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RATES OF SURFACE PROCESSES ON SLOPES, SLOPE RETREAT AND DENUDATION

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ABSTRACT

Results taken from 270 publications on rates are summarized, and collated with those from 149 publications reviewed previously (Young, 1969, 1974). The data are classified by major climatic zone, normal or steep relief, and consolidated or unconsolidated rocks. Representative rates and their ranges are given for soil creep, solifluction, surface wash, solution (chemical denudation), rock weathering, slope retreat, cliff (free face) retreat, marine cliff retreat, and denudation, the last being compared with representative rates of uplift. Solifluction is of the order of 10 times faster than soil creep, but both cause only very slow ground loss. Solution is an important cause of ground loss for siliceous rocks, on which it may be half as rapid as on limestones. Total denudation, brought about mainly by surface wash, reaches a maximum in the semi-arid and probably also the tropical savanna zones. Acceleration of natural erosion rates by human activities ranges from 2–3 times with moderately intense land use to about 10 times with intensive land use (and considerably higher still where there is recognized accelerated soil erosion). Where there is active uplift, typical rates are of the order of 10 times faster than denudation, although in some high, steep mountain ranges these may approach equality.

KEY WORDS Denudation *Erosion rates* *Slope processes*

INTRODUCTION

In 1960 little was known about the absolute rates of operation of geomorphological processes on slopes. Reasons were the slowness of such activity in comparison with a human lifetime, the previous concentration of research effort on landforms rather than processes, and the low level of technical sophistication of most geomorphologists at the time.

A revolution in geomorphology followed, which led to as much or more attention being paid to processes as to form (Young, 1978). A steady stream of publications emerged reporting measured rates of processes, particularly surface processes on slopes and total denudation. In 1969 one of the present authors summarized 40 estimates of rates of denudation, and in 1974 a further 109 records of processes on slopes and slope retreat (Young, 1969, 1974). For the period 1960–74 there were about 10 such 'rate' publications per year. In the seven years since the latter study we have assembled a further 270 such publications, or nearly 40 per year. Moreover, this latter collection is certainly less comprehensive than the former, and trying to keep up with current publication is like cleansing the Augean stables. Here we present a summary of such records to date.

For obvious practical reasons, a high proportion of field measurements cover activity over 1–3 years. The main exceptions are three long-period records of soil creep over 12 years by Young (1978), 17 years by Jahn (1981), and 21 years by Hauswirth and Scheidegger (1976). An earthflow in New Zealand has been monitored for 14 years (Anon, 1977). However, the limitations inherent in short-term records have been modified by the

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addition of results of a different nature, namely estimates for longer periods based on archaeological evidence, dendrochronology, and/or geological reconstruction. Reassuringly, results for such periods confirm in order of magnitude those obtained by direct measurement. For example, the rate of denudation over the eastern seaboard of North America as estimated from present-day river loads is very similar to that obtained as an average for the 225 M years since the Triassic (Gilluly, 1964).

We have only attempted brief analyses of each set of data. The coverage of non-English publications is less comprehensive than English. For surface wash, the control plots on soil erosion experimental stations could form the subject of an independent review. The literature on hydrology contains abundant records of river loads; some of this has been used here, but more could no doubt be analysed in terms of denudation rates. A variety of minor processes exist, particularly those related to fauna; these have been omitted partly for reasons of space and partly because there is no comparable climatic coverage. There is scope for others to amplify the presentation given here, by adding further data, by more extended discussion of the possible sources of error in the measurement of each process, and by more comprehensive analyses of the results.

TREATMENT OF THE DATA

The data in the sources is highly heterogeneous, and fairly drastic measures have been taken to reduce it to a form in which results from different studies are comparable. In default of sufficient evidence for the relative reliability of such a wide range of data, all reported results have been treated as if they were of equal standing. All results for slope retreat or ground loss are converted into Bubnoff units, B, where 1 B = 1 mm per 1000 years, equivalent to 1 μm per year, 1 m per million years, and 1 $m^3\ km^{-2}$ per year; in terms of mass, for rocks of s.g. 2.65, 1 B is approximately 0·02 t/ha per year. Arithmetic means of a set of observations are often not available, and the description 'mean' is used here to refer also to a typical or approximately central value. Where authors report a range of values this is given, except that apparently exceptional extremes are omitted; thus a set of data such as 0·05, 1, 2, 4, 4, 5, 7, 10 and 88 B would here be reported as a 'range' of 1–10 B. If both a mean and a range are reported, these are given in the tables as follows, e.g. 5: 1–10. Results in Bubnoff units nominally refer to ground loss, perpendicular to the ground surface, and hence to slope retreat or ground lowering according to steepness; the accuracy of results is never sufficient to justify refined distinctions between horizontal retreat, vertical lowering or perpendicular ground loss.

The main variables affecting rates of processes on slopes are climate (with associated vegetation), rock type, slope steepness, and the influence of man. The aim of this study is to obtain natural rates, without acceleration by man, although as discussed below this is often impossible; however, the many records which are intentionally of accelerated soil erosion (agricultural or other) are omitted. A simple and highly generalized classification of climate is adopted, as follows:

Climate	Abbreviation in Figures 1–5	Approximate Köppen equivalent	
Glacial	—	—	Presently covered by ice.
Polar/montane	P/M	E	Periglacial; includes both polar regions and temperate-latitude montane areas.
Temperate maritime	Tm	Cfb, c	Including Western Europe and the eastern seaboard of USA.
Temperate continental	Tc	Df	Including Central and Eastern Europe and humid interior USA.
Mediterranean	Med	Cs	Including similar climates in other continents e.g. California.
Semi-arid	S-A	BS	Approximately rainfall 250–500 mm in subtropical and tropical latitudes.
Arid	—	BW	Below approximately 250 mm rainfall.
Subtropical humid	ST	Cfa	E.g. southeastern USA, Natal.
Savanna	TrS	Aw	Tropical climates with wet and dry seasons.
Rainforest	TrR	Af, Am	Permanently humid tropical climates.

Rock types are listed as given in sources; in the interpretation of results particular note is taken of unconsolidated rocks such as clays and glacial drift. For chemical denudation, limestones are distinguished. Slope steepness is classified into 'steep' and 'normal', where steep refers to mountainous or other steeply-dissected regions, or individual slopes above 25°. Special note is taken of badland relief.

The *tables* are supplementary to those in Young (1974). The *figures*, on the other hand, include additionally data in the 1974 paper. To reduce the otherwise very large number of *references*, most are referenced by giving their abstract number in Geo Abstracts (see note under REFERENCES).

SOIL CREEP

There is no sharp distinction between soil creep (Table I and Figure 1) and solifluction, and some studies in montane environments, recording rates of soil movement normally associated with solifluction, describe the results as creep. All records of soil movement from polar and montane regions have been classed here as solifluction.

The Bubnoff unit is not applicable to creep and solifluction since nearly all results refer not to ground loss but to downslope movement of the soil. This is given either as a linear movement close to the surface, as $mm^{-1}y$, or as a volumetric movement, as $cm^3\ cm^{-1}\ y^{-1}$ (cubic centimetres per centimetre width of slope, per year). Conversion between these units depends on the depth distribution of movement, but where both are reported they are usually within a numerical range of $\times 0{\cdot}5$ to $\times 3$.

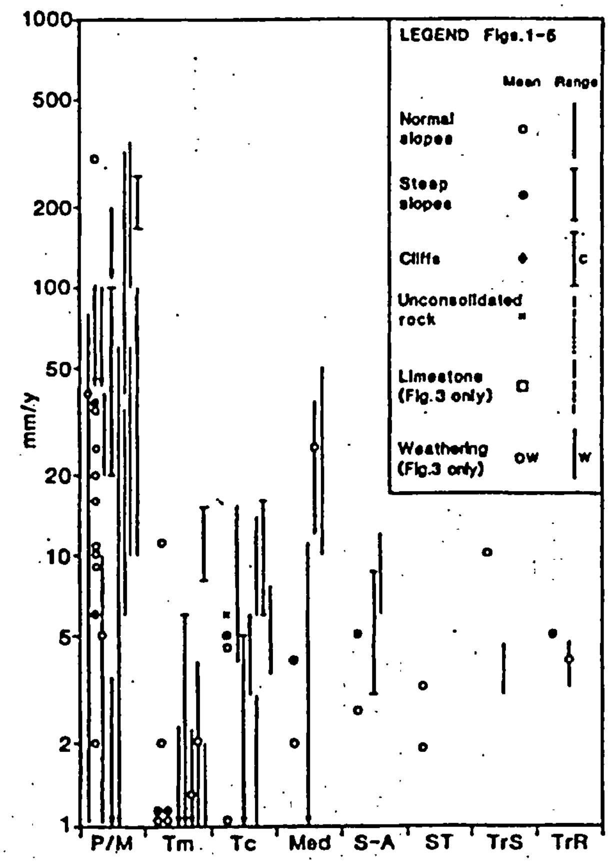

Figure 1. Rates of solifluction (polar and montane climates) and soil creep. Rates refer to linear movement close to the ground surface. Note that scales in Figures 1–5 are logarithmic. For abbreviations of climatic zones, see p. 474.

Table I. Rates of soil creep. Rates in Tables I–IX are supplementary to those listed in Young (1974). For citation of references, see note on p. 499.

Climate	Rock	Slope angle degrees	Movement Surface (mm y^{-1})	Movement Volumetric (cm^3 cm^{-1} y^{-1})	Method	Location	Source	*Geo. Abstracts* No.	Notes
Temperate maritime	Silurian mudstone	27°	0·3–6	1–3	Young pits	Aberystwyth, Wales	Day, M. J. (1977)	—	
Temperate maritime	Colluvium	11°	1·3:0·4–2·2		Six methods	Weardale, England	Anderson, E. W., and Cox, N. J. (1978)	79A/1206	Maximum rate at 25 mm below root mat
Temperate maritime	Various	2·5°–24°		1·5–2·5	Three methods	Taunus Mts, Germany	Göbel, P. (1977)	—	Movement to 10–15 cm depth
Temperate maritime	Igneous	Steep	8–15	200	Inclinometers	Oregon, U.S.A.	Swanson, F. J., and Swanston, D. N. (1977)	79A/0126	Deep creep, to 15 m; rates correlated with soil moisture
Temperate maritime	Sandstone	0–25°		4	Plates	Mendips, U.K.	Finlayson, B. (1977)	78A/0763	
Temperate maritime	Carboniferous sandstone	25°	0·25	0·6	Young pit	Derbyshire, England	Young, A. (1978)	79A/1216	12 y record; also vertical movement
Temperate maritime	Carboniferous mudstone	11° average	0·3–2·4	0·4–1·2	Six methods	Weardale, U.K.	Anderson, E. W. (1977)	—	Rate correlated with soil moisture. Good agreement between different methods
Temperate maritime	Chalk plus drift	25°	1		Buried cylinders	Netherlands	Nieuwenhuis, J. D., and Kleinendorst, D. (1971)	72A/2073	Movement to 20 cm depth
Temperate maritime	Pumaceous deposits	7°–33°	2:1–4	25–50	Buried cones	North I., New Zealand	Selby, M. J. (1974)	74A/1795	Rates increase with depth, to 4–7 mm y^{-1} at 75 cm
Temperate continental	Granite schist	8°–39°	3–6		Buried pillars	Sudety Mts., Poland	Jahn, A. and Cielinska, M. (1974)	75A/1082	10 y; movements to 25 cm depth
Temperate continental	Various	8°–39°	4–15		Buried pillars and tubes	Sudety Mts., Poland	*Jahn, A. (1981)*		*19 pits at 4 sites; one site 17 y*

Temperate continental	Granite schist	8°–39°	3–6		Buried pillars	Sudety Mts., Poland	Jahn, A. and Cielinska, M. (1974)	75A/1082	10 y movements t[illegible] m depth
Temperate continental	Various	8°–39°	4–15		Buried pillars and tubes	Sudety Mts., Poland	Jahn, A. (1981)		[illegible] at 4 sites; one site 17 y
Temperate continental	Clay	70°	6–16		Inclinometer	Ottawa, Canada	Eden, W. J. (1977)	78A/1948	
Temperate continental	Limestone	Steep	0–5		Surface markers	Hallstatt, Austria	Hausworth, E. K., and Scheidegger, A. E. (1976)	76A/1992	21 y record
Temperate continental	Loam	5°–28°		5–15	Young pits	S. W. U.S.S.R.	Dedkov, A. P. *et al.* (1978)	79A/1219	Rates correlated with soil moisture
Temperate continental	Badlands	—	6		Surface markers	N. Dakota, U.S.A.	Clayton, L., and Tinker, J. R., (1971)	74A/0370	
Temperate continental	—	15°–24°	6–14		Buried tubes	E. Sudetes, Poland	Jahn, A. (1979)	79A/2785	Movement to 11 cm depth
Temperate continental	—	Steep	5		Surface stones	Hamilton, Wisc., U.S.A.	Black, R. F., and Hamilton, T. D. (1971)	73A/0860	Surface 2–20 mm y^{-1} on terracettes. Also vertical movement
Mediterranean	Sandstone, claystone	7°–8°	0–11		Buried pipes, tiltmeter	Calif., U.S.A.	Fleming, R. W. (1976)	77A/0086	Maximum rate occurs following wetting
Mediterranean	Sandstone, claystone	7°–8°	25:12–37	150:105–195	Buried pipes, tiltmeter	Central Calif., U.S.A.	Fleming, R. W., and Johnson, A. M. (1975)	75A/1080	Clay soil, probably with montmorillonite
Mediterranean	Granite	Steep normal	4 2	1·7	Young pits	Catalan Ranges, Spain	Sala, M. (1981)		
Semi-arid	—	8°	2·6	1·5	Young pits	La Paguera, Puerto Rico	Lewis, L. A. (1975)	76A/0076	
Subtropical humid	Granite Sandstone	2°–21°		1·9 3·2	Young pits	N.S.W., Australia	Williams, M. A. J. (1973)	74A/0425	
Tropical savanna	—	—	3·0–4·6	2·1–3·4	Young pits, with strips	Puerto Rico	Lewis, L. A. (1976)	77A/1381	
Tropical savanna/ rainforest	Alluvium	8°–15° max. 30°	10		Surface markers	Guyana	Kesel, R. H. (1977)	78A/0747	Under forest
Tropical rainforest	—	17°–20°	4:3·2–4·6	7–9	Young pits	Puerto Rico	Lewis, L. A. (1974), (1976)	74A/0877 77A/1381	Listed in Young (1974) as unpublished

Of the many techniques which have been devised, that of pits with buried rods or plates, infilled and re-excavated after a period of years (Young pits) has been the most widely used. It also has the potential for recording vertical movements as well as movements parallel to the ground surface. Also successfully used have been surface rods, buried and re-excavated cylinders, cylinders with tilt recorded by viewing cross-wires vertically, and deformation of plastic tubes, although this last is near to its limit of sensitivity for creep. Notable agreement between different techniques (coupled with a relationship of creep rate to soil moisture) was achieved by Anderson (1977).

The largest number of records are for the temperate climates. Surface movement in the temperate maritime zone is predominantly 0·5–2 mm y^{-1}, with appreciable movement typically extending to 20–25 cm depth. A strong relationship with soil moisture usually masks any possible correlation with slope angle. In the temperate continental zone rates may occasionally be as low as the maritime climates but are more often higher, 2–10 mm y^{-1}. Results for the remaining climates are too few to make confident generalizations.

In Mediterranean, semi-arid, and savanna climates, whatever the absolute rate of creep may be it is probably rendered unimportant by higher rates of surface wash. It would be of interest to have more data for the rainforest environment, with its deep, moist regolith and high activity of soil fauna; the available results agree at 4–5 mm y^{-1}.

Creep represents downslope transfer of regolith, and as such cannot be directly translated into ground loss. Putting observed rates of volumetric movement into process-response models has demonstrated that ground lowering through the agency of creep is very slow indeed except on convexities of high curvature (e.g. Young, 1963, 1972, p. 115). Thus creep can only be an important cause of ground loss (as distinct from smoothing of breaks of slope) if all other processes are slow.

SOLIFLUCTION

Solifluction (Table II and Figure 1) is more easily measured than creep owing to its faster rates. The method of buried plastic tubes, with deformation measured by inclinometers or strain gauges, is successful, whilst the techniques employed for soil creep can also be used. Movements recorded here include both the components which contribute to regolith movement in solifluction, frost creep (heave), and gelifluction (flow).

Rates cover a wide range, from less than 1 to over 300 mm y^{-1}, but the greater number of records are clustered in the range 10–100 mm y^{-1}. Movement typically extends to 50 cm depth, and is considerably more rapid on moister sites. Thus solifluction in the polar and montane zones is some 10 times faster than soil creep in the temperate zone; this may not necessarily be true of the land surface as a whole, however, owing to bias in selecting sites for measurement of solifluction on which the process is seen to be particularly active. As with creep, the effects of quite rapid downslope soil movement produce only slow ground loss; thus Jahn (1981) calculated that solifluction at 20 mm y^{-1} would cause retreat of a slope 100 m long by only 0·05 mm y^{-1} or 50 B.

SURFACE WASH

Techniques for measurement of surface wash (Table III and Figure 2) employ one of two principles: collection of transported sediment or measurement of ground loss. Ground loss can be recorded directly by erosion pins, marked rods on which a washer is placed to record the position of the ground surface, but this technique is only sensitive to rates exceeding 1000 B. Sediment collection is by some form of wash trap: simple tins with the upper rim just below the ground surface, more complex combinations of metal or plastic guttering with tubes and collection bins (Gerlach troughs), or the enclosed plots with cement outlet rims as employed on agricultural soil erosion research stations. All suffer from the problem of edge effects, the disturbance of the ground at the point of collection. Conversion of sediment transport to ground loss is straightforward if the catchment is enclosed, but this further disturbs the surface; otherwise, it is possible to assume that the effective catchment is an area the width of the collecting rim extending to the crest of the slope, although this is questionable. Moreover, when traps have been installed at intervals down a slope (offset laterally), with the intention of obtaining ground loss as different in sediment collected by adjacent traps, an irregular pattern

Table II. Rates of solifluction

Climate	Rock	Slope angle degrees	Movement Surface mm y^{-1}	Volumetric cm^3 cm^{-1} y^{-1}	Method	Location	Source	*Geo Abstracts* No.	Notes
Polar	Till	4°–17°	10–60		Surface markers	Norway	Harris, C. (1972)	72A/2455	Frost heave; moisture content more important than angle
Polar	Granitic	14°–22°	6–35		Plastic tubes, strain gauge	Yukon Territory, Canada	Price, L. W. (1973)	75A/0296	Depth of movement 10–66 cm
Polar	Till	4°–17°	0–60	75	Young pit	Norway	Harris, C. (1973)	73A/1797	Movement to 15–40 cm depth
Polar	Till	4°–17°	16		Young pit	Norway	Harris, C. (1977)	77A/1532	Movement to 50 cm depth; no internal shearing
Polar	—	—	10		—	N.W. Territory, Canada	Kerfoot, D. E., and Mackay, J. R. (1972)	74A/2003	
Polar	Till	30°–50°	6		Strain probe	S.E. Alaska	Barr, D. J., and Swanston, D. N. (1970)	71A1625	Moisture content important; movement to 15–46 cm depth
Polar	—	—	20–40		Surface markers	Svalbard	Jahn, A. (1976)	77A/1538	
Montane		Steep	168–260		—	Alberta, Canada	Harris, S. A. (1972)	73A/1238	Rates related to aspect and log sin θ, fastest on S-facing
Montane	Various	3°–20°	40–323		Plastic tubes	Alberta, Canada	Harris, S. A. (1973)	74A/1320	Movement of saturated soil on thawing
Montane	Various	—	0·6–3·5		—	Colorado, U.S.A.	Benedict, J. B. (1976)	76A/1719	Lobes and frontal terraces only
Montane	Igneous	10°–15°	100–350	13	Young pit, surface markers	British Columbia, Canada	Mackay, J. R., and Mathews, W. H. (1974)	75A/0891	Needle ice the most important agent
Montane	—	Steep	20–100		—	Alps, France	Pissart, A. (1972)	73A/1043	
Montane	—	Steep	37		Surface markers	Alps, Switzerland	Gamper, M. (1981)		Frost creep and gelifluction; vegetation hampers solifluction
Montane	Rhyolite	10°–30°	10–100		Surface markers	Japanese Alps	Sohnia, H. *et al.* (1979)	80A/0995	Frost creep

Table III. Rates of surface wash. B = Bubnoff units = mm 1000y^{-1}

Climate	Rock	Relief	Ground Lowering B	Volumetric movement $cm^3 cm^{-1} y^{-1}$	Method	Location	Source	*Geo Abstracts* No.	Notes
Temperate maritime	—	Normal	2·3		Traps	Luxembourg	Van Zon, H. J. M. (1978)	78A/1399	
Temperate maritime		Normal	1·3		Traps	Bedfordshire, England	Morgan, R. P. C. (1977)	77A/1174	Accelerated, 160 B
Temperate maritime	Silurian mudstones	Normal	0·4–0·6		Traps	Wales	Day, M. J. (1977)	—	Maximum at crest of slope
Temperate maritime	Sandstone	Normal	1·5–3·5		Stream sediment yields	Mendip Hills, England	Finlayson, B. (1977)	78A/0763	Includes wash plus solution
Temperate maritime	Sandstone, shales	Normal	0–10 000		Erosion pins	Yorkshire, England	Imeson, A. C. (1974)	74A/1720	Accelerated by heath burning
Temperate maritime	Shales, grits	Normal	34–2285		Traps, erosion pins	Peak district, England	Evans, R. (1974)		Accelerated by overgrazing of sheep
Temperate maritime	Colluvium	Normal	241–1126		Traps	Luxembourg	Imeson, A. C. *et al.* (1980)	80A/1611	Rates very variable
Temperate continental	—	Normal	12 000		Erosion pins	Ontario, Canada	Pearce, A. J. (1976)	77A/0334	Accelerated by two orders of magnitude by vegetation destruction
Temperate continental	—	Steep	1·3		Traps	Poland	Lankauf, K. R. (1975)	76A/0398	By rain and snow melt; correlation with slope angle; accelerated 670 B
Temperate continental	—	Normal	8–17		Various	Eastern USA	Patric, J. H. (1976)	77A/0723	For forested land
Temperate continental	Flysch	Steep	1300–9600		Traps	Carpathians, Poland	Gerlach, T. (1976)	77A/1389	Strongly affected by vegetation cover
Temperate continental	Badlands	Steep	3750–5000		Measuring frame	Alberta, Canada	Campbell, I. A. (1974)	75A/0648	Slope angle not a major influence

Temperate continental	Flysch	Steep	1300–9600		Traps	Carpathians, Poland	Gerlach, T. (1976)	77A/1389	Strongly affected [illegible]getation
Temperate continental	Badlands	Steep	3750–5000		Measuring frame	Alberta, Canada	Campbell, I. A. (1974)	75A/0648	Slope angle not a major influence
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Temperate continental	Badlands	Steep	2800–10400		—	N. Dakota, USA	Clayton, L., and Tinker, J. R. (1971)	74A/0370	Varies with aspect and rock formation
Temperate continental	Various	Normal	0·03		Traps	Beskids, Poland	Czeppe, Z. (1970)	71A/1192	Under forest; 100 × higher under pasture
Mediterranean	Granite	Steep Normal	7500 5000		Traps	Catalan Ranges, Spain	Sala, M. (1981)		
Arid	Metamorphic	Normal	2·6:1·2–6·9		Traps	S. Israel	Yair, A., and Klein, M. (1973)		Inverse relation to θ, because coarser debris on steep slopes
Semi-arid	—	Normal		4–5	Erosion pins	Arizona, USA	Kirkby, A., and Kirkby, M. J. (1974)	75A/0448	In braided channels 100 × faster
Subtropical humid	Badlands	Steep	17400		Measuring frame	Hong Kong	Lam, K.-C. (1977)	78A/0651	
Subtropical humid	Granite Sandstone	Normal	54 103		Traps	N.S.W., Australia	Williams, M. A. J. (1973)	74A/0425	
Tropical savanna	Granite Sandstone	Normal	54 56		Traps	N. Territory, Australia	Williams, M. A. J. (1973)	74A/0425	
Tropical savanna	Sandstone	Normal	7:0·6–10		Traps	Mato Grosso, Brazil	Townshend (1970) and personal communication	71A/0465	
Tropical rainforest	Various	Normal	2–67		Traps	Ivory Coast	Roose, E. (1977)		
Tropical rainforest	Shale	Normal		0·3	Traps	Malaya	Leigh, C. H. (1978)		Dissolved load 6% of total
Tropical rainforest	—	Steep		2·3	Traps	Jamaica	Richardson, J. H. (1979)		
Tropical rainforest	—	Normal	40		Traps	Ivory Coast	Roose, E. J. (1970)		Erosion selective toward 0–20 μ particles

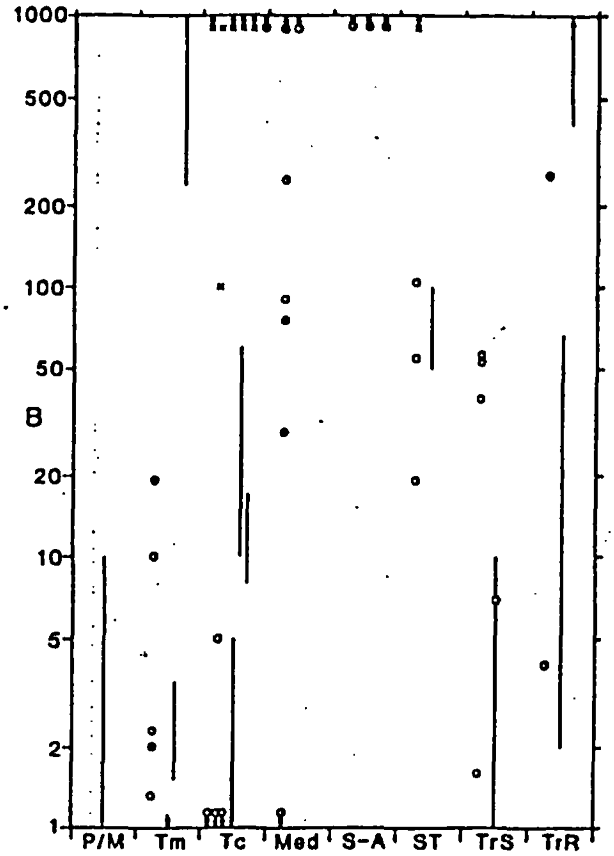

Figure 2. Rates of surface wash. B = Bubnoff units, = 1 mm/1000 y^{-1}

including areas of ground gain has been recorded (Townshend, 1970). It would be of much interest to combine erosion pins with traps at intervals down a slope undergoing rapid wash.

Downslope transport can be achieved by rainsplash alone, without any surface runoff. As this process has not often been recorded separately, it is included here with wash.

The wide scatter of values for rates of surface wash reflects the fact that this process is highly dependent on vegetation cover. Five studies in temperate climates have obtained a ground lowering of less than 2 B, which is probably the minimum obtainable owing to disturbance caused by installation of instruments. On the other hand, once unconsolidated rocks are dissected into badlands, rates rise above 1000 B, or 1 mm y^{-1}. The same high order of magnitude can occur on normal rocks in the semi-arid zone, caused by intense rainstorms falling on ground poorly protected by vegetation. Results in the range 10–100 B are found for Mediterranean, subtropical humid, and savanna climates. Wherever Man has removed or reduced the natural vegetation cover, rates of wash are accelerated enormously, often by two orders of magnitude.

Seven reports of *gullying* (not reproduced) show rates either of headward channel development or ground lowering of the order of 1000–100 000 B, or 1 cm to 1 m per year.

SOLUTION (CHEMICAL DENUDATION) AND WEATHERING

Limestone geomorphologists have always recognized that loss of rock material in chemical solution is the main cause of denudation (Tables IV and V and Figure 3), and were the first to record rates for this process. It is now firmly established that solution is also a major process on siliceous rocks; this is demonstrated by the quantities

Table IV. Rates of solution, or chemical denudation

Climate	Rock	Ground loss	Method	Location	Source	*Geo Abstracts* No.	Notes
Polar	Limestone	40–100	Review	Climatic zone	Smith, D. I., and Atkinson, T. C. (1976)	77A/0103	
Polar	Limestone	2	Water sampling	Somerset I., N. Canada	Smith, D. I. (1976)	72A/2492	
Polar	Limestone	11	Water sampling	Spitzbergen	Hellden, U. (1973)	73A/1975	
Montane	Various	19–132	Dissolved river load	Caucasus, U.S.S.R.	Gabrielyan, H. (1971)	73A/1888	
Temperate maritime	Limestone	75–83	Dissolved river load	Pennines, UK	Pitty, A. F. (1968)	69A/0838	
Temperate maritime	Devonian Carboniferous	13–29	Dissolved river load	Devon, UK	Walling, D. E., and Webb, B. W. (1978)	78A/1175	
Temperate maritime	Limestone	51	Dissolved river load	Fergus Basin, Ireland	Williams, P. W. (1963)	64/0122	
Temperate maritime	Devonian	5–8	Hydropedology	Luxembourg	Verstraten, J. M. (1977)	77A/2153	
Temperate maritime	Mesozoic sedimentary	54	Dissolved river land	Sussex, U.K.	Collins, M. B. (1981)		
Temperate maritime	Various	20–60	Dissolved river load	United Kingdom (general)	Douglas, I. (1964)	65/0696	
Temperate maritime	Silurian greywackes	2	Dissolved river load	Montgomeryshire, Wales	Oxley, N. C. (1974)	74A/1721	
Temperate maritime	Sandstone	1·6	Hydrochemical budget	Mendips, U.K.	Waylen, M. J. (1979)	79A/2536	
Temperate maritime	Crystalline rocks	0–12	Dissolved river load	West Germany, Luxembourg	Hohberger, K., and Einsele, G. (1979)	80A/0854	Much higher rates than for non-dissolved load
	Sandstone	2–14					
	Shales, slates	6–18					
	Limestone, dolomite	24–42					
	Gypsum, anhydrite	400					
	Sand and gravel	0–36					
Temperate maritime	Limestone	50–100	Water sampling	Mendips, U.K.	Drew, D. P. (1974)	74A/1322	
Temperate	Limestone	20–110	Review	Climatic zone	Smith, D. I., and Atkinson, T. C. (1976)	77A/1013	
Temperate continental	Various	4–29	Dissolved river load	N.E. and central U.S.A.	Douglas, I. (1964)	65/0696	
Temperate continental	Siliceous	14–19	Dissolved river load	Bialej Lady basin, Poland	Buraczynski, J., and Michalczyk, Z. I. (1973)	76A/1100	
Temperate continental	Various	36–60	Dissolved river load	Czechoslovakia	Starkel, L. (1962)	64/0778	

Table IV—*Contd.*

Climate	Rock	Ground loss	Method	Location	Source	*Geo Abstracts* No.	Notes
Temperate continental	Flysch	17	Dissolved river load	Carpathians, Poland	Gerlach, T. (1976)	77A/1389	
Temperate continental	Sandstone, shale	50–73	Dissolved river load	Carpathians, Poland	Welc, A. (1978)	80A/0429	Include dissolved input from precipitation and fertilizers
Temperate continental	Siliceous metamorphic	13–38	Dissolved river load	New Hampshire, U.S.A.	Johnson, N. M. *et al.* (1968)	69A/1318	
Temperate continental	Limestone	30–100	Water sampling	Tatra Mts, Poland	Kotarba, A. (1972)	73A/1083	
Arid	Limestone	3	Review	Climatic zone	Smith, D. I., and Atkinson, T. C. (1976)	77A/0103	
Semi-arid	Various	1–12	Dissolved river load	Western U.S.A.	Douglas, I. (1964)	65/0696	
Semi-arid	—	10–19	Dissolved river load	Wyoming, U.S.A.	Hembree, C. H., and Rainwater, F. H. (1959)		
Tropical semi-arid/savanna	Igneous and metamorphic silicates	3–10	Dissolved river load	Kenya	Dunne, T. (1978)	79A/0005	Solution = $0.28R^{0.66}$, R = mean annual runoff
Subtropical humid	Various	0·23	Dissolved river load	N.S.W. Australia	Douglas, I. (1978)	80A/0857	
Subtropical humid	Limestone	24:11–41	Groundwater analysis	N.S.W., Australia	Jennings, J. N. (1972)	73A/1649	Wide variability from year to year
Subtropical humid	Siliceous	2–3	Dissolved river load	Hong Kong	Lam, K.-C. (1974)	—	
Tropical savanna	Granite	6–15	Dissolved river load	Zimbabwe	Owens, L. G., and Watson, J. P. (1979)	79A/3024	Rate is for calculated soil formation
Tropical savanna	Granite	8	Groundwater analysis	Uganda	Trendall, A. F. (1962)	63/0025	
Tropical humid	Limestone	30–100	Review	Climatic zone	Smith, D. I., and Atkinson, T. C. (1976)	77A/0103	
Tropical rainforest	Various	2–6	Dissolved river load	Malaysia; Queensland, Australia	Douglas, I. (1978)	80A/0857	

Table V. Rates of rock weathering

Climate	Rock	Weathering Loss B	Method	Location	Source	*Geo. Abstracts* No.	Notes
Montane	Rhyodacite	4–5	Rock tablets	Colorado, U.S.A.	Caine, N. (1979)	80A/1347	
Temperate maritime	Marble, sandstone	90:197–210	Tombstones	Edinburgh, Scotland	Geikie, A. (1880)	—	Pioneer study; not included in Figure 3
Temperate maritime	Sandstone	8–13	Rock tablets	Mendips, England	Finlayson, B. (1977)	78A/0763	
Temperate maritime	Carboniferous limestone	2·5:1·2–3·6	Tombstones	Belgium	Kupper, M., and Pissart, A. (1974)	—	Faster in industrial area than rural cemetry
Temperate maritime	Silurian mudstone	1–2	Rock tablets	Wales	Day, M. J. *et al.* (1980)	81A/0849	Faster in topsoil than deeper horizons
Temperate continental	Quartzite Gabbro	119 126	*In situ* disintegration	Sudbury, Ontario, Canada	Pearce, A. J. (1976)	76A/1018	
Tropical rainforest	Coral limestone	260:100–500	Micro-erosion meter	Aldabra I., Indian Ocean	Trudgill, S. T. (1976)	77A/0922	Subaerial weathering
Tropical rainforest	Silurian mudstone	3	Rock tablets	Malaysia	Day, M. J. *et al.* (1980)	81A/0849	Faster within soil than exposed on surface

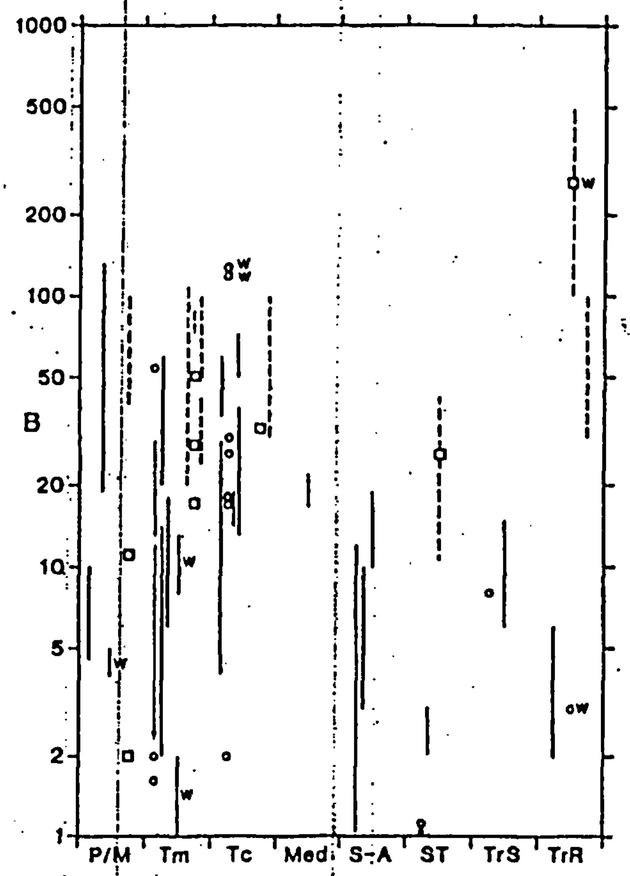

Figure 3. Rates of solution, or chemical denudation, and weathering

of soluble salts, exchangeable cations and silica in river waters, and by the relative loss of these elements as evidences in the chemical composition of soils. Thus the largely theoretical calculations of solution loss made by Carson and Kirkby (1972, pp. 242–271) are now substantiated by field evidence.

Most of the data are obtained by sampling river water, analysing for dissolved constituents, calibrating in relation to discharge records, and then dividing the dissolved material by the catchment area. Thus solution of river channels (and, on limestones, caves and fissures) is included. On slopes, the technique devised to measure (water) throughflow, consisting essentially of Gerlach troughs installed at various depths in a pit, can be employed to record laterally-transported dissolved load (Day, 1977). A few observers have measured dissolved substances added to the catchment in rainfall, finding that this can account for amounts of the order of 25 per cent of the total dissolved output.

The bulk of the results refer to humid temperate climates. Taking maritime and continental areas together, results for siliceous rocks are clustered in the range 2–50 B, whilst limestones span 20–100 B. For other climates records are fragmentary, most often 2–20 B and showing no clear relations with temperature or rainfall. Thus rates for siliceous rocks overlap those for limestones, with some suggestion that under otherwise equal conditions they may be of the order of half as high. Where both dissolved and suspended load has been recorded for the same catchment, they are usually of comparable magnitude.

Results in Table V refer to *weathering*, by which is meant the loss of matter from rock surfaces. There are three techniques for measuring this: weighing prepared rock tablets, the micro-erosion meter, or studying historical monuments. Results vary through two orders of magnitude, 2–200 B, being no doubt strongly influenced by lithology. Day *et al.* (1980) contrived to bury discs from the same (Welsh) site in humid temperate and rainforest climates, and were relieved to find that weathering of the latter was 3½ times faster, although absolute rates were very low.

SLOPE RETREAT BY LANDSLIDING

Estimates of the average rate of slope retreat by landsliding (Table VI) can be obtained by combining the volumes of debris for individual mass movements with their spatial distribution, and then finding some way of estimating their frequency of occurrence. Irrespective of climate, reported results are clustered in the range 500–5000 B, or 0·5–5·0 mm y^{-1}. These high rates refer, of course, to areas chosen for their evidence of active landsliding. With regard to the magnitude/frequency question (i.e. which accomplishes more denudation, occasional catastrophic events or long-continued slow-acting processes), the results serve only to confirm what could reasonably have been presumed: that where there are many visible landslides or their scars, the effects of these outweigh the mass transport accomplished by continuous processes.

Speeds of landslide movement are now commonly estimated or, for slower examples, recorded directly, including by motion-picture films (La Chapelle and Land, 1980; D. E. Prior, pers. commun.). They range from as low as 1–10 mm y^{-1} for earthflows to debris avalanches and mudflows moving at 20 m s^{-1}, as fast as flowing water on a steep slope. We have not systematically collected landslide volumes, but any bids for the largest single slide will have to exceed the 130 Mt of the Hope Landslide, British Columbia (Mathews and McTaggart, 1969).

SLOPE AND CLIFF RETREAT

By various means it has sometimes been possible to estimate the rate of ground loss from a slope, as distinct from the effects of a particular process (Tables VII, VIII, and IX, and Figure 4). Techniques include erosion pins inserted in the slope, recording the rate of rockfall or talus material accumulating below a cliff, and geological or geomorphological reconstruction of the former position at an assumed time, this last approach allowing an estimate for long periods. For unconsolidated rocks, repeated surveying or (especially for marine cliffs) comparison with early maps can be employed. Paired photographs at long time intervals, so useful for recording vegetation change, do not usually show visible slope changes; years ago M. Arber failed to detect changes from photographs of Devon cliffs taken by her father E. A. Arber 50 years previously, and very carefully relocated photographs of the Grand Canyon of Colorado 100 years apart show even apparently loose rocks in the same positions (Shoemaker and Stephens, 1975).

The data are grouped according to whether there is a regolith cover, termed slopes, or a free face (bare rock), termed cliffs. Most recorded results are for temperate and montane environments and span two orders of magnitude, 10–1000 B; for hard rock cliffs a value of 100 B, or 0·1 mm y^{-1}, appears typical. Values in other climates are widely scattered. Rates for unconsolidated rocks are mainly 2000 B and upwards; in the one exception to this, the dating of fault scarps on which the evidence rests is stated to be unsure (Wallace, 1977).

Rates of *river bank erosion* have been the subject of a separate review by Hooke (1980). Rates in actively undercut alluvium usually exceed 50 mm y^{-1}. The fastest recorded retreat of a slope of any kind appears to be a bluff of the Mississippi at 250 MB, or 250 m y^{-1}.

The retreat of *marine cliffs* probably spans three ranges. For unconsolidated glacial drift an average rate of 1 m y^{-1} has been established as typical both for the eastern coast of England and for the North American Great Lakes; but major storms can set off landslides which cause retreat of 10 m or more in a day. Recorded retreat of cliffs in consolidated rocks range from 4000 to 800 000 B. There is a third group, however, not shown in the table since nobody tries to measure their retreat; cliffs in crystalline and hard Palaeozoic sedimentary rocks show little or no response to Holocene changes in sea level, hence it appears likely that their retreat can average under 1 mm y^{-1}.

DENUDATION

More interest has been shown in rates of denudation (Table X and Figure 5) than in individual processes, and an appreciation of such rates is fundamental to the understanding of landform evolution. Denudation is here

Table VI. Rates of ground loss through landsliding

Climate	Rock	Relief	Ground loss B	Method	Location	Source	*Geo Abstracts* No.	Notes
Temperate maritime	Sedimentary	Normal	500–1000	Volume estimate	New Zealand	Selby, M. J. (1974)		Under forest. Under pasture becomes 2000–5000 B. 1 in 100 y forest event, 1 in 30 y pasture event
Temperate maritime	London Clay	Normal	3900–10 000	Historical data	Essex, England	Hutchingson, J. N., and Gostelow, T. P. (1976)	71A/0888	Man-accelerated
Temperate maritime	Sand, silt, clay	Steep	1500–2000	Historical data, erosion pins	Dorset, England	Brunsden, D. (1974)	75A/0450	Mudslides, rotational slips
Temperate maritime	Greywacke sandstone and siltstone	Normal	250–1000	Volume estimate	New Zealand	Selby, M. J. (1976)	76A/1999	Mainly debris avalanches
Temperate maritime	Clay, mudstone, marl	Steep	130 000–2 600 000	Historical data	Dorset, England	Brunsden, D., and Jones, D. K. C. (1980)	80A/2880	
Temperate maritime	Tertiary basalts	Steep	277–1617	Traps	Co. Antrim, Northern Ireland	Douglas, G. R. (1980)	80A/2879	Correlation with number of freeze/thaw cycles
Temperate maritime	Various	Normal	3800	Volume estimate	New Zealand	Eyles, R. J. (1971)	73A/1242	Possibly accelerated by deforestation
Subtropical humid	—	Steep	1000	Paired photographs	Japan	Tanaka, M., and Mori, M. (1976)	76A/1481	
Tropical savanna	Meta-igneous	Steep	270–540	Volume estimate	Tanzania	Temple, P. H., and Rapp, A. (1972)	74A/0087	Accelerated by forest clearance; 99% of landslides originate in cleared land
Tropical rainforest	Various	Steep	800–1000	Photographic survey, river load	Papua, New Guinea	Pain, C. F., and Bowler, J. M. (1973)	74A/0770	Earthquakes trigger off debris avalanches

Table VII. Rates of slope retreat

Climate	Rock	Relief	Ground loss B	Method	Location	Source	*Geo Abstracts* No.	Notes
Polar	Various	Normal	300	Volume estimates	Svalbard	Jahn, A. (1976)	77A/1538	
Temperate maritime	Slag waste	Normal	2300–3800	Erosion pins	Blaenavon, Wales	Haigh, M. J. (1977, 1978, 1979)	78A/1164, 79A/0552 80A/0514	Vegetated; 4800–9500 B unvegetated
Temperate maritime	Slag waste	Normal	2000	Erosion pins	Waunavon, Wales	Haigh, M. J. (1979)	79A/2364	Vegetated; 3000–6000B
Temperate continental	Igneous	Normal	13–18	Geological data	Quebec, Canada	Pearce, A. J., and Elson, J. A. (1973)	73A/1130	
Temperate continental	Loess	Steep	0–10 000	Bench marks, surveying	Poland	Koreleski, K. (1974)	74A/1786	Roadside cuttings and banks
Temperate continental	Badlands	Steep	7000	Periodic surveying	Alberta, Canada	Barendregt, R. W., and Ongley, E. D. (1978)	79A/2358	
Temperate continental	Slag waste	Steep	9500–10 400	Erosion pins	Oklahoma, U.S.A.	Haigh, M. J. (1978)	79A/0553	
Arid	Sandstone Granite	Normal	100–400 100–200	Geological data	Sinai	Yair, A., and Gerson, R. (1974)	75A/0456	Sporadic retreat by disintegration
Arid	Shales	Normal	0	Paired photographs	Utah, U.S.A.	Hunt, C. B. (1973)	73A/1230	30 y record
Semi-arid	—	Normal	431	Root exposure	Utah, U.S.A.	Eardley, A. J. (1966)	67A/1281	
Semi-arid	Unconsolidated	Steep	192	Dam sedimentation	S. E. Alberta, Canada	Barendregt, R. W., and Ongley, E. D. (1977)	79A/1723	Retreat due to piping
Semi-arid	Cretaceous sedimentary	Steep	3000	Geomorphological reconstruction	Colorado Plateau, U.S.A.	Schmidt, K-H. (1980)	80A/0011	
Sub-tropical humid	Clay, sedimentary	Steep	133	Geological data	N.S.W., Australia	Young, A. R. M. (1977)	78A/0785	
Tropical savanna	Igneous, metamorphic	Normal	3000	Erosion pins	Ghana	Aghassy, J. (1975)		Possibly accelerated
Tropical rainforest	Pleistocene coral reefs	Normal	31–42	Radiometric dating	Papua New Guinea	Dunkerly, D. L. (1980)	80A/2285	Over 280 000 y

Table VIII. Rates of retreat of cliffs (free faces)

Climate	Rock	Ground loss B	Method	Location	Source	*Geo Abstracts* No.
Polar (past)	Sandstone	23 000	Geological data	Wester Ross, Scotland	Sissons, J. B. (1976)	77A/1025
Montane	Various	20–1000	Field survey plus review	Tatra Mts., Poland	Kotarba, A. *et al.* (1979)	81A/0104
Montane	Various	2500	Talus volume in rock glaciers below	Alps, Switzerland	Barsch, D. (1977)	78A/0229
Montane	Igneous Meta-sedimentary	7–30 20–170	Lichenometry, volume estimate	Yukon Territory, Canada	Gray, J. T. (1972)	
Montane	Limestone	100	Geological data	Dolomites	Durr, E. (1970)	72A/1521
Temperate continental	Limestone, dolomite	100–3000	Geological data	Tatra Mts., Poland	Kotarba, A. (1972)	73A/1083
Temperate continental	Igneous	18–40	Volume estimate	Quebec, Canada	Pearce, A. J., and Elson, J. A. (1973)	73A/1130
Temperate continental	Badlands	3700–8600	Periodic surveying	Alberta, Canada	Barendregt, R. W., and Ongley, E. D. (1979)	79A/2358
Semi-arid	Alluvium	0–100	Paired photographs, surveying	Nevada, U.S.A.	Wallace, R. E. (1977)	78A/0436
Semi-arid	Alluvium, colluvium	37 000–126 000	Paired photographs, surveying	Montana, U.S.A.	Wallace, R. W. (1980)	80A/2272
Various	Alluvium	5×10^4–2.5×10^6	Review	Various: river bank erosion	Hooke, J. M. (1980)	80A/2745

Table IX. Rates of marine cliff retreat

Climate	Rock	Ground loss B	Method	Location	Source	*Geo Abstracts* No.	Notes
Polar	Unconsolidated	2 300 000	Periodic surveying	N.W. Territories, Canada	Kerfoot, D. E., and Mackay, J. R. (1972)	74A/2003	
Temperate maritime	Till	800 000–1 200 000	Historical data	Eastern England	Cambers, G. (1976)	76E/1831	
Temperate maritime	Shales, till	48 770	Historical data	Yorkshire, England	Agar, R. (1960)		
Temperate maritime	Shales, slates	630 000	Periodic surveying	Devon, England	Derbyshire, E. *et al.* (1975)	76A/1170	High rates due to undercutting
Temperate maritime	Till	8×10^6–16×10^6	Periodic surveying	Eastern England	Steers, J. A. *et al.* (1979)	80E/0078	Maxima for exceptional storm years
Temperate maritime	Till	15 200	Erosion pins	Co. Down, Northern Ireland	McGreal, W. S., and Gardiner, T. (1978)	79A/1065	
Temperate maritime	Shales, slates	750 000	Periodic surveying	Devon, England	Derbyshire, E. *et al.* (1979)	79A/2366	
Temperate maritime	Clay, mudstone, marl	400 000–500 000	Historical data, erosion pins	Dorset, England	Brunsden, D., and Jones, D. K. C. (1980)	80A/2880	
Temperate continental	Till	500 000–3 000 000	Historical data	Lake Erie, U.S.A.	Quigley, R. M. *et al.* (1977)	78A/0471	
Temperate continental	Clays	2 200 000	Surveying and historical data	Lake Erie, Canada	Quigley, R. M., and Di Nardo, L. R. (1980)	80A/2875	Recent; for historical period, 2 000 000 B
Temperate continental	Till	690 000	Paired photographs	Lake Ontario, Canada	Bryan, R. B., and Price, A. G. (1980)	80A/2874	1922–52 420 000 B; 1952–70 1 030 000 B

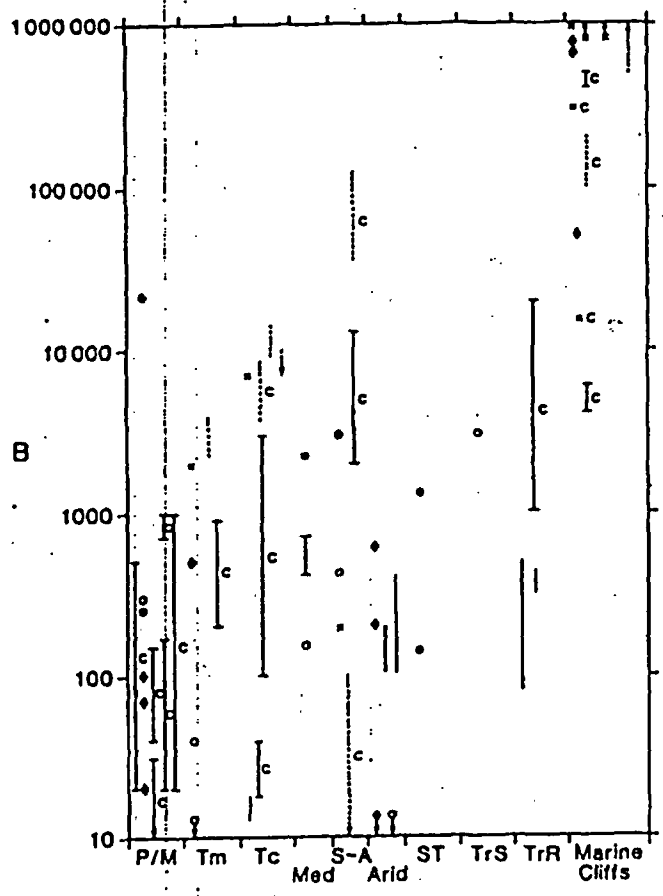

Figure 4. Rates of slope and cliff retreat. Note different scale from other figures

used to mean average ground loss from a river basin or other area. Previous reviews, which cover many aspects not discussed here, include those of Schumm (1955, 1963), Corbel (1959, 1964), Fournier (1960), Strakhov (1967), Holeman (1968), Judson (1968a), Young (1969, 1974), Ahnert (1970, 1981), Slaymaker (1974), and Selby (1974).

The most widely used technique is that of estimating river load and dividing by catchment area; the latter can range from first-order catchments to major continental basins. Reservoir sedimentation is the next most common method, taking advantage of places where man has conveniently built enormous sedimentation tanks. An interesting comparison is provided by various forms of geologic reconstruction, sometimes including radiometric dating. These yield average rates over periods of geological time; notwithstanding changes in climate, these are of the same order of magnitude as rates based on contemporary processes.

Recent studies have revealed numerous problems and sources of error in river load techniques, which are largely ignored in earlier work. Values cover not only slope processes, in which the debris reaching the river is removed by it, but river bed and bank erosion. Many records refer to suspended load only. The ratio of dissolved to suspended sediment varies widely. Bed load has rarely been measured, yet may accomplish significant transport, particularly after storms. Non-denudational components to basin sediments occur: atmospheric (dissolved and particulate) and organic materials. Temporal variability in loads is considerable, and it is difficult to take account of extreme events. Sources of sediment may be difficult to identify; some reports have indicated that a high proportion of load may be accounted for by bank and bluff erosion (the anomalously high rate obtained by Young, 1958, may be ascribed to bare bluffs in soft shale). Temporary stores

Table X. Rates of denudation

Climate	Rock	Relief	Ground loss B	Method	Location	Source	*Geo Abstracts* No.	Notes
Glacial	Various	Normal	50	Estimate	Mean for Antarctica	Voranov, P. S. (1964)	67A/0793	
Glacial	—	—	1000–5000	Review	Typical for glacial	Embleton, C., and King, C. A. M. (1968)	68A/1804	
Glacial	Various	Normal	50–200	Estimate	Canadian Arctic	Andrews, J. T. (1972)	72A/2506	
Polar	Lava	Steep	1000–4000	Geological data	Washington, U.S.A.	Mills, H. M. (1976)	77A/0415	Recent glacial retreat
Polar	Cretaceous/ Jurassic	Normal	124	Geological data	Lincolnshire, England	Straw, A. (1979)	80A/1197	Wolstonian denudation
Montane	Various	Steep	700	River sediment load, review	World, mountain environments	Hewitt, K. (1972)		
Montane	Various	Steep	4–880	River sediment load	British Colombia, Canada	Slaymaker, H. O. (1974)		4–880 B small basins 5–250 B medium basins 70–220 B large basins
Montane	Various	Steep	70	River sediment load	Alberta Rocky Mts., Canada	Luckman, B. H. (1981)		
Montane	Various	Steep	200	River sediment load	Caucasus, U.S.S.R.	Gabrielyan, H. (1971)	73A/1888	
Montane	Various	Steep	120	Geological data	French Alps	Monjuvent, G. (1973)	73A/1887	For Quaternary; 70 My average 40 B
Montane	Various	Steep	400–1000	Geophysical data	Alps	Clark, S. P., and Jäger, E. (1969)	70A/0676	
Montane	Various	Steep	255	Various	Kirghiz, S.S.R., U.S.S.R.	Iveronova, M. I. (1969)	71A/1203	
Montane	Various	Steep	570	River sediment load	Swiss Alps	Wegman, E. (1957)		
Montane	Various	Steep	977	River load	Himalayas	Khosla, N. A. (1953)		
Montane	Various	Steep	500–5000	River load	E. Nepal Himalayas	Brunsden, D., *et al.* (1981)	81A/1527	Tamur catchment 4700 B
Montane	Granite, gneiss	Normal	100:10–1000	Traps	Colorado, U.S.A.	Bovis, M. J., and Thorn, C. E. (1981)	81A/1826	
Temperate maritime	Carboni- ferous/ Devonian	Normal	9–125	River sediment load	Devon, England	Walling, D. E., and Webb, B. W. (1978)	78A/1175	
Temperate maritime	Sedimentaries; drift	Normal	10	Reservoir sedimentation	Midlothian, Scotland	Lovell, J. P. B. *et al.* (1973)	74A/0008	

Table X—*Contd.*

Climate	Rock	Relief	Ground loss B	Method	Location	Source	*Geo Abstracts* No.	Notes
Temperate maritime	Carboniferous shale, sandstones	Normal	1016	Reservoir sedimentation	Pennines, England	Young, A. (1958)		Much sediment from bare shale buffs
Temperate maritime	Silurian sedimentary	Normal	2	River sediment load	Wales	Oxley, N. C. (1974)	74A/1721	
Temperate maritime	Basalt	Normal	32	Geological data	Mull, Scotland	Walker, G. P. L. (1970)		Average over 59 My
Temperate maritime	Sedimentary	Normal	0–57	Quantitative pedology	Luxembourg	Jungerius, P. D. (1980)	80A/0009	
Temperate maritime	Siliceous sediments	Normal	10	River sediment load	Devon, England	Clark, C. (1978)		
Temperate maritime	Mesozoic sedimentary		67:55–132	River load, suspended and dissolved	Sussex, U.K.	Collins, M. B. (1981)		
Temperate maritime	Sandstone, marl	Normal	5	Traps	Luxembourg	Van Zon, H. J. (1980)	81A/0654	
Temperate maritime	Jurassic sedimentary	Normal	19–54	River sediment load	Yorkshire, England	Arnett, R. R. (1979)	80A/0426	
Temperate maritime	Various	Normal	5	River sediment load	New England, U.S.A.	Gordon, R. B. (1979)	80A/0428	Over 8000 y
Temperate maritime	Mesozoic volcanics	Normal	27–42	Geochemical analysis of rock samples	New England, U.S.A.	Doherty, J. T., and Lyons, J. B. (1980)	80A/1446	Over geologic time
Temperate maritime	Various	Normal	3	River sediment load	Maryland, U.S.A.	Cleaves, E. T. *et al.* (1970)	71A/1188	
Temperate maritime	Sedimentary	Normal	18	Reservoir sedimentation	Strathclyde, Scotland	Ledger, D. C. *et al.* (1980)	81A/0465	
Temperate maritime	Various	Normal	70 127	River sediment load Reservoir sedimentation	Northern England	Hall, D. G. (1967)	70A/1136	
Temperate maritime	Igneous	Normal	20	Reservoir sedimentation	Normandy, France	Journaux, A. (1956)		
Temperate maritime	Precambrian	Normal	12	Reservoir sedimentation	Leicestershire, England	Cummins, W. A., and Potter, H. A. (1967)	67A/1081	
Temperate maritime	Igneous Calcerous marls	Normal	5 50	Geological reconstruction	Massif Central, France	Bout, P. *et al.* (1960)	61/0126	
Temperate maritime	Calcerous sandstone	Normal	29	River sediment load	Quercy, France	Cavaille, A. (1953)		

[illegible] maritime	[illegible] Calcerous marls	[illegible]	50	[illegible] ...nstruction	France	(1960)	[illegible]	
Temperate maritime	Calcerous sandstone	Normal	29	River sediment load	Quercy, France	Cavaille, A. (1953)		
Temperate continental	Various	Normal	52–98	River sediment load plus reservoir sedimentation	U.S.A., 500–2500 mm rainfall	Schumm, S. A. (1963)	64/0156	Large basins 52 B Small basins 98 B
Temperate continental	Various	Normal	63	Sedimentation	Black Sea basin, U.S.S.R.	Degens, E. T. *et al.* (1976)	77A/0710	Man's impact has accelerated rate × 3
Temperate continental	Flysch	Normal	10–100	Processes, integrated study	Carpathians, Poland	Gerlach, T. (1967)	68A/1674	
Temperate continental	Various	Normal	25–100	River sediment load	Bavaria	Wundt, W. (1952)		
Temperate continental	Various	Normal	110–260	River load and reservoir sedimentation	Czechoslovakia	Starkel, L. (1962)	64/0778	
Temperate continental	Various	Normal	22	River load and geological reconstruction	Eastern seaboard of N. America	Gilluly, J. (1964)	65/0673	Over 225 My since Triassic, average 16 B
Temperate continental	Various	Normal	16	Reservoir sedimentation	Sudetes, Poland	Jahn, A. (1968)	69A/0014	
Temperate continental	Shale, siltstone	Normal	27–35	Reservoir sedimentation	Orange Free State, S. Africa	Le Roux, J. S., and Roos, Z. N. (1979)		
Temperate continental and montane	Various	Steep	127	Lake sedimentation	Switzerland	Steiner, A. (1953)		Over post-glacial
Mediterranean	Various	Normal	20–30	Geological, archeological data, river load	Rome, Italy	Judson, S. (1968b)		Before man; present, human-accelerated, 200–400 B
Mediterranean	Various	Steep	10–30	Geological data	California, U.S.A.	Marchand, D. E. (1971)	71A/1951	
Mediterranean	Sedimentary	Normal	500–5000	River sediment load	California, U.S.A.	Scott, K. M., and Williams, R. P. (1978)	78A/1794	
Semi-arid	—	Normal	290: 140–670	Dendrochronology	Utah, U.S.A.	Eardley, A. J., and Viavant, W. (1967)	68A/1342	Varies with sin angle
Semi-arid	Sedimentary	Normal	220–330	Dendrochronology	Colorado, U.S.A.	Carbara, P. E., and Carroll, T. R. (1979)	80A/0427	Pre-man; last 100 y since into. of cattle 1750 B
Semi-arid	Various	Normal	96–160	River load plus reservoir sedimentation	U.S.A.	Schumm, S. A. (1963)	64/0156	Large basins 96 B Small basins 160 B
Semi-arid	Various	Normal	38–170	River load	Western U.S.A.	Judson, S., and Ritter, D. F. (1964)	64/0811	
Semi-arid	—	Normal	838	C^{14} dating of lake sediments	Utah, U.S.A.	Eardley, A. J. (1966)	67A/1281	
Semi-arid	Volcanic	Normal	3000–17 800	Direct measurement	Kenya	Dunne, T. *et al.* (1978)	79A/1068	Accelerated by overgrazing
Subtropical humid	Various	Steep	153–862	Reservoir sedimentation	Japan	Yoshikawa, T. (1974)	74A/2178	

Table X—*Contd.*

Climate	Rock	Relief	Ground loss B	Method	Location	Source	*Geo Abstracts* No.	Notes
Subtropical humid	Various	Steep	39	River sediment load	Hong Kong	Lam, K.-C. (1974)		On badlands 17450 B
Subtropical humid	Various	Normal	8:2–17	River sediment load	N.S.W., Australia	Douglas, I. (1973)	74A/1246	
Subtropical humid	—	Normal	500–1500	River sediment load	Southeastern U.S.A.	Trimble, S. W. (1977)	78A/0756	
Subtropical humid	—	Normal	12–48	River sediment load	Miss., U.S.A.	Ursic, S. S. (1963)		Under forest
Subtropical humid	Various	Normal	30–49	Geological reconstruction	Natal, S. Africa	King, L. C. (1940)		
Tropical savanna	Basalt	Steep	120–240	River sediment load geological data	Ethiopia	McDougall, I. *et al.* (1975)	75A/1055	Present; over 23 My, average 12 B
Tropical savanna/semi-arid	Granite	Normal	200–730	Reservoir sedimentation	Tanzania	Rapp, A. *et al.* (1972)	74A/0298	Man-accelerated
Tropical savanna	Various	Normal	27	River load	Tropics, general	Corbel, J. (1959)		
Tropical savanna	Alluvium, shale	Normal	125–291	Erosion pins	Guyana	Kesel, R. H. (1977)	78A/0747	
Tropical rainforest and savanna	Various	Steep	700	Volume estimate	Himalayas	Curray, J. R., and Moore, D. G. (1971)	71A/1953	
Tropical rainforest	Various	Steep	1070	Geological data	New Guinea	Loffler, E. (1972)	74A/0012	
Tropical rainforest	Alluvium, shale	Normal	275–323	Erosion pins	Guyana	Kesel, R. H. (1977)	78A/0747	
Tropical rainforest	Various	Normal	20	River sediment load	Queensland, Australia	Douglas, I. (1973)	74A/1246	
Tropical rainforest	Basement complex	Steep	260	River sediment load	Tanzania	Rapp, A. (1972)	74A/0299	Includes 10% catchment accelerated by Man
Tropical rainforest	Triassic shale	Normal	2600	Erosion pins	Malaya	Leigh, C. H. (1978)		
Tropical rainforest	—	Normal	6–17	River sediment load	Various	Slaymaker, O. (1978)	79A/2622	
Tropical rainforest	Basalt	Normal	130	River sediment load, volume estimate	Hawaii	Moberly, R. (1963)	64/0482	
Tropical rainforest	Various	Normal	50	River load	Tropics, general	Corbel, J. (1959)		
Tropical rainforest	Igneous	Steep	7·5	Lake sedimentation	Papua New Guinea	Oldfield *et al.* (1980)		Pre-man; acceleration 70 to 20 y ago × 3, last 20· 7·5

of sediment, as colluvium, alluvium, gravel bars, etc., are often extensive; the residence time of sediment tends to increase downstream, and thus from small to large basins. The sediment delivery ratio, the ratio between erosion within the catchment and sediment yield at its outlet, suffers from high variability (Trimble, 1977). In converting river load to denudation rate there is a tacit assumption that the system is in a steady state; however, fluctuations in sediment delivery of several time scales are known or suspected to occur. In some areas, contemporary river load is derived from Pleistocene deposits. Finally, nearly all catchments are substantially influenced by man (see below).

The results (Figure 5) at first sight appear to be widely scattered, but can be rationalized on a climatic basis by ignoring infrequent but extreme values and in some cases separating steep from normal relief. This yields the following typical ranges:

Climate	Relief	Typical range for rate of denudation, B Minimum	Maximum
Glacial	Normal (= ice sheets)	50	200
	Steep (= valley glaciers)	1000	5000
Polar/montane	Mostly steep	10	1000
Temperate maritime	Mostly normal	5	100
Temperate continental	Normal	10	100
	Steep	100	200+
Mediterranean	—	10	?
Semi-arid	Normal	100	1000
Arid	—	10	?
Subtropical	—	10?	1000?
Savanna		100	500
Rainforest	Normal	10	100
	Steep	100	1000
Any climate	Badlands	1000	1 000 000

Typical values for glacial erosion are taken from a review by Embleton and King (1968). When compared with the present data, they show that valley glaciation is substantially faster than normal erosion in any climate, but erosion by ice sheets not necessarily so. Values for polar and montane environments span a wide range, perhaps reflecting the large range in rainfall.

Humid temperate climates show the lowest minimum and possibly the lowest maximum rates of denudation; creep is slow, wash very slow owing to the dense vegetation cover, and solution fairly slow because of low temperatures. It is ironic that the British Isles, the scene of such a disproportionately large amount of geomorphological research activity, should prove to have such an inactive landscape! Other conditions being equal, denudation in temperate continental climates is probably somewhat faster. Evidence for Mediterranean regions is scanty, and hard to come by in the old-world Mediterranean owing to great acceleration by Man.

An earlier review (Langbein and Schumm, 1958) suggested for the U.S.A. a maximum rate of denudation in the semi-arid zone. On limited evidence, it is possible that the tropical savanna zone may have equally high rates, the greater (but still partial) protection by grasses being balanced by greater agressivity of rainfall. This does not contradict Langbein and Schumm's findings, since the U.S.A. lacks areas of savanna climate. The rainforest environment has a special geomorphological interest; core regions have possibly escaped substantial recent climatic change and thus show landforms resulting from present processes, and there remain areas little altered by Man. Despite the protection afforded by the forest cover, denudation rates are moderately high, a result of the combined effects of creep, wash, solution and landsliding, all of which have been recorded at substantial rates.

Badlands, or other sites where unconsolidated rocks are exposed without a vegetation cover, show denudation rates of 1000 B and upwards; this rate may be about the threshold which prevents establishment of

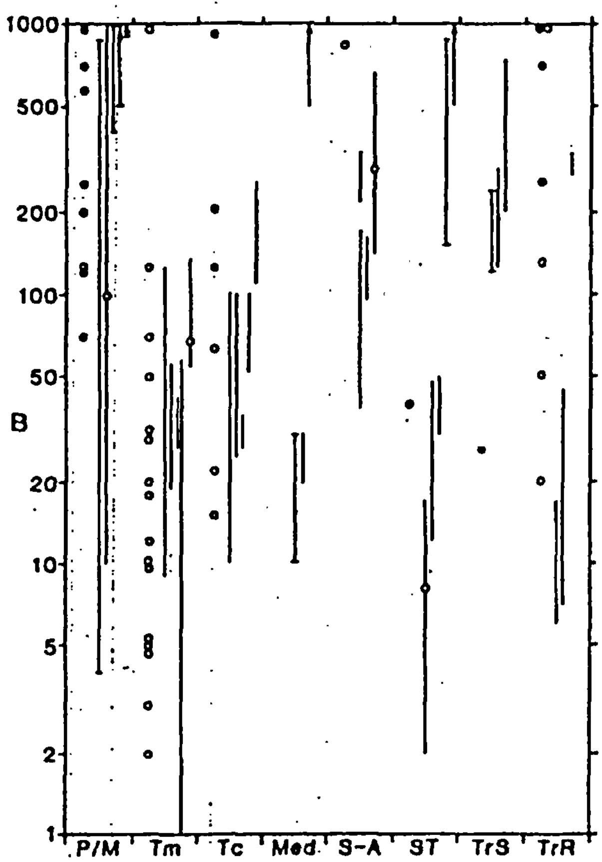

Figure 5. Rates of denudation

a vegetation cover. One of the fastest eroding large catchments in the world is the Tamur basin in the Himalayas, averaging 4700 B or nearly 5 mm y^{-1}; besides very active uplift, the presence of weakly consolidated formations and an input from glaciation, erosion in this catchment has been accelerated by Man.

In an earlier review it was suggested that denudation rates were of the order of 10 times as fast in mountainous or steeply-sloping areas as on normal relief; typical rates of 50 B for normal relief and 500 B for steep relief were quoted (Young, 1969). These estimates are not contradicted by the evidence in Figure 5, although the ranges are so large that they are better given as 10–100 B for normal relief and 100–1000 B for steep relief. The same fundamental causes, steepness of slope and rate of river erosion, account for previously noted positive relationship between basin relief and rate of denudation, and the observation that small basins on average erode faster than large ones.

The influence of man on denudation rates had previously been suggested as an acceleration of ×2 to ×3. This now appears to be a modest estimate. Four studies in Table X permit comparison between pre-Man and Man-accelerated rates; they give multipliers of ×3 (temperate continental climate), ×10 (Mediterranean), ×3 to ×8 (semi-arid) and ×10 to ×20 (savanna). Many other studies observe that the recorded rate is undoubtedly accelerated without giving a figure. One might hazard the generalization that in catchments where there is moderately intense land use but little apparent soil erosion, denudation may have been accelerated by about 3 times; but where there has been intensive land use the multiplier may be as high as 10. Recent support for both these rates of acceleration comes from a remarkable study of lake sedimentation in the highlands of Papua New Guinea in which two increases in the rate of deposition were recorded, believed to correspond to the onset of sparse and more intensive cultivation respectively (Oldfield *et al.*, 1980). Areas with a recognized 'soil erosion problem' are omitted from the data recorded here, but frequently have rates 100 to 1000 times faster than normal erosion. Even the 'maximum tolerable erosion' employed in soil conservation design is probably well above the rate of soil replacement by weathering; consequences have been discussed by Stocking (1978).

Finally one may compare denudation rates with rates of uplift (Table XI). It appears from this selection of records that where there is active uplift it is likely to be in the range 1000–10000 B, or 1–10 mm y^{-1}, and unusually active uplift may be still faster. By comparison, average denudation rates for all climates are 10–1000 B. This confirms the finding of Schumm (1963), that typical rates of uplift are of the order of 10 times faster than denudation under most conditions. It may be that occasionally denudation can catch up; the Southern Alps, New Zealand, are now in a steady state with uplift balancing erosion (Adams, 1980), whilst the Tamur catchment in the Himalayas, eroding at 4700 B, attains a typical rate for uplift. Valley glaciation reaches the same order of magnitude. Therefore it is possible that in high-altitude, steeply-dissected mountain ranges, denudation can keep pace with still-active uplift for short periods.

Table XI. Rates of uplift; this table gives examples only, and is not intended as a comprehensive list

Location	Rate of uplift B	Source	*Geo Abstracts* No.	Notes
Caucasus	20000–25000	Gabrielyan, H. (1971)	73A/1888	
Central Europe	−2000–5000	Zuchiewicz, N. (1978)	79A/1678	Range from minus 2000 B
Sweden	50000–500000	Morner, N.-A. (1980)	81A/0540	Peak in glacio-isostatic uplift
California, U.S.A.	7600 maximum	Scott, K. M., and Williams, R. P. (1978)	78A/1794	
California, U.S.A.	10000–17000	Castle, R. O. *et al.* (1976)	76A/1520	Maximum along San Andreas fault
California, U.S.A.	5000–8000	Bandy, O. L., and Marincovich, L. (1973)	74A/0052	
Japan	500–2200	Pearce, A. J., and Elson, J. A. (1973)	73A/1130	
Nevada, U.S.A.	300	Wallace, R. E. (1978)	79A/1143	One 3 m movement every 10000 y
Antilles	50	Herweijer, J. P., and Focke, J. W. (1978)	79A/0737	
Continental platform areas	4000–5000	Gopwani, M. V., and Scheidegger, A. E. (1971)	72A/0528	Review; Maximum 10000 B
World, typical	7600	Schumm, S. A. (1963)	64/0156	Review

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Note: In order to reduce the otherwise large number of references, publications are cited in Tables I–XI by giving their abstract numbers in *Geomorphological Abstracts* (1960–65), *Geographical Abstracts* (1966–71) and *Geo Abstracts* (1972–present). Many of the citations in the text clearly relate to a particular table, where the abstract number will be found. The following list of references covers only those for which (at the time of going to press) there is no abstract number, together with text citations which do not relate to a table.

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