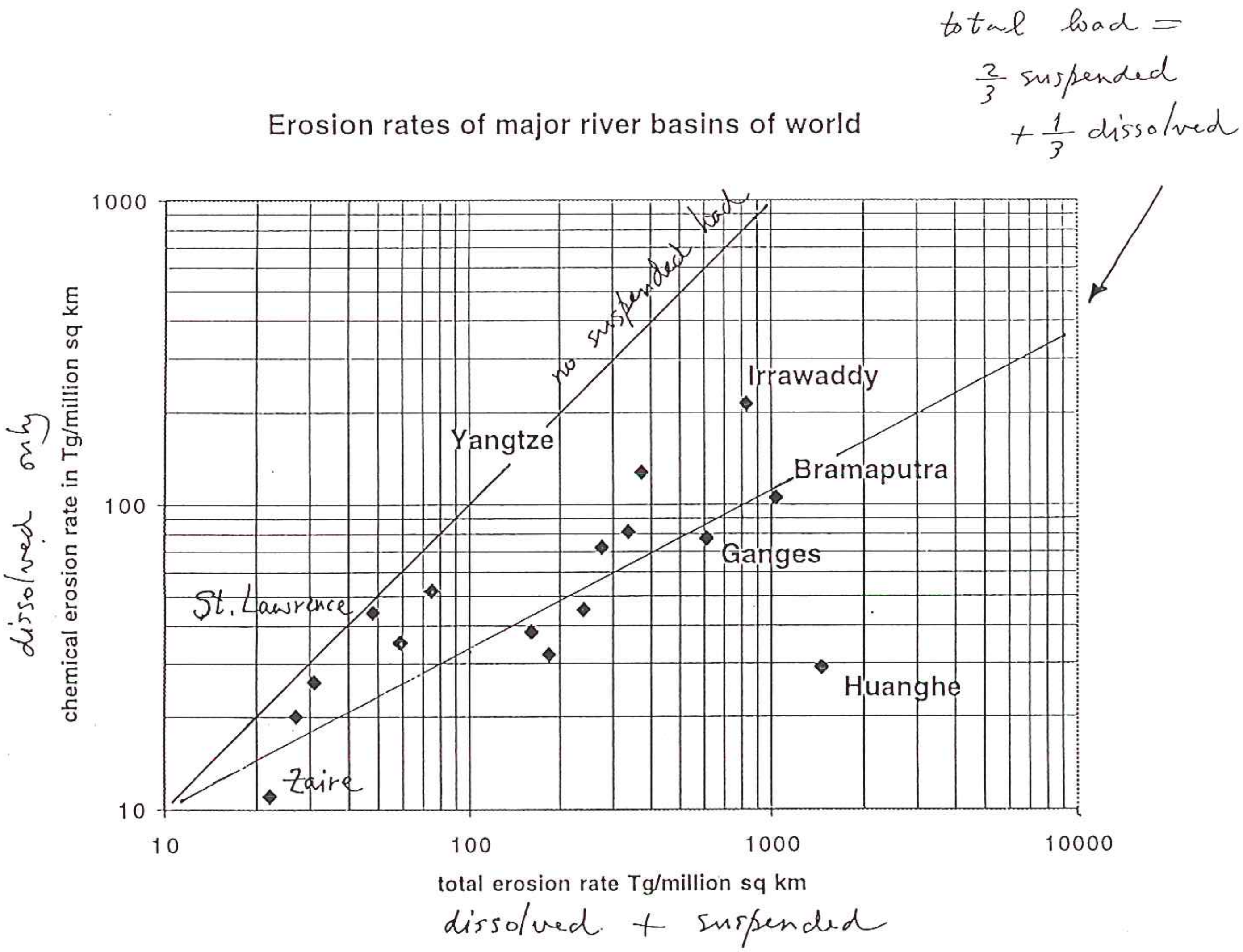
sediment yield $100 \frac{tons}{km^2\,yr} = 0.04 \frac{km}{Myr}$ erosion rate

TABLE 5.1 Major Rivers that Flow to the Sea, Listed in Order of Discharge

River	Location	Annual Discharge: Water (km^3/yr)	Annual Discharge: Dissolved Solids (Tg/yr)	Annual Discharge: Suspended Solids (Tg/yr)	Dissolved/ Suspended Ratio	Drainage Area (10^6 km^2)
1. Amazon	S. America	6300	275	1200	0.23	6.15
2. Zaire (Congo)	Africa	1250	41	43	0.95	3.82
3. Orinoco	S. America	1100	32	150	0.21	0.99
4. Yangtze (Chiang)	Asia (China)	900	247	478	0.53	1.94
5. Brahmaputra	Asia	603	61	540	0.11	0.58
6. Mississippi	N. America	580	125	210 (400)	0.60	3.27
7. Yenisei	Asia (Russia)	560	68	13	5.2	2.58
8. Lena	Asia (Russia)	525	49	18	2.7	2.49
9. Mekong	Asia (Vietnam)	470	57	160	0.36	0.79
10. Ganges	Asia	450	75	520	0.14	0.975
11. St. Lawrence	N. America	447	45	4	11.3	1.03
12. Parana	S. America	429	16	79	0.20	2.6
13. Irrawaddy	Asia (Burma)	428	92	265	0.35	0.43
15. Mackenzie	N. America	306	64	42	1.5	1.81
17. Columbia	N. America	251	35	10 (15)	3.5	0.67
20. Indus	Asia (India)	238	79	59 (250)	1.3	0.975
Red (Hungho)	Asia (Vietnam)	123	?	130	?	0.12
Huanghe (Yellow)	Asia (China)	59	22	1100	0.02	0.77

Note: Tributaries are excluded. Tg = 10^6 tons = 10^{12} g.

Sources: Water and suspended solids from Milliman and Meade (1983) and Milliman and Syvitski (1992). Dissolved solids calculated from Table 5.7 and Pinet and Souriau (1988) (for the Irrawaddy). Suspended load values in parentheses indicate pre-dam values.



- Climate
  - increased rainfall ⇒ increased overland runoff and ground water flow into streams
  - more important — increase in weathering rate (governed by percolation of rainwater down through leaf litter and soil horizons

    There is some erosion of rock, e.g., by Colorado River in Grand Canyon gorge, but most erosion is of soil. Hence, the soil formation rate is critical
  - climate also controls vegetation — rate of organic acid formation — strong control on erosion rate.

This main reason for large Arctic – tropical difference. Very little precipitation & slow-growing plants in Arctic

Low erosion rates < 10 ~~tons~~ tons/km^2/Myr

i.e., < 0.004 km/Myr erosion

Yensei, Lena (Russia), Mackenzie (Canada) rivers all low

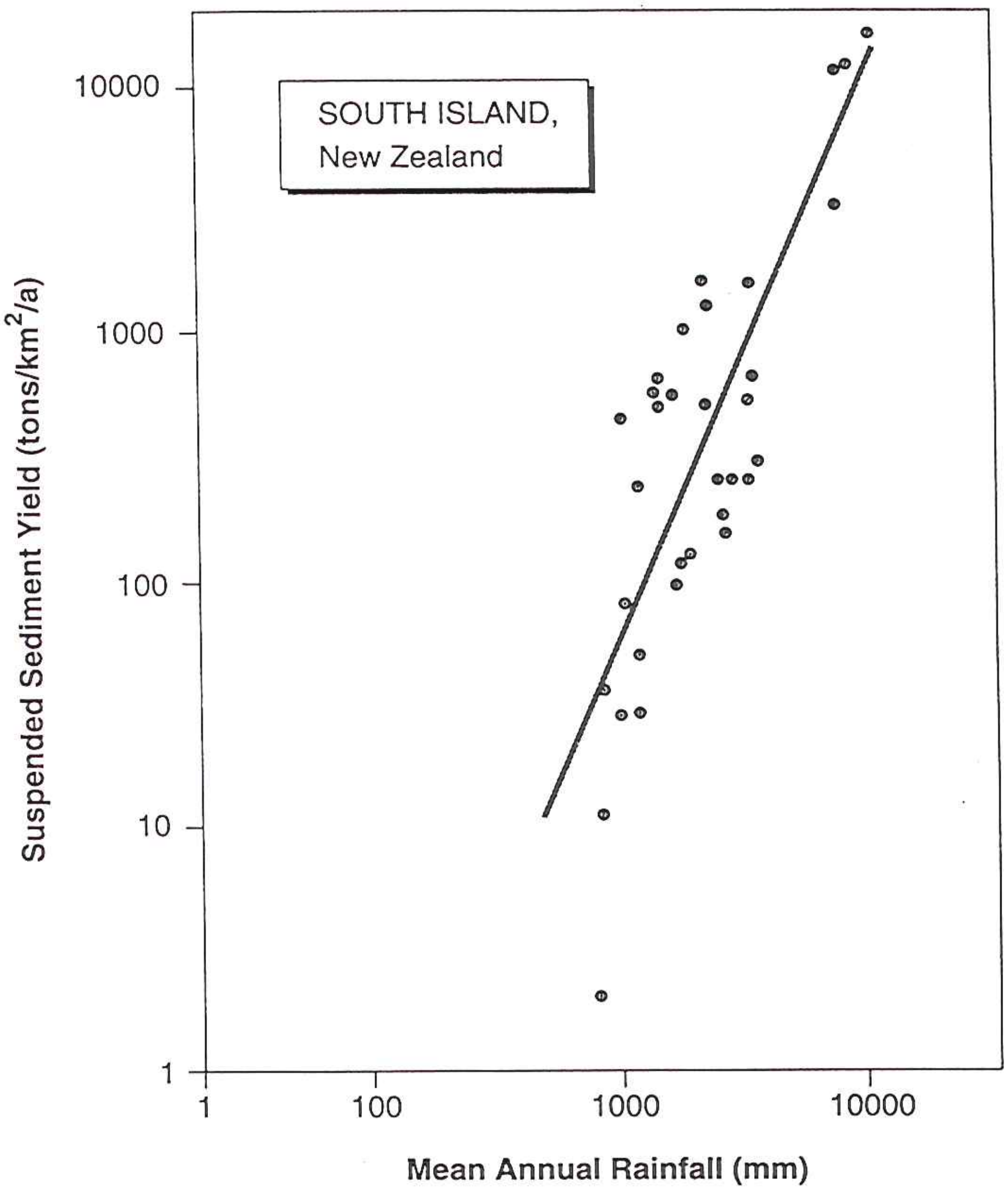


Figure 3-11
Log-log plot of suspended sediment yield versus mean annual precipitation for South Island of New Zealand. Suspended sediment yield is positively correlated with mean annual precipitation (from Walling and Webb, 1983).

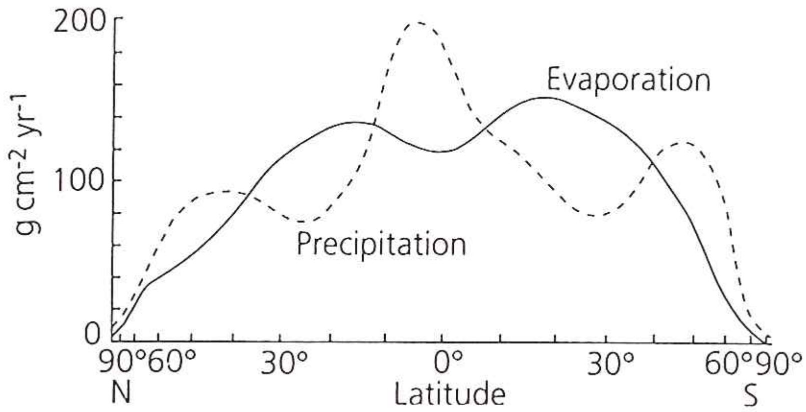


Fig. 1.19 Zonally averaged precipitation and evaporation as a function of latitude.

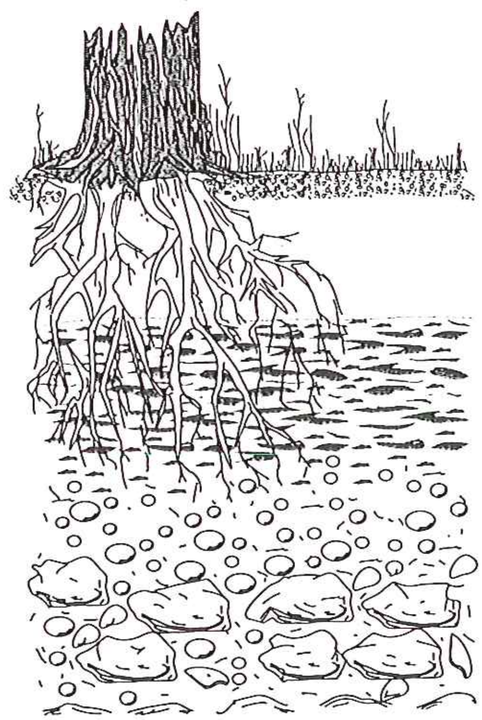


Figure 4.6. Soil horizons formed in a temperate humid climate (James I. Drever, *The Geochemistry of Natural Waters*, 2e, © 1992, p. 145. Reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey.)

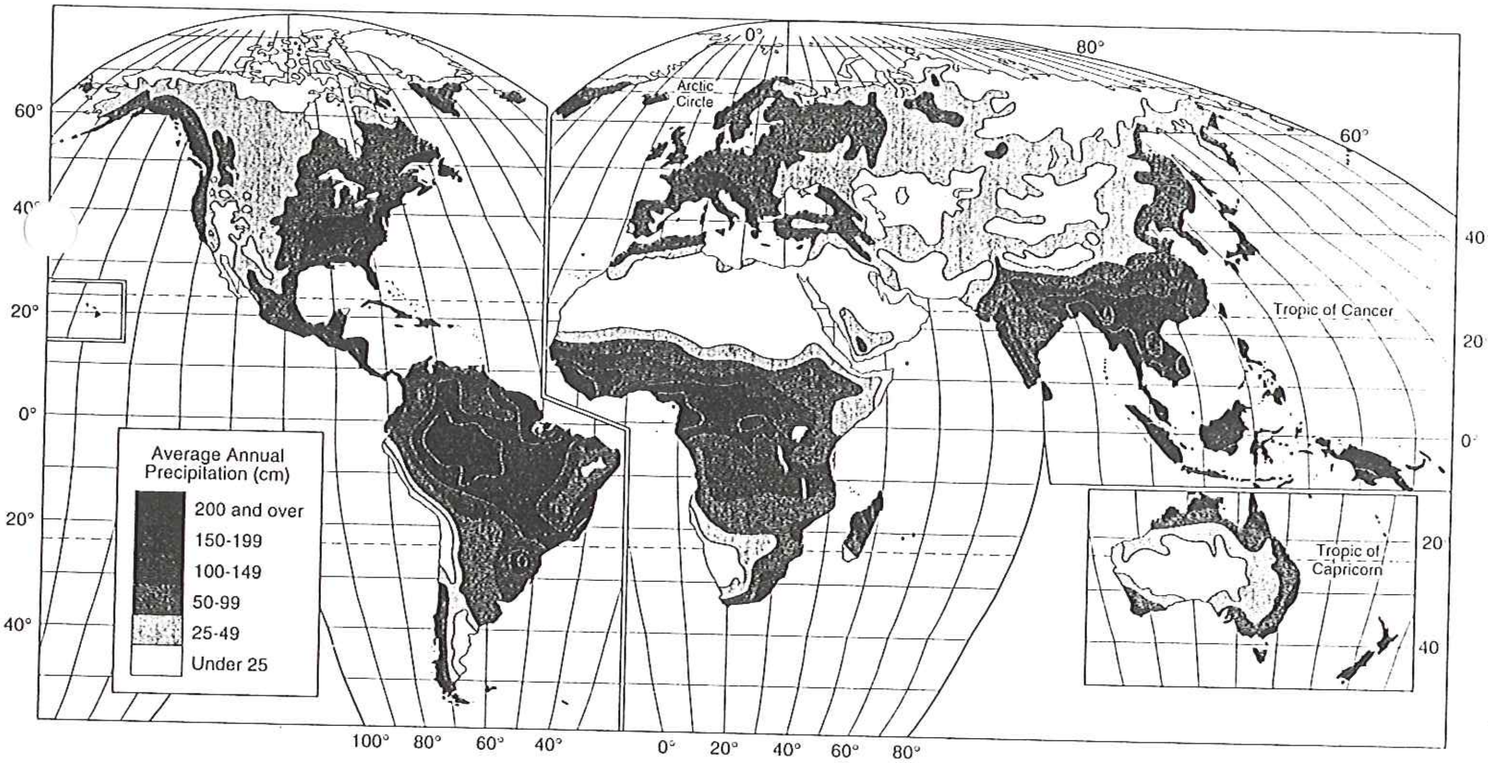
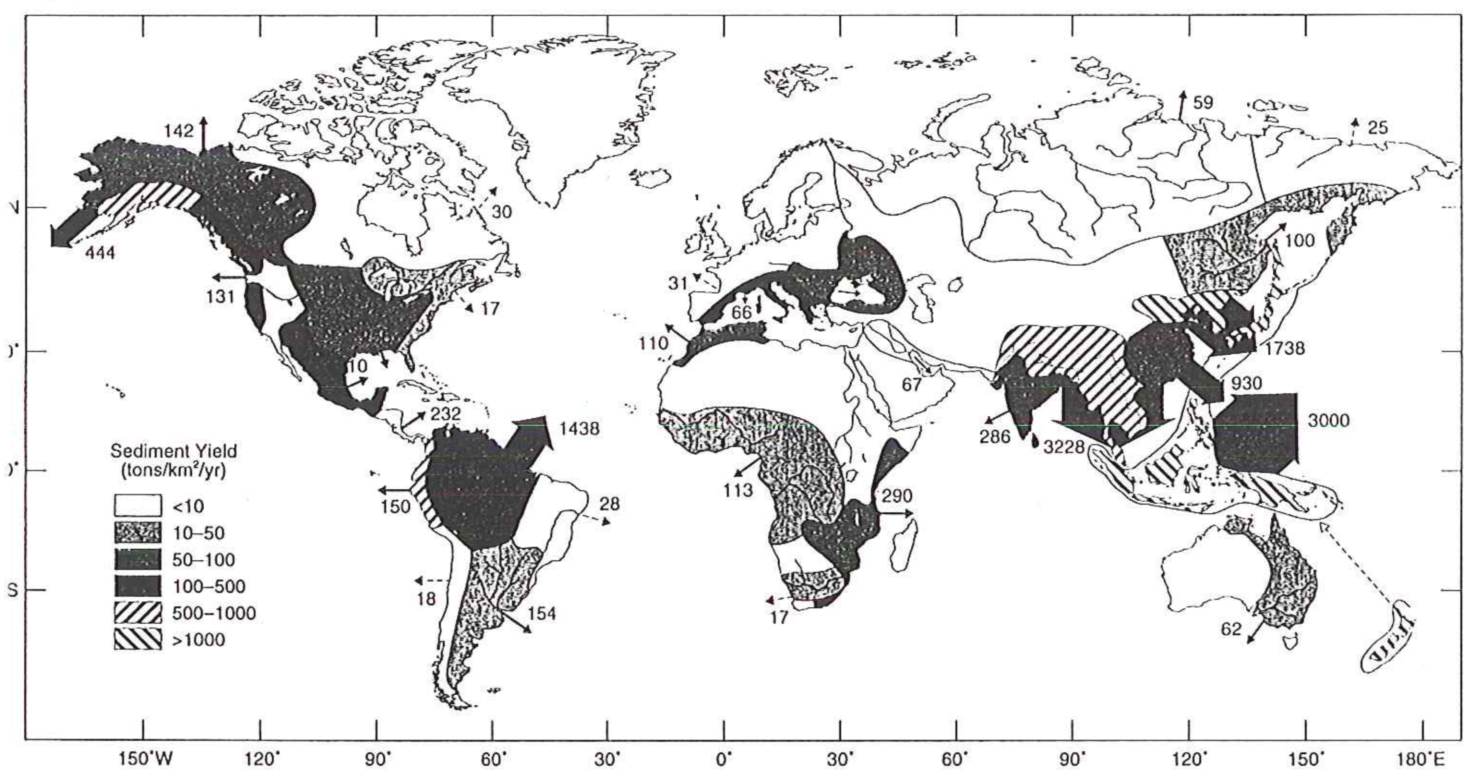


Figure 1.2 Global average annual precipitation. (From Tom L. Mc Knight, *Physical Geography: A Landscape Appreciation*, 5th ed. Copyright © 1996 Prentice Hall, Inc., Upper Saddle River, N.J.)



ɿurᵋ .. Discharge of suspended sediment from world drainage basins (in 10^6 tons/yr) as indicated by arrows. Sediment yield (tons/km²/yr) for various drainage ·ins is also shown by appropriate pattern (see legend). Open pattern indicates essentially no sediment discharges to the oceans. [After J. D. Milliman and R. H. ·ade. "World-Wide Delivery of River Sediment to the Oceans," *Journal of Geology* 91(1): 16. Copyright © 1983 by The University of Chicago Press, reprinted permission of the publisher.]

EROSION RATES OF MAJOR RIVER BASINS OF THE WORLD
(listed in order of water discharge)

	total erosion/area $Tg/10^6 km^2$	dissolved/area $Tg/10^6 km^2$
Amazon	240	45
Zaïre (Congo)	22	11
Orinoco	184	32
Yangtze (Chiang)	373	127
Bramaputra	1036	105
Mississippi	161	38
Yensei } in Russia	31	26
Lena } in Russia	27	20
Mekong	275	72
Ganges	610	77
St. Lawrence	48	44
Parana	37	6
Irrawaddy	830	214
Mackenzie	59	35
Columbia	75	52
Indus	337	81
Huanghe (Yellow)	1457	29

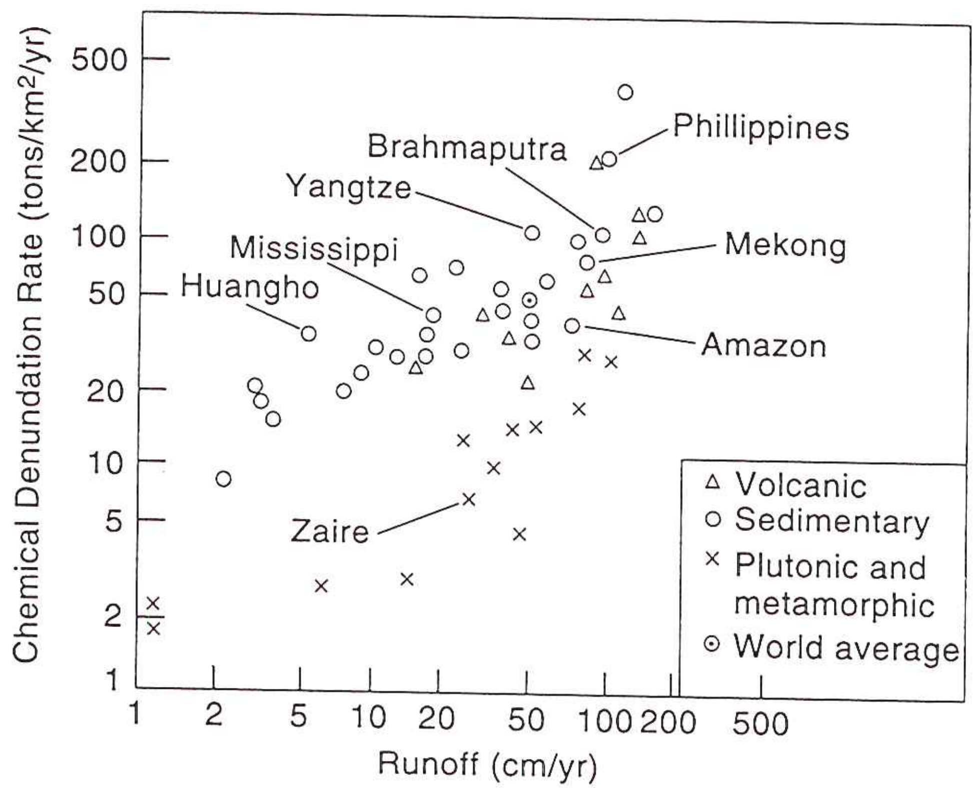


Figure 5.7. Influence of rock composition on total dissolved load per unit area (chemical denudation rate) versus runoff per unit area for major world rivers and some small basins. Certain major rivers discussed in the text are also included. (Adapted from Meybeck 1980; additional data from Hu et al. 1982.)

worldwide average chemical erosion rate
50 tons / km² yr
= 0.02 km/Myr
≈ 1/5 × total

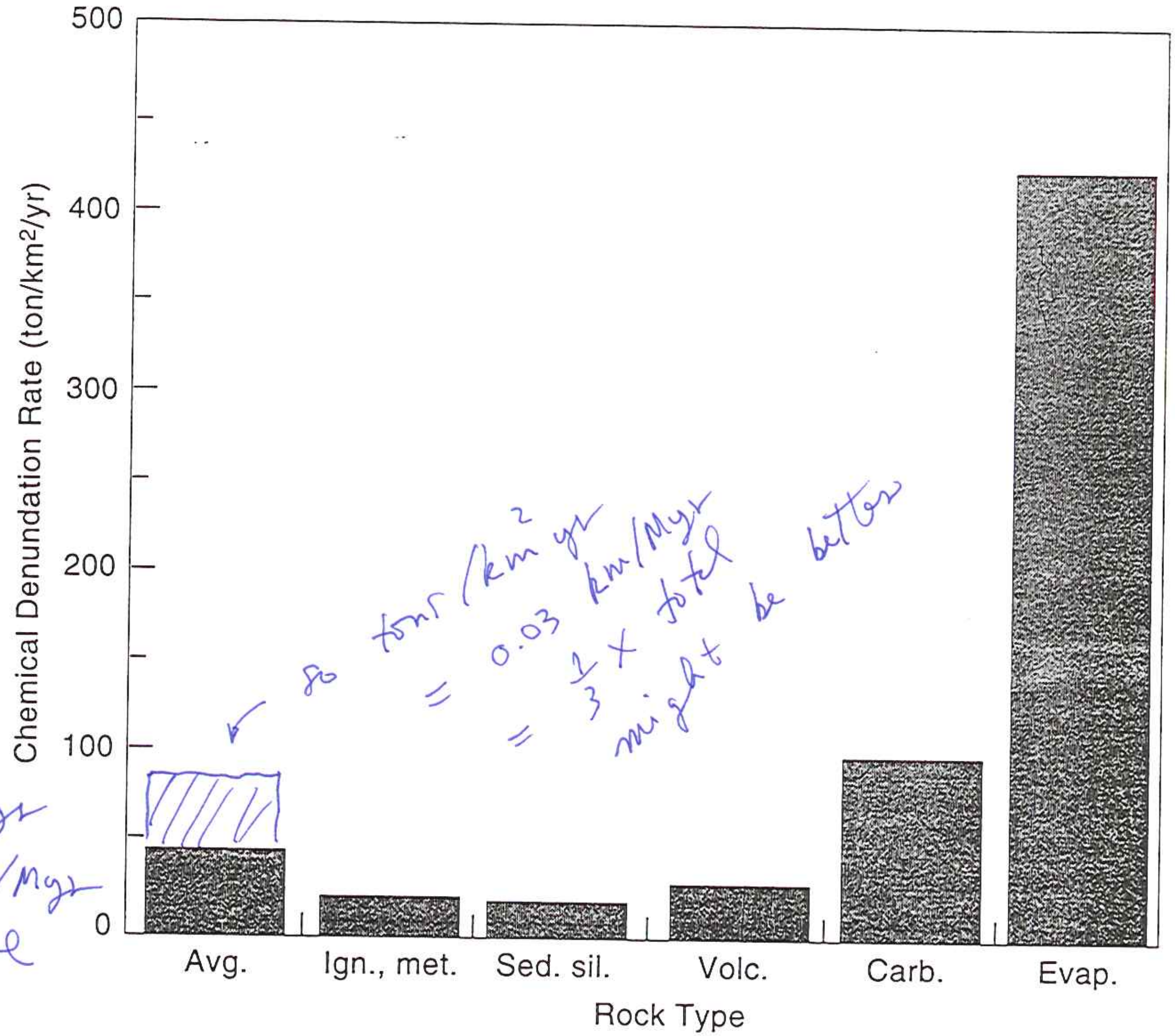


Figure 5.8. Relative chemical denudation rate in tons/km²/yr of various rock types compared to the average rate. Abbreviations for rock types are as follows: avg. = average; ign., met. = igneous and metamorphic; sed. sil. = sedimentary silicates; volc. = volcanics; carb. = carbonates; evap. = evaporites. (Data from Meybeck 1987.)

Desert areas also very low
- Sahara
- Atacama in Chile

- Rock type

Generally speaking, crystalline plutonic and metamorphic rocks are more resistant to ~~[illegible]~~ chemical weathering than sedimentary rocks — grains of latter held together by relatively soluble cements

Figure 5.7 of Berner illustrates this
- o sedimentary
- x crystalline

note increase with runoff, as expected — more rain, more weathering

Roughly a factor of 5 difference at a fixed runoff (equivalent precipitation) rate

The Congo (Zaire) ~~[illegible]~~ is a tropical river; however, it drains a crystalline lowland area — very low erosion rate

See also Fig. 5.8 — chemical erosion rate very dependent on rock type, esp. carbonates & evaporites.

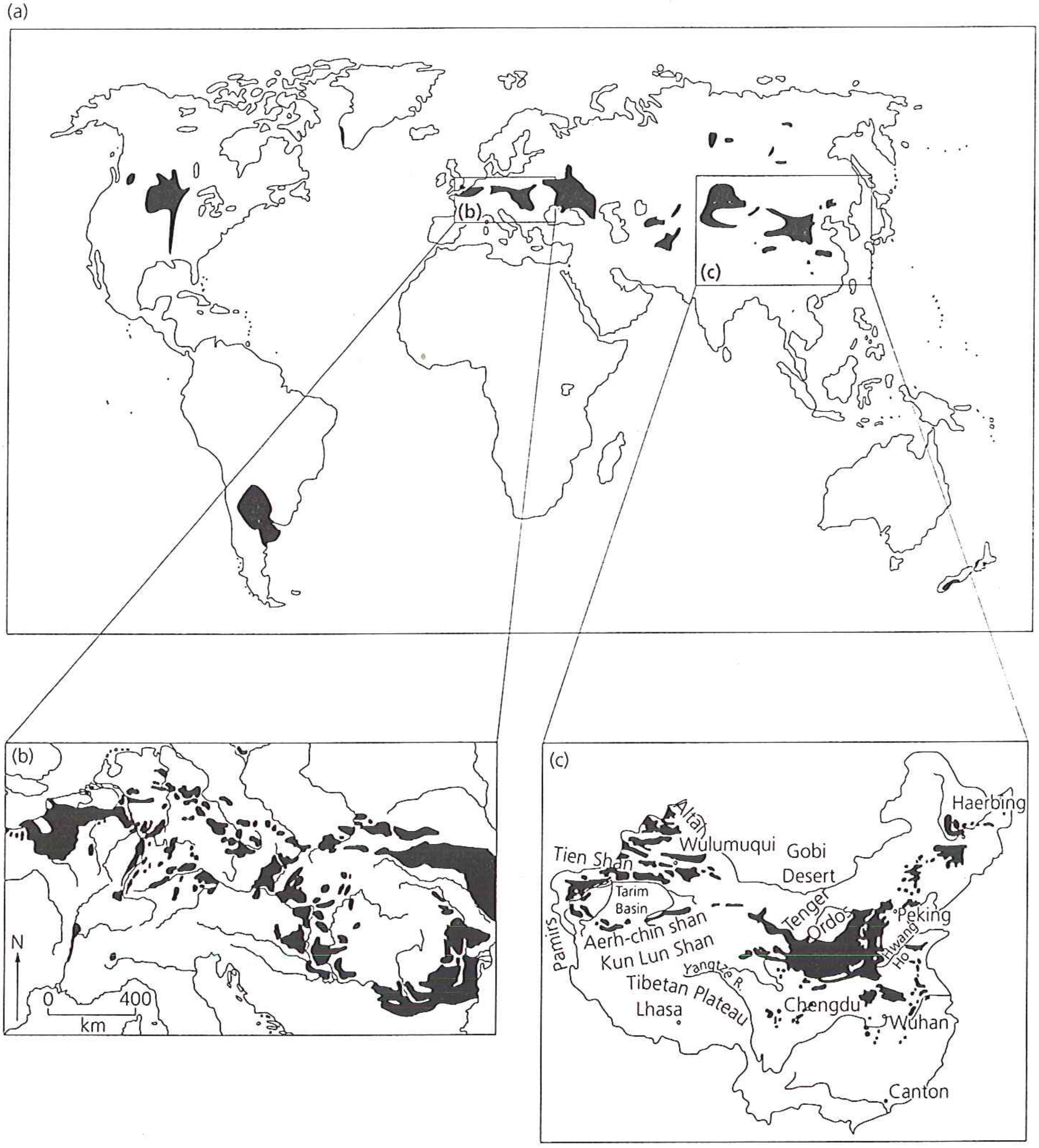


Fig. 2.12 Occurrence of loess. (a) Global distribution of main deposits. Distribution of loess in (b) Europe and (c) China. After Pye (1987) [14].

The most easily eroded "rock" type of all is unlithified loess: windblown dust dating from last glaciation

Map, figure 2.12, shows global distribution of loess deposits.

Largest single loess field, hundreds of meters thick, in drainage basin of Huanghe (Yellow) River in China.

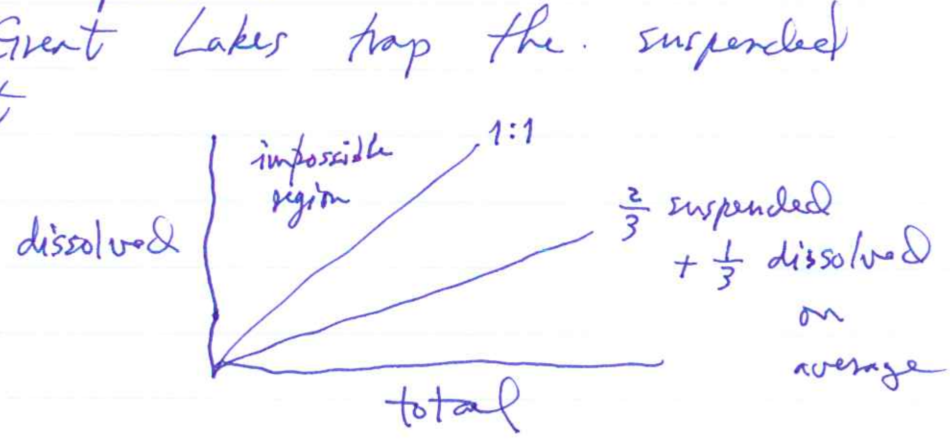
Very large erosion rate:

- $\dot{e} = 0.6$ km/Myr
- 98% suspended load (reason for name, very muddy)
- only 2% dissolved

Other extreme is St. Lawrence River

- 90% dissolved load
- 10% suspended

Reason — Great Lakes trap the suspended sediment



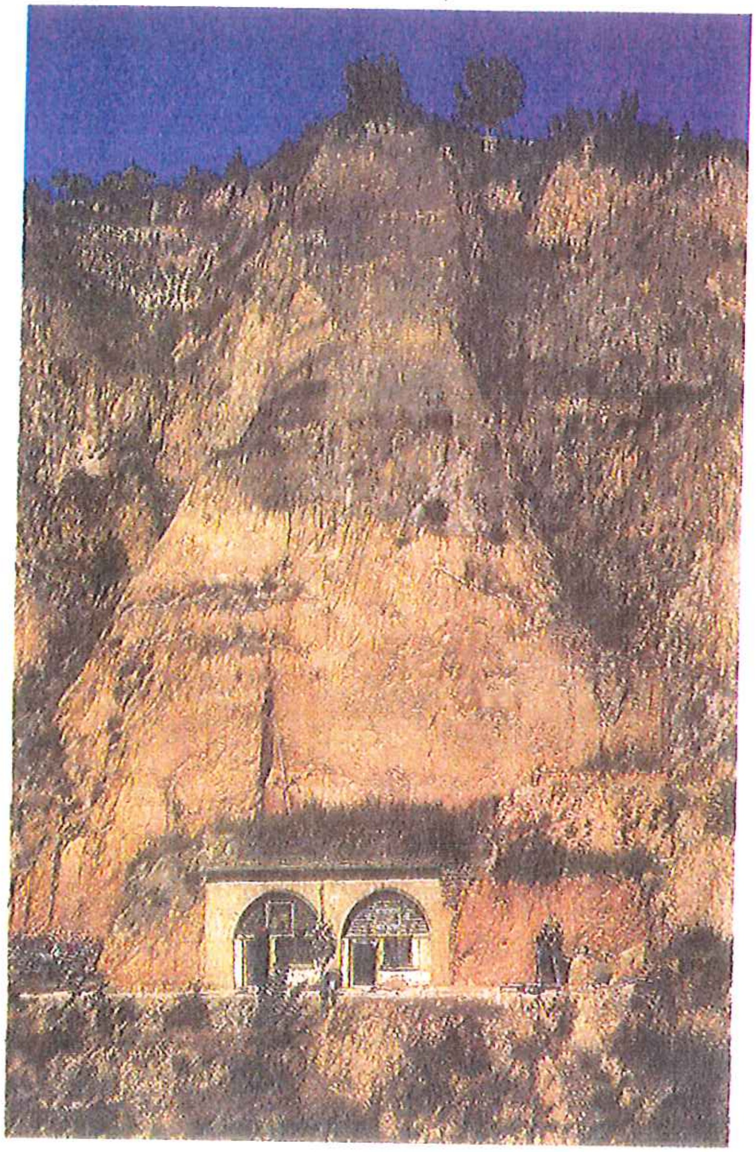
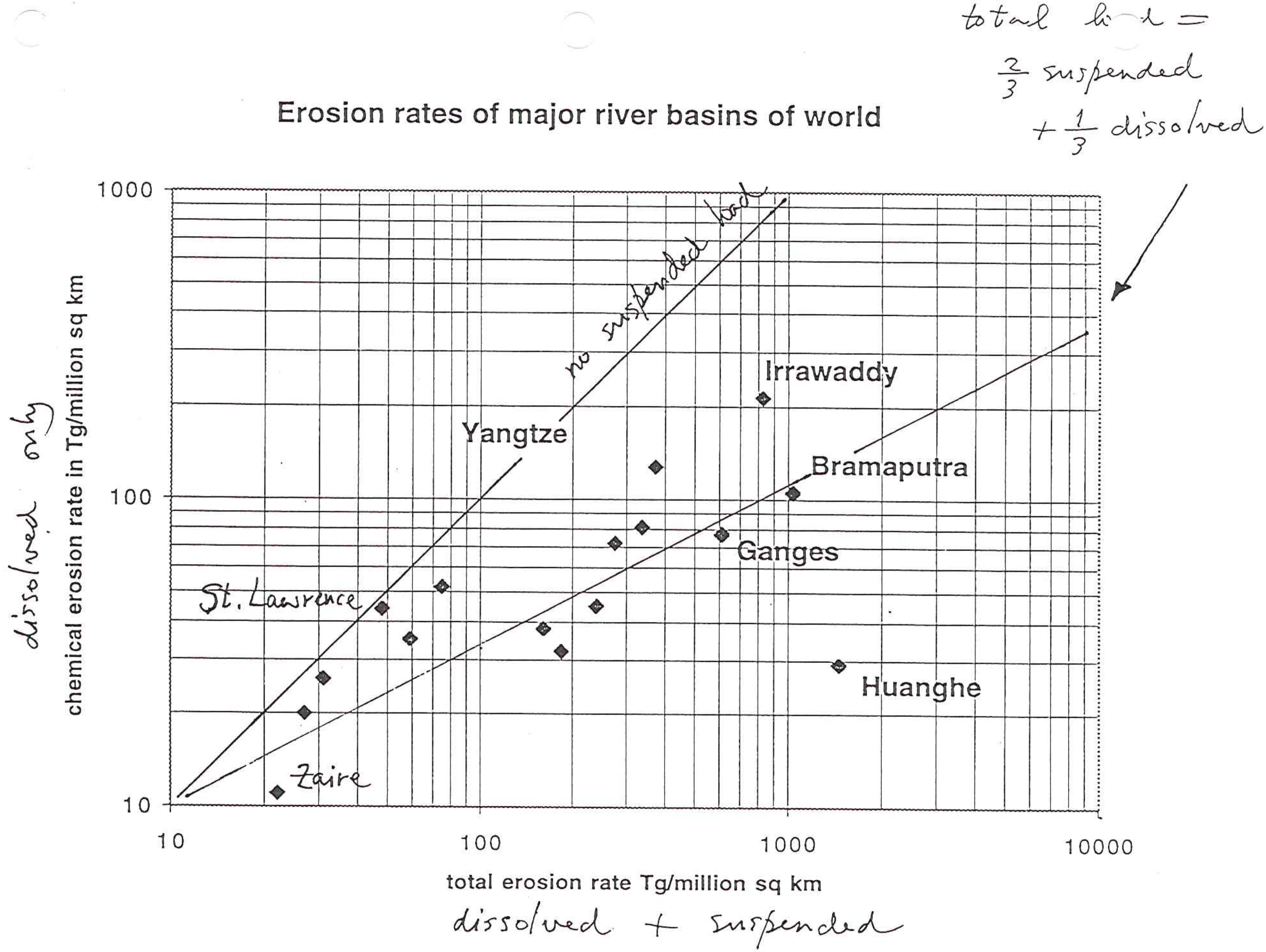


Figure 14.19 Comfortable dwelling caves hand-carved into steep cliffs of loess in central China. These deposits of windblown dust accumulated in the past 2.5 million years, reaching a thickness of as much as 400 m.
[*Stephen C. Porter.*]

Erosion rates of major river basins of world



Another interesting example of influence of rock type:

Guyana highlands in Venezuela

Very rugged relief — Angel Falls — one km high

Yet erosion rate of the highlands is virtually zero.

Streams coming off have little or no suspended or dissolved sediment

Reason: dominant rock type is the Roraima sandstone — very resistant

quartz grains with quartz cement

 ← qtz cement

Stockton ss, in contrast, has calcite cement — not the ideal bldg stone

Quartz is practically insoluble — little or no weathering

for this reason

Recall that 95% of sedimentary rocks are shale, often with easily soluble calcite cement:

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{++} + 2HCO_3^-$$

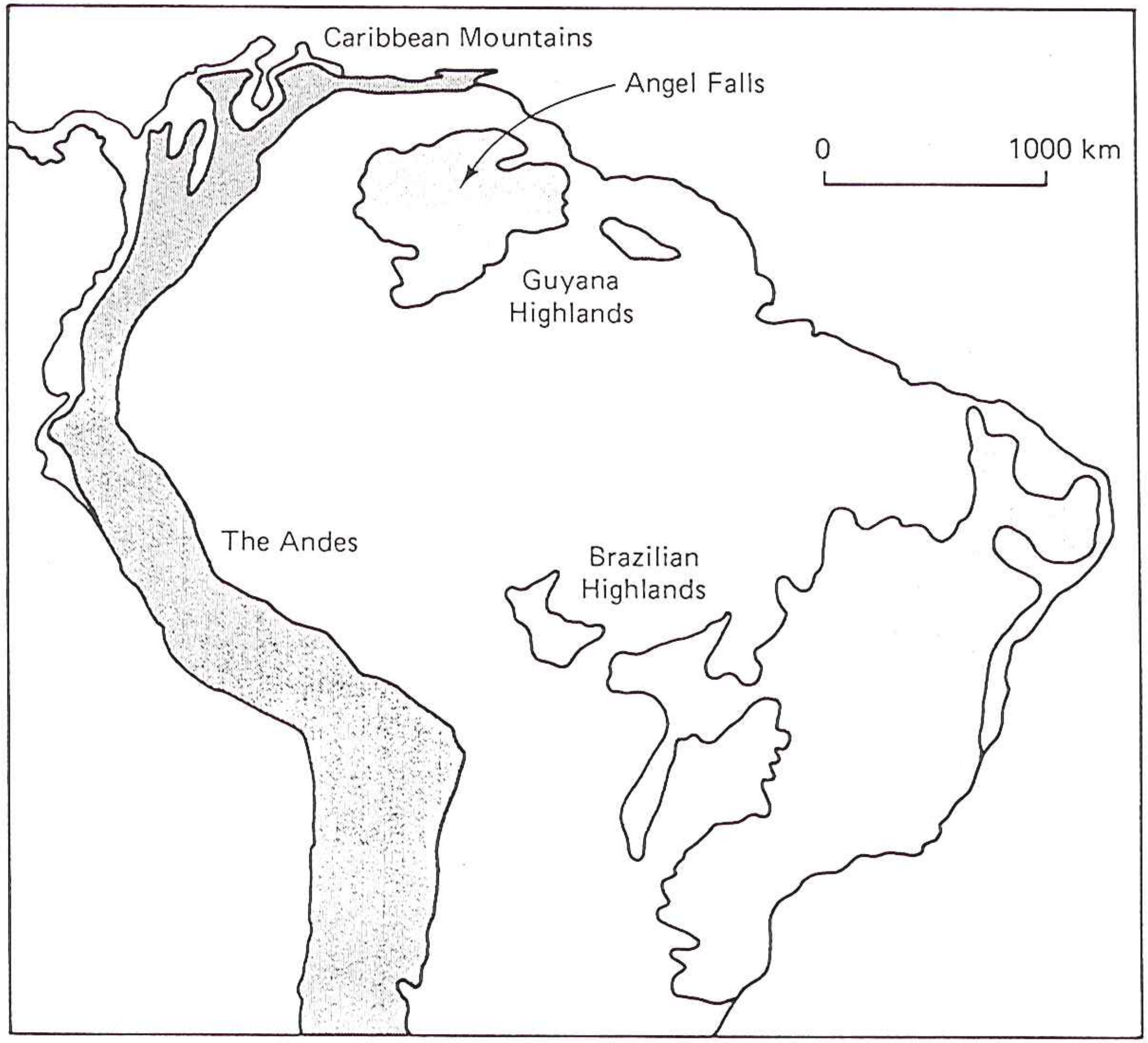


FIGURE 1–4 Topography of northern South America, showing the regions above 500 m in a shaded pattern. The Guyana and Brazilian highlands are epeirogenic uplifts, whereas the Andes and Caribbean Mountains are orogenic uplifts.

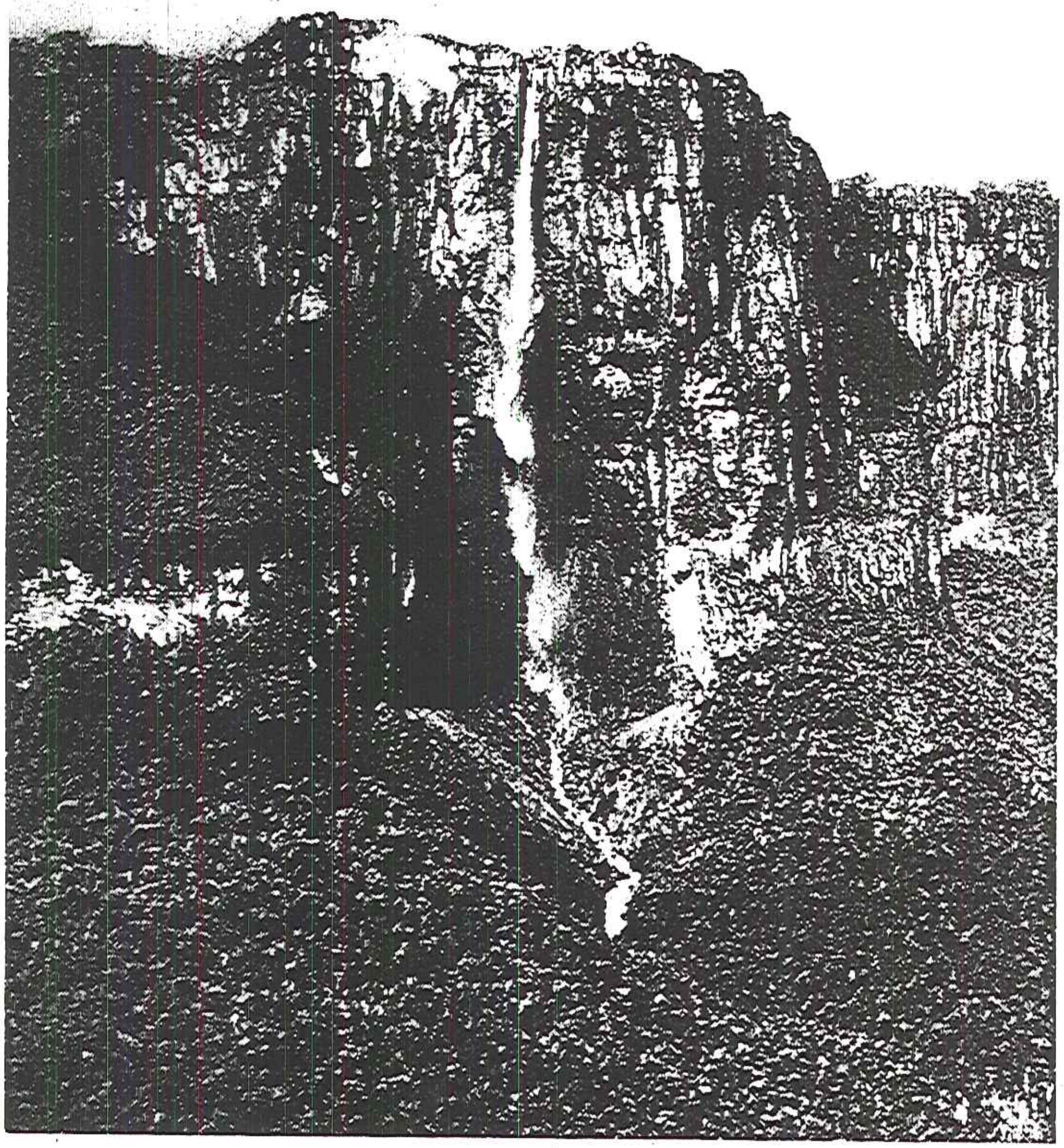
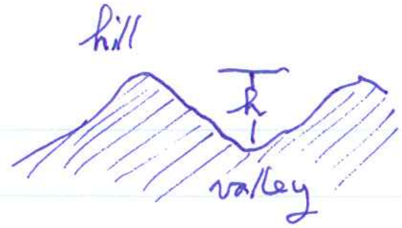


FIGURE 1–5 One-kilometer-high Angel Falls in the Guyana Highlands of the southern Venezuelan craton. The high relief suggests that this is a region of active epeirogenic uplift. (Photograph by R. Hargraves.)

- <u>Relief</u> ≡ elevation change



Many reasons why should ~~affect~~ affect erosion rate

- increased relief ⇒ increased overland flow & stream transport during storms
- increased ground water flow ⇒ increased ~~[illegible]~~ transport of dissolved species
- increased landsliding — we shall investigate this in more detail in a later class

<u>Evidence</u> of influence of relief

- Compare erosion rate in Andes to Pacific with flux to Amazon Basin

$\dot{e} = 0.2 - 0.4 \frac{km}{Myr}$

$\dot{e}_{\text{whole basin}} = 0.02 - 0.04$ km/Myr

factor of 10 lower

But, as we have noted, this is misleading because mostly derived from Andes

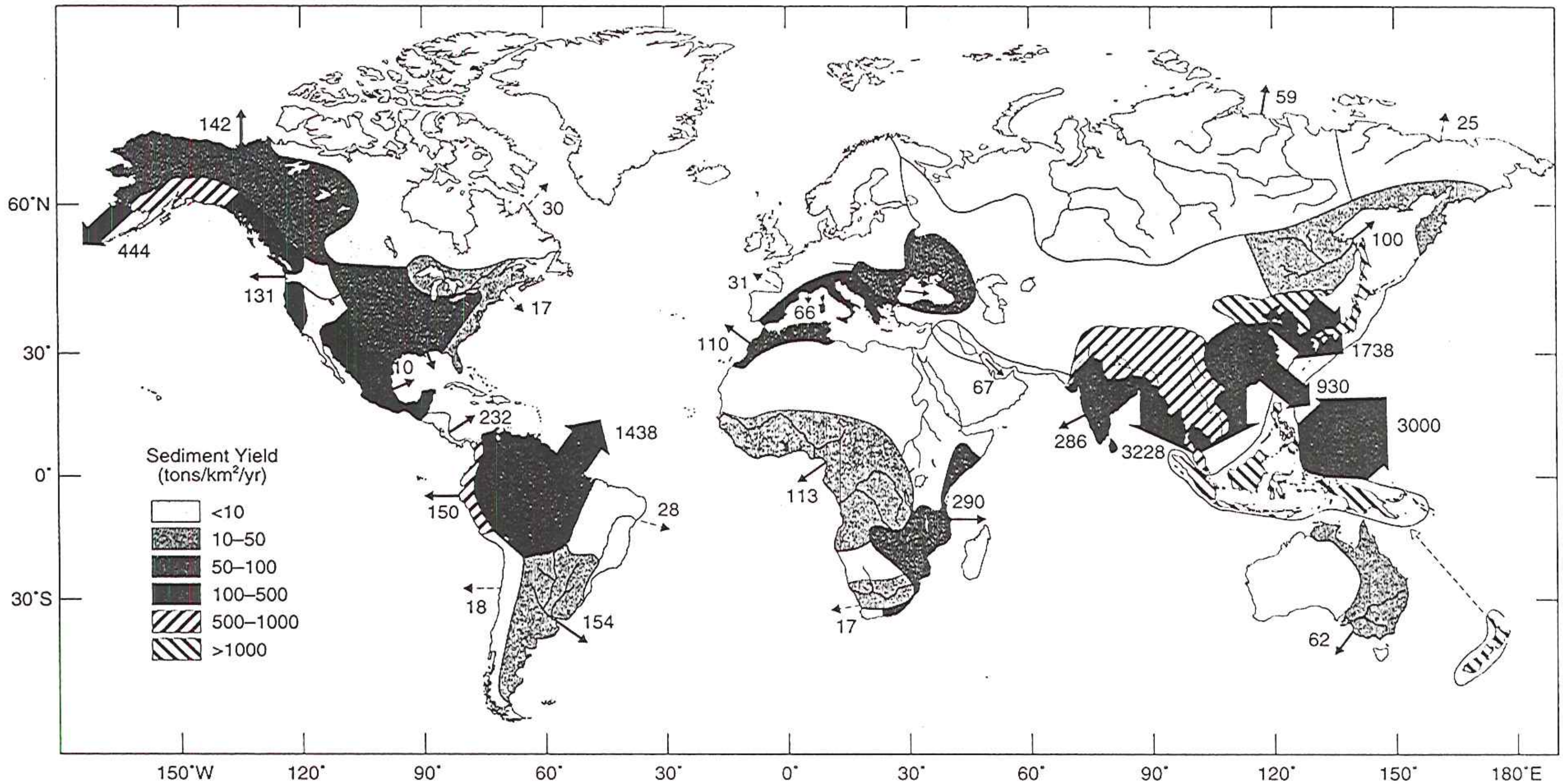


Figure 5.1. Discharge of suspended sediment from world drainage basins (in 10^6 tons/yr) as indicated by arrows. Sediment yield (tons/km^2/yr) for various drainage basins is also shown by appropriate pattern (see legend). Open pattern indicates essentially no sediment discharges to the oceans. [After J. D. Milliman and R. H. Meade. "World-Wide Delivery of River Sediment to the Oceans," *Journal of Geology* 91(1): 16. Copyright © 1983 by The University of Chicago Press, reprinted by permission of the publisher.]

sediment yield $100 \frac{\text{tons}}{\text{km}^2\,\text{yr}} = 0.04 \frac{\text{km}}{\text{Myr}}$ erosion rate

Figure 5.6 (Berner) plots the erosion rate for the major continental areas versus the mean elevation

Clear trend — upland areas have increased erosion rates

Figure 3.29 shows another compilation from a different source

erosion rate versus drainage basin area

It looks as if larger catchment basins have lower yields, but in fact this is also an elevation effect.

Larger basins are in lowland areas
Smaller basins have a relatively higher proportion of mountains and highland

Figure 3.26 shows yet a third analysis

erosion rate versus runoff (precipitation rate) — see same trend as before — but now instead of rock type:

○ lowlands
▲ mountains

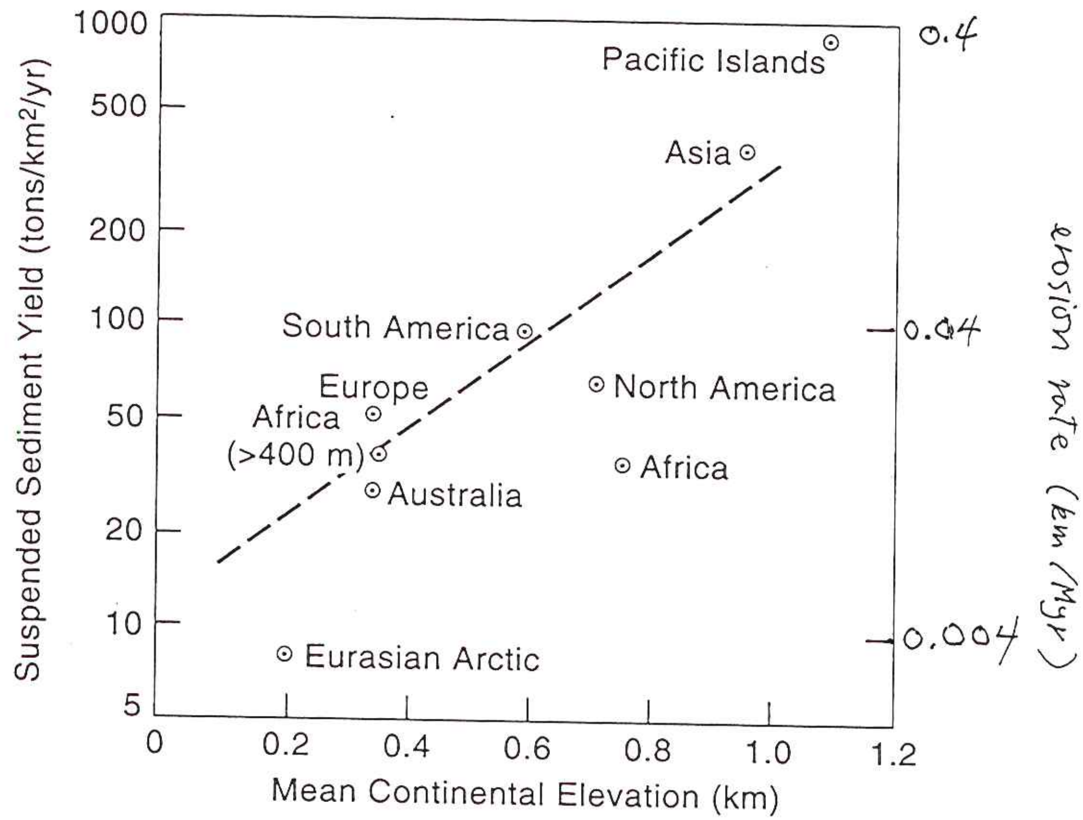


Figure 5.2. Suspended sediment yield (tons/km^2/yr) versus mean continental elevation (km). [Suspended sediment data from Milliman and Meade (1983); mean continental elevation from Fairbridge (1968), except for the Pacific Islands and Eurasian Arctic, which are our rough estimates.]

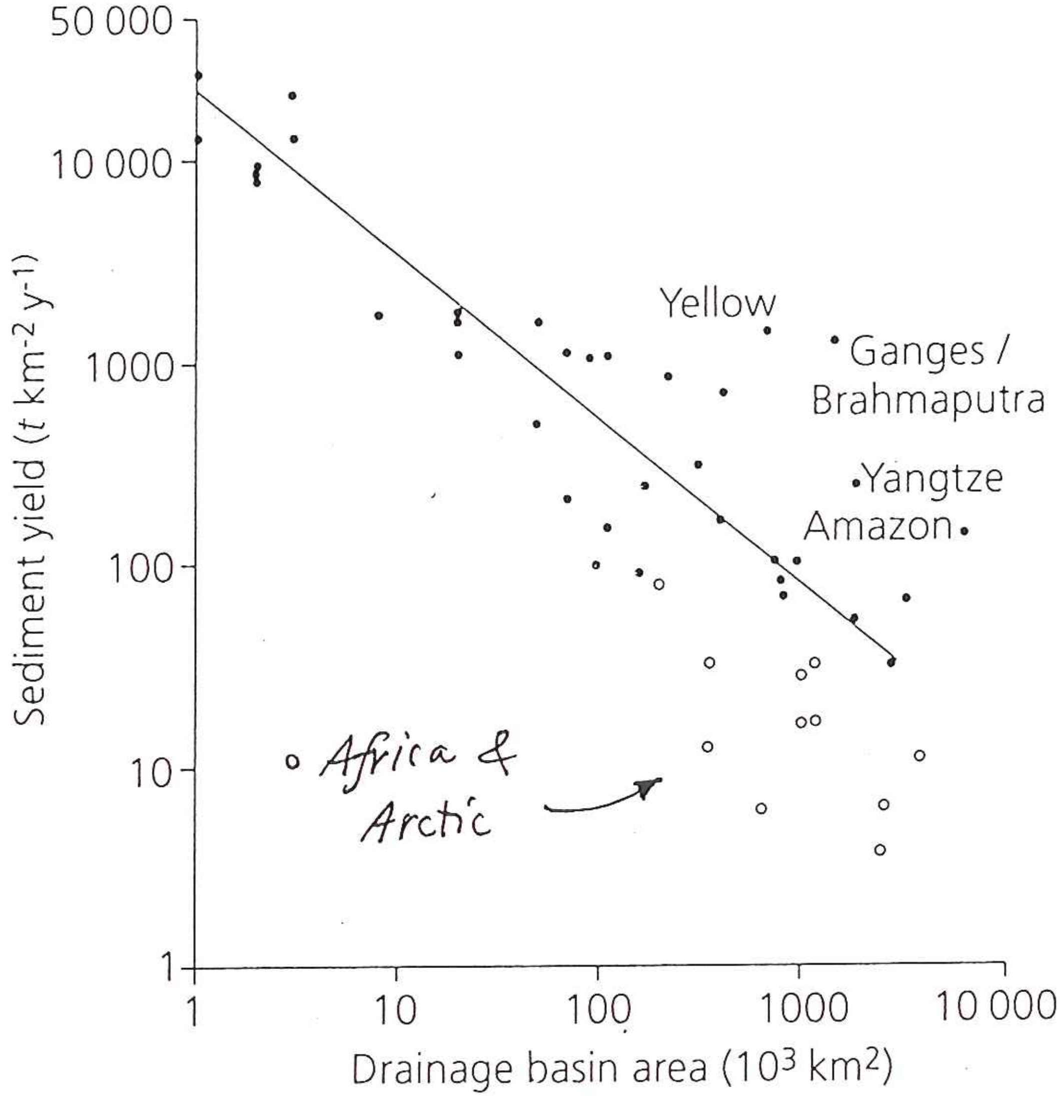


Fig. 3.29 Sediment yield versus drainage basin area for the world's major sediment discharging rivers (over 10 Mt y^{-1}). The open circles are the low yield rivers of Africa and the Eurasian Arctic. The named large rivers all have very high yields compared to their drainage basin area. The slope of the correlation line reflects the area averaging involved in calculating sediment yield, with larger basins having relatively larger proportions of lowland and smaller basins having relatively larger proportions of highland. After Milliman & Meade (1983) [29].

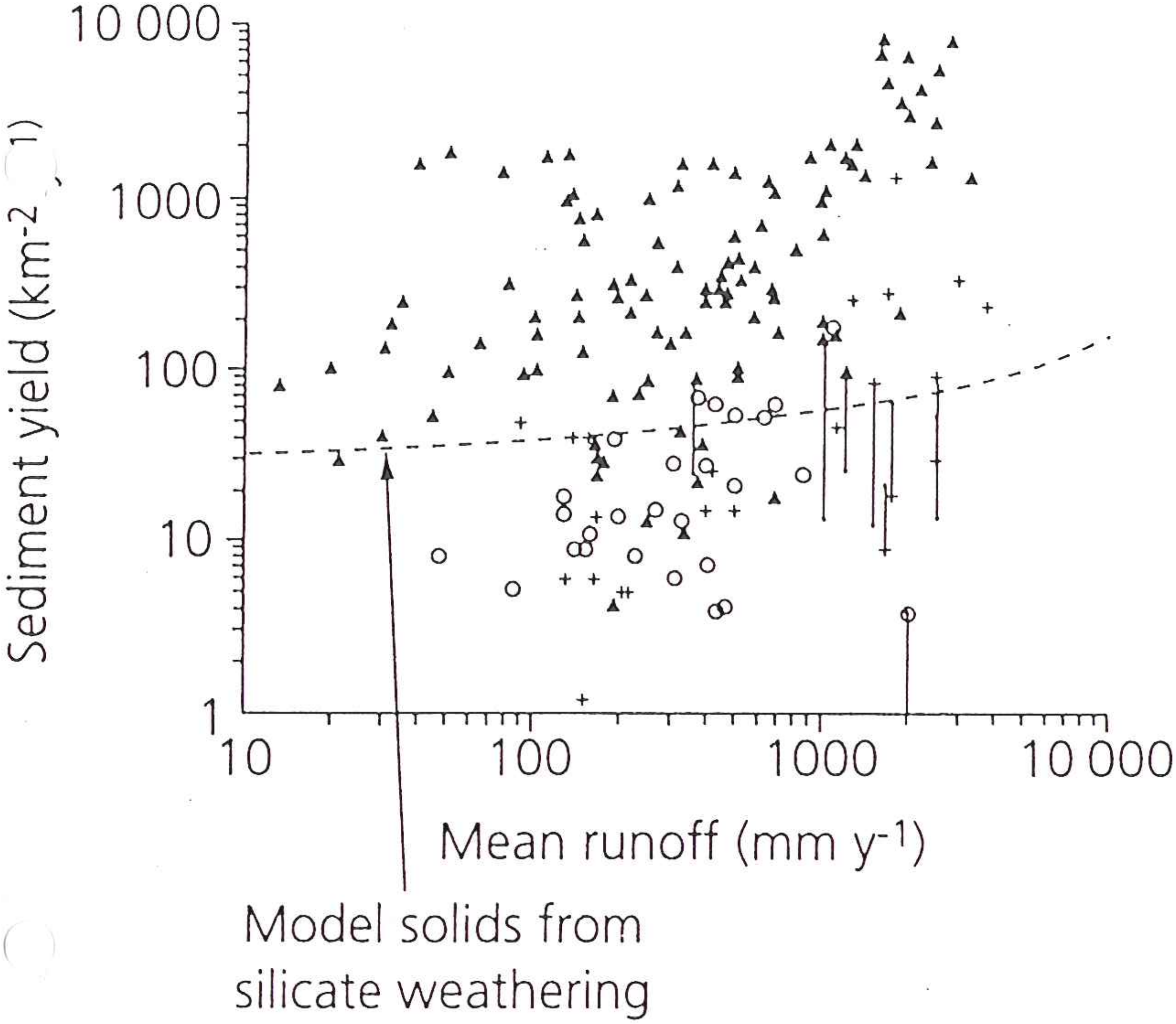
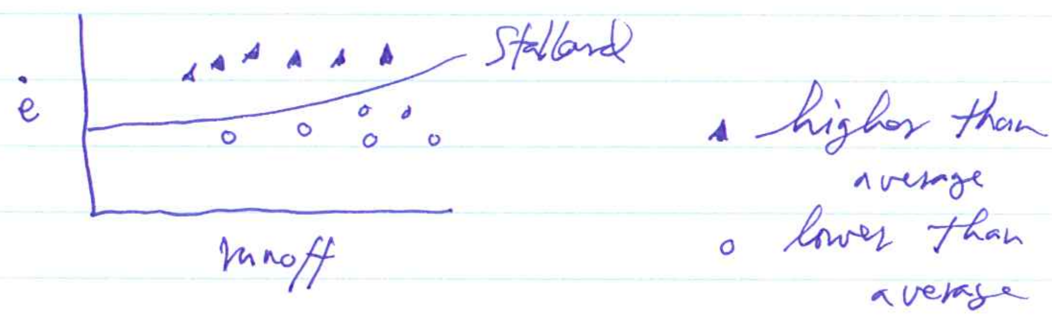


Fig. 3.26 Relation between mean runoff and sediment yield for rivers throughout the world. Open circles, coastal plain (0–100 m headwaters) and lowland (100–500 m); crosses, upland rivers (500–1000 m); solid triangles, mountain (1–3 km) and high mountain (>3 km). Model curve is prediction for solids derived by silicate weathering (after Stallard (1995) [33]), showing that mountainous catchments provide high solid yields for a given runoff, whereas lowland rivers provide low solid yields for the same runoff.

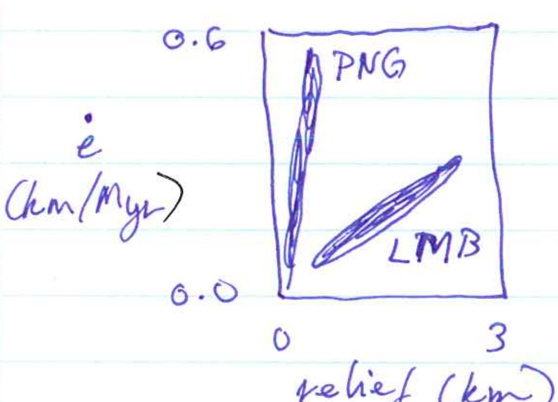
The curve is Bob Stallard's predicted <u>mean</u> dependence on runoff, derived on the basis of observed Si and Na concentrations in the dissolved load (as a function of runoff) — his argument too complicated to give here

But



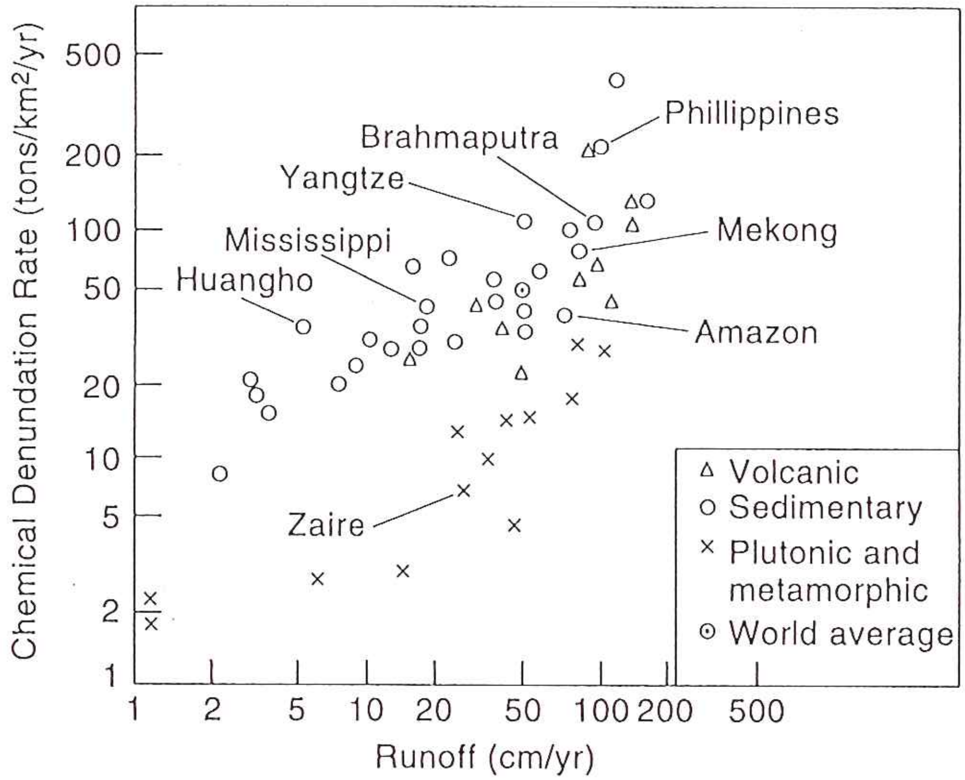
The most compelling data come from careful studies of relatively small areas — other factors (climate & rock type) ≈ same

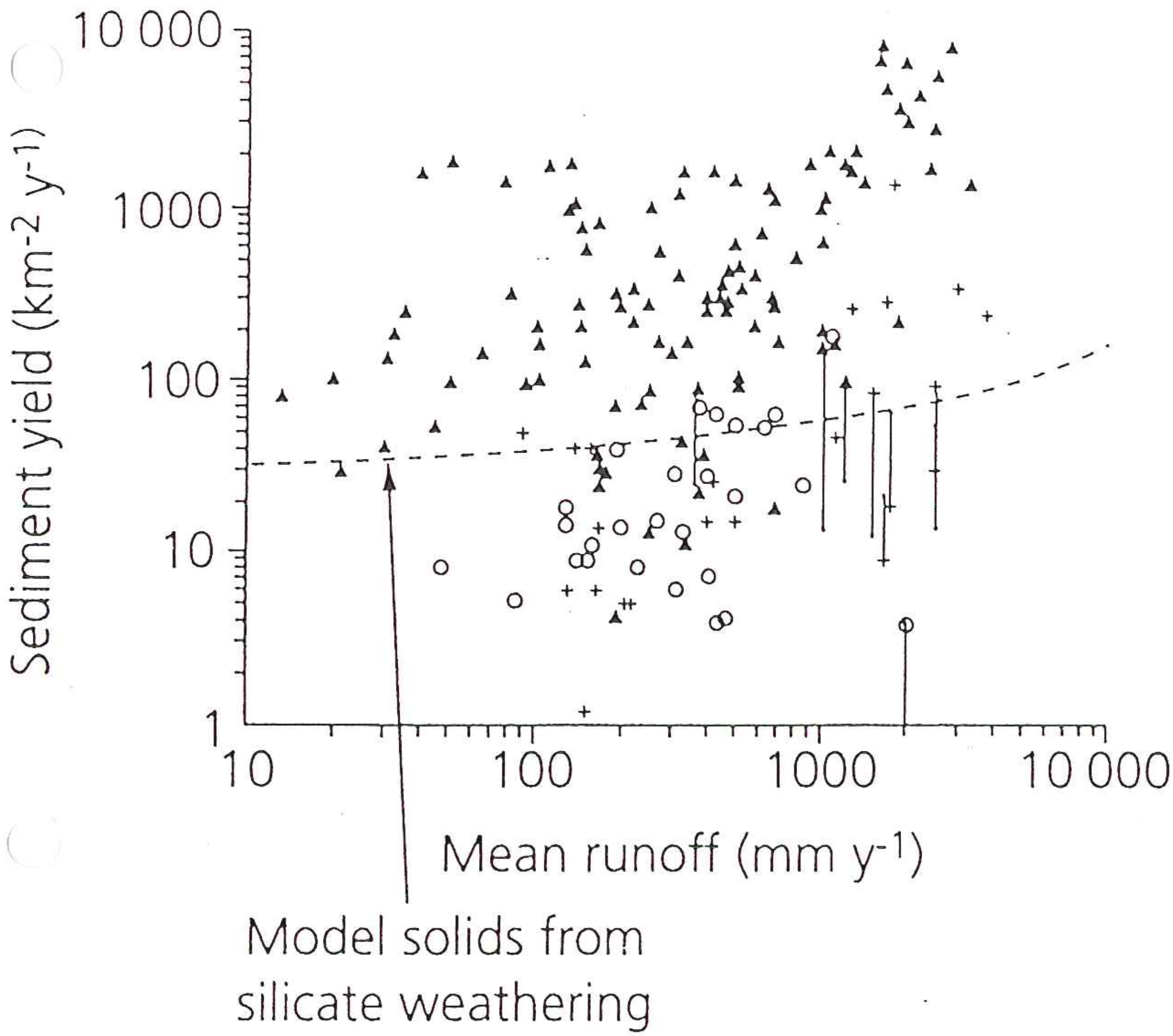
Figure from Suppe shows

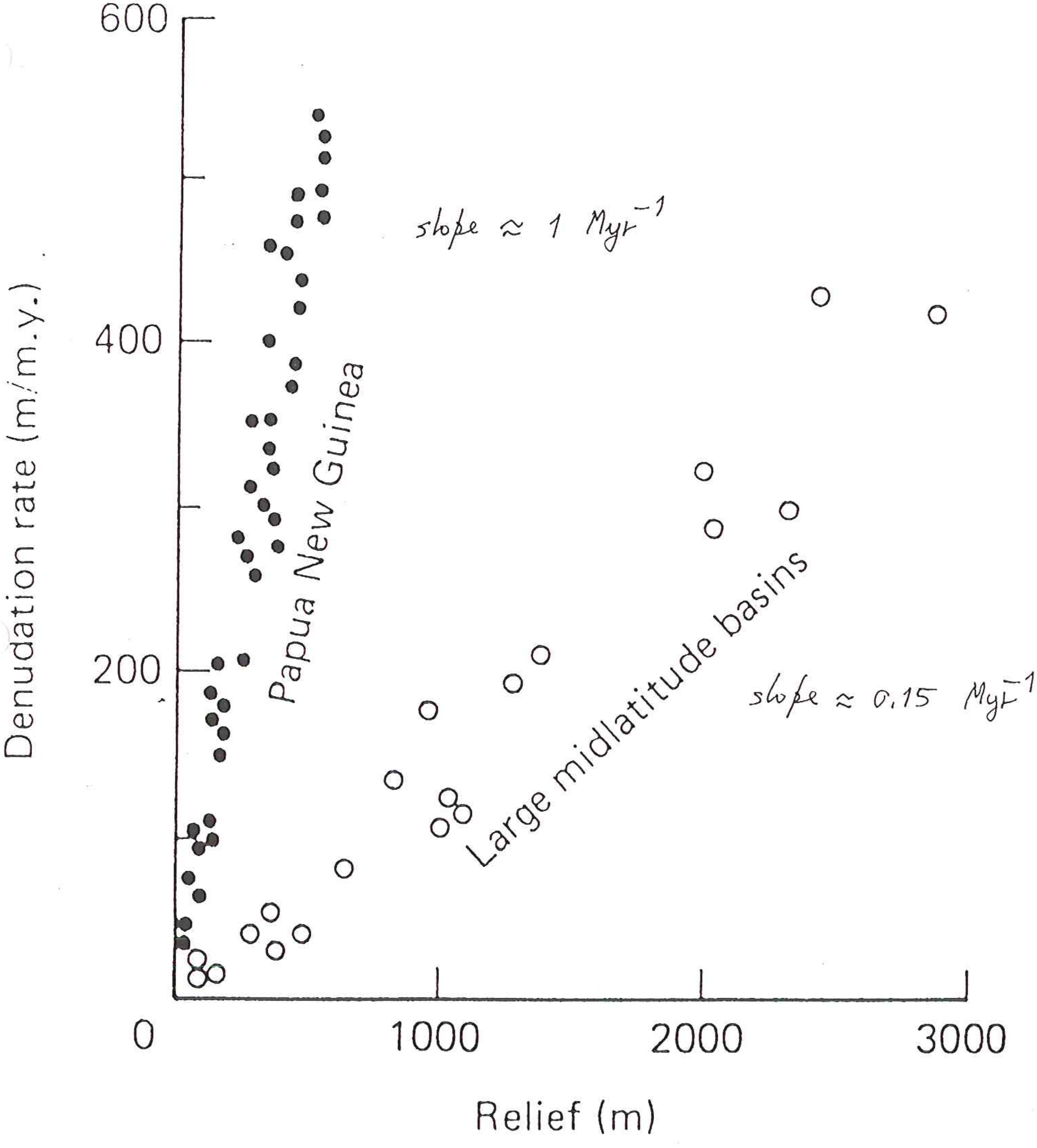


PNG = Papua New Guinea (Hydrographer's Range) Ruxton & McDougall (1967)

LMB = large midlatitude basins (not in tropics) — all have ~ same precipitation rate


Chemical Denudation Rate (tons/km²/yr)
500
200
100
50
20
10
5
2
1
Phillippines
Brahmaputra
Yangtze
Mississippi
Huangho
Mekong
Amazon
Zaire
Volcanic
Sedimentary
Plutonic and metamorphic
World average
1
2
5
10
20
50
100
200
500
Runoff (cm/yr)


Sediment yield (km-2 y-1)
10 000
1000
100
10
1
10
100
1000
10 000
Mean runoff (mm y-1)
Model solids from silicate weathering



Ruxton & McDougall (1967)
Ahnert (1970)

The data exhibit a linear relation of the form:

$$\dot{e} = \alpha h$$

- $\dot{e}$: erosion rate (km/Myr)
- α: slope of line (Myr^{-1})
- h: relief (km)

region	α (Myr^{-1})
Papua, New Guinea	1
midlatitude basins	0.15

Erosion rates in PNG are $\frac{1}{0.15} \approx 6$ times greater than typical midlatitude basins — this an effect of climate & rock type — changes the slope α

Note: PNG on map is highest rate shown

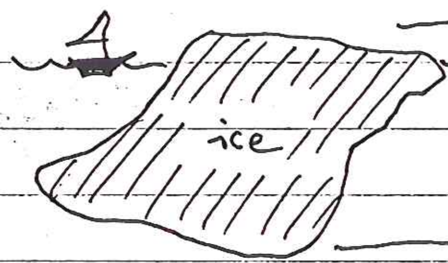
Let us now develop a model of continental-scale erosion based upon the presumption that $\dot{e} = \alpha h$ — ignores other important variables (climate & rock type) do this first

isostasy — from old notes — ice cube example

Simple application: an iceberg in the ocean (or an icecube in a glass)

$\rho_{ice} = 0.9\, \rho_{water} = 900\ \mathrm{kg/m^3}$

Ice expands upon freezing — a very unusual property



10% above — visible

90% below — this is why ship captains avoid icebergs

Note — if one bevels off the top of the ice cube the bottom will move up relative to $ so that 1/10 — 9/10 ratio is maintained

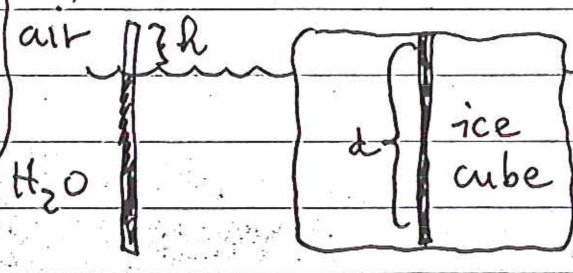
The principle of isostasy: equal mass in two columns

columns balancing

$\rho_i d = \rho_w (d - h)$

$h = \left(1 - \frac{\rho_i}{\rho_w}\right) d$

$h = \frac{1}{10} d$

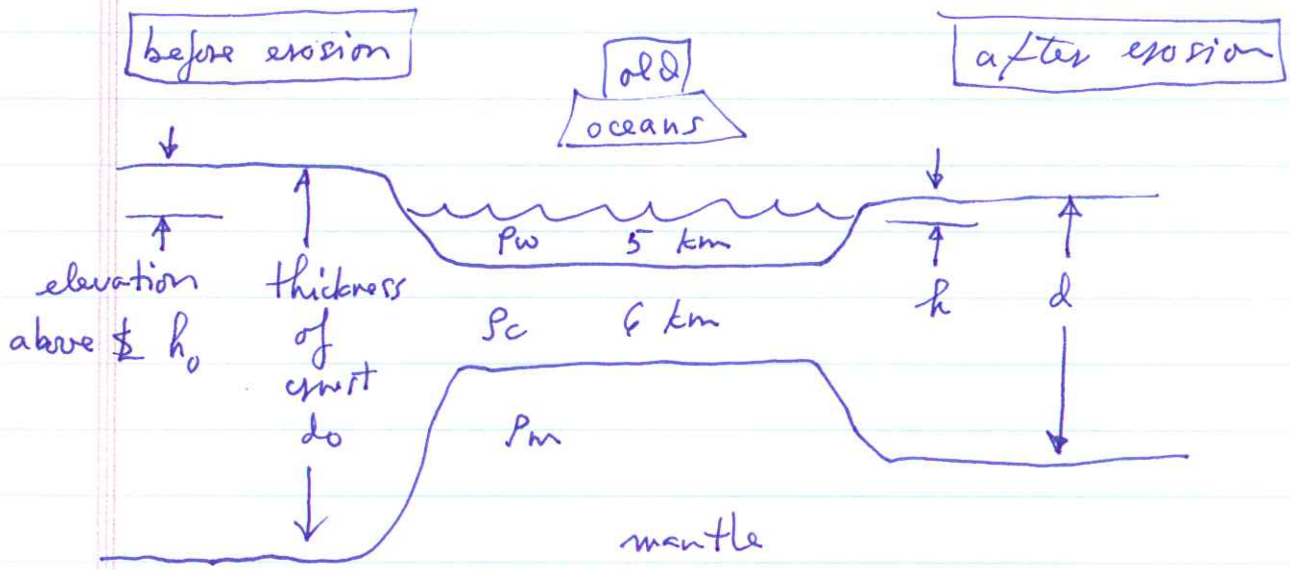


$\rho_{air} \approx 0$

need to draw similar sketch for homework #3

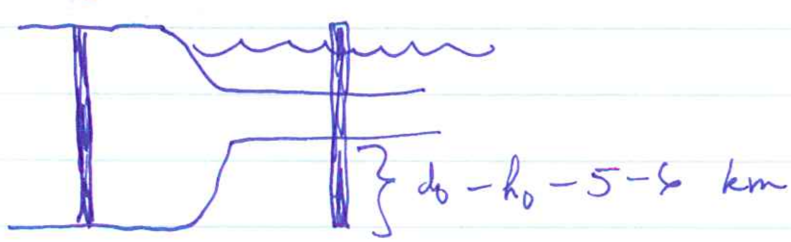
We shall need to invoke the principle of isostasy — only appropriate for horizontal scales > 100 – 1000 km

Our model can be sketched as follows



5 km of H_2O and 6 km of basaltic crust in the oceans.

Balancing columns: before erosion & oceans



$$\rho_c d_0 = \rho_w 5 + \rho_c 6 + \rho_m (d_0 - h_0 - 5 - 6)$$

Solve for d_0: $$d_0 = 6 + 5\left(\frac{\rho_m - \rho_w}{\rho_m - \rho_c}\right) + \frac{h_0}{1 - \rho_c/\rho_m}$$

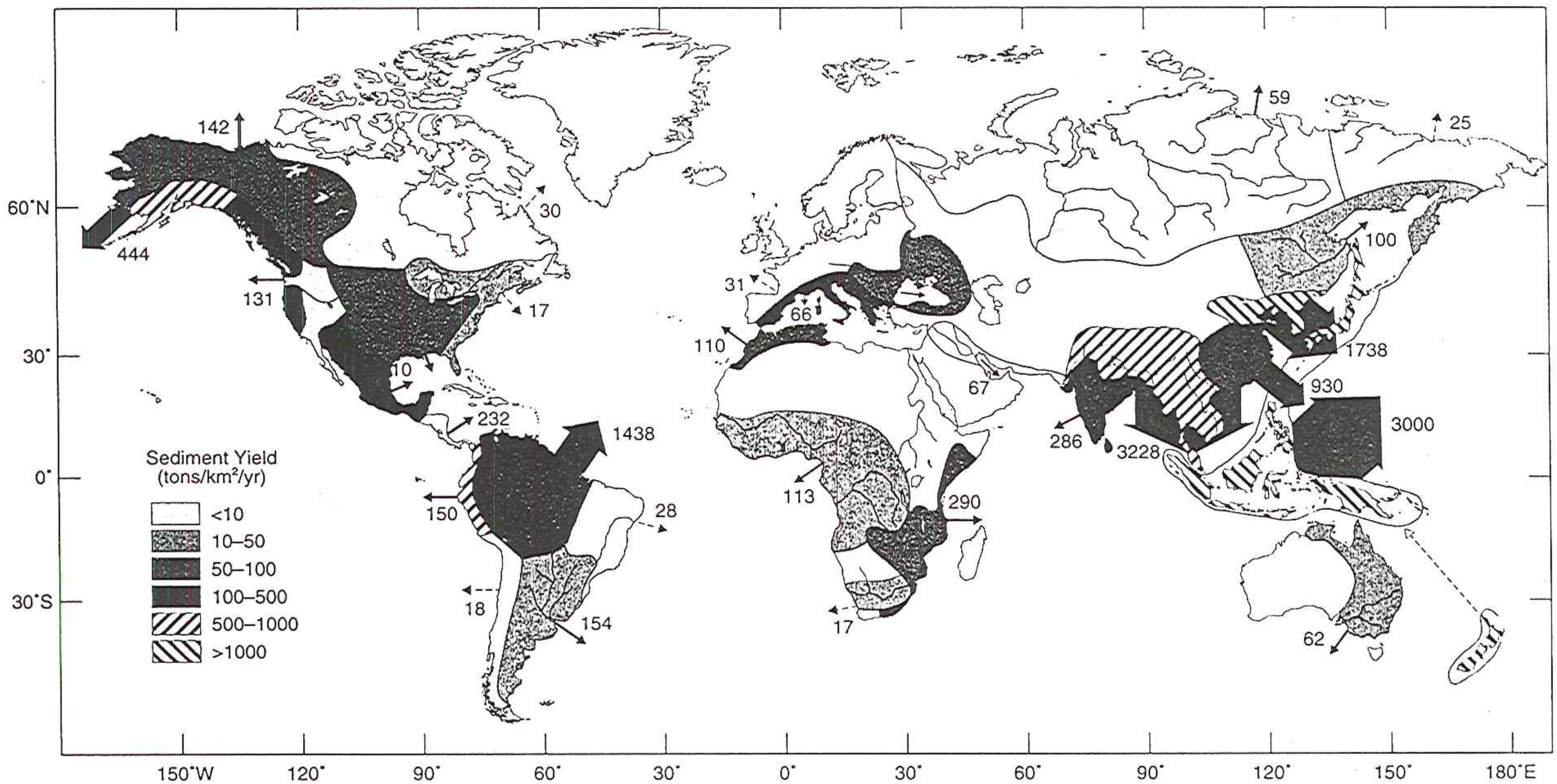


Figure 5.1. Discharge of suspended sediment from world drainage basins (in 10^6 tons/yr) as indicated by arrows. Sediment yield (tons/km²/yr) for various drainage basins is also shown by appropriate pattern (see legend). Open pattern indicates essentially no sediment discharges to the oceans. [After J. D. Milliman and R. H. Meade. "World-Wide Delivery of River Sediment to the Oceans," *Journal of Geology* 91(1): 16. Copyright © 1983 by The University of Chicago Press, reprinted by permission of the publisher.]

sediment yield $100 \frac{\text{tons}}{\text{km}^2\,\text{yr}} = 0.04 \frac{\text{km}}{\text{Myr}}$ erosion rate

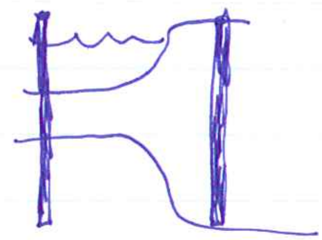
Set
$$\rho_w = 1000 \ kg/m^3$$
$$\rho_c = 2900 \ kg/m^3$$
$$\rho_m = 3300 \ kg/m^3$$

$$d_0 = 35 + \frac{h_0}{1-\rho_c/\rho_m}$$

↑ thickness of lowland (\$) crust

$$d_0 = 35 + 8h_0$$

Likewise, balancing



after erosion

$$d = 35 + \frac{h}{1-\rho_c/\rho_m}$$

$$d = 35 + 8h$$

The total amount of eroded material is

$$e = d_0 - d = \frac{h_0 - h}{1-\rho_c/\rho_m}$$

$$e = d_0 - d = 8(h_0 - h)$$

Rewrite as $h_0 - h = (1 - \rho_c/\rho_m)\, e = \frac{1}{8} e$

Differentiate

$$\frac{dh}{dt} = -\left(1 - \frac{\rho_c}{\rho_m}\right)\frac{de}{dt}$$

But $\frac{de}{dt} = \alpha h \Rightarrow$

$$\frac{dh}{dt} = -\left(1 - \frac{\rho_c}{\rho_m}\right)\alpha h = -\lambda h$$

where $\lambda = \left(1 - \frac{\rho_c}{\rho_m}\right)\alpha$

The solution to this differential equation

$$\frac{dh}{dt} = -\lambda h \qquad dh = -\lambda h\, dt$$

Like radioactive decay

$$\frac{dN}{dt} = -\lambda N \qquad dN = -\lambda N\, dt$$

proportionality constant = decay rate (λ); $\propto$ time interval (dt)

dN: # of decays in time dt; N: $\propto$ # atoms presence

$$h = h_0 e^{-\lambda t} \quad \text{where} \quad \lambda = \alpha\left(1 - \frac{\rho_c}{\rho_m}\right) = \frac{\alpha}{8}$$

λ: decay rate; α: climate, rock type, etc.; $\left(1 - \frac{\rho_c}{\rho_m}\right)$: isostatic factor

Landscape decays exponentially!

↑ In the absence of any relief-building processes – tectonism

If $\alpha = 0.15\ \mathrm{Myr}^{-1}$ (mid-latitude basins) what is the decay rate

$$\lambda = 0.15\left(1 - \frac{2900}{3300}\right) = 0.018\ \mathrm{Myr}^{-1}$$

The corresponding half life is

$$t_{1/2} = \frac{\ln 2}{\lambda} \cong 40\ \mathrm{Myr}$$

↑ half life for topography

The corresponding total amount of erosion & the change in crustal thickness are:

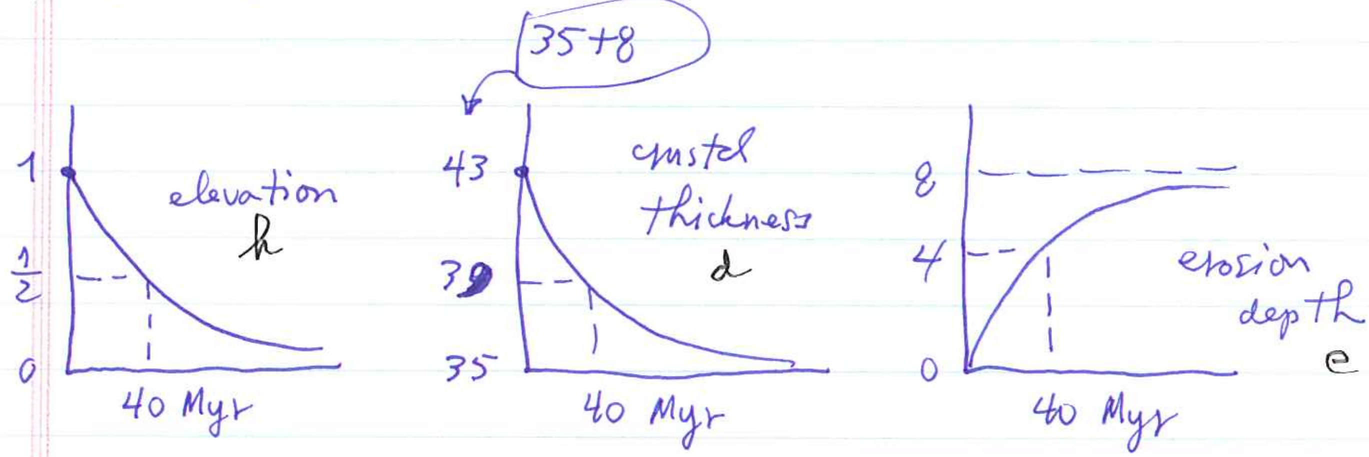
$$d = 35 + \frac{h}{1 - \rho_c/\rho_m} \cong 35 + 8 h_0 e^{-\lambda t}$$

↑ decays to the equilibrium (35) thickness

$$e = \frac{h_0 - h}{1-\rho_c/\rho_m} = 8h_0\left(1-e^{-\lambda t}\right)$$

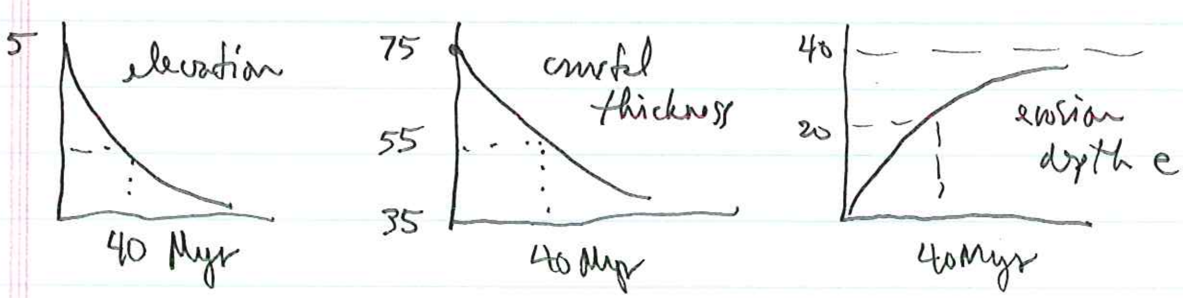
Total depth of erosion in limit $t \to \infty$ extends to $8\times$ initial elevation

Say, e.g., $h_0 = 1$ km:



Conclude with 1600's quotes — concept of decay of the landscape not as quantitative then, but decidedly more eloquent.

Example 2: Tibet: $h_0 = 5$ km (after collision ceases)



".....if the World were eternal, by the continual fall and wearing of waters all the protuberances of the earth would infinite Ages since have been levelled, and the Superficies of the Earth rendered plain, no mountains, no Vallies, no inequalities would be therin, but the Superficies thereof would have been as level as the Superficies of the Water."

Matthew Hale,
The Primitive Origination of Mankind,
p. 95, (London, 1677)

“[Erosion] would certainly reduce all the Mountains of the Earth, in tract of time, to equality; or rather lay them all under Water: for whatsoever moulders or is washt away from them, is carried down into the lower grounds, and into the Sea, and nothing is ever brought back again by any circulation: Their losses are not repair'd, nor any proportionable recruits made from any other parts of Nature. So as the higher parts of the Earth being continually spending, and the lower continually gaining, they must of necessity at length come to an equality.”

Thomas Burnet,
The Theory of the Earth,
I, Bk. I, pp. 37-38, (London 1684)