# 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.

## 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

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 $\mu$m 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. |

Figure 1.

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 $\times 0.5$ to $\times 3$.
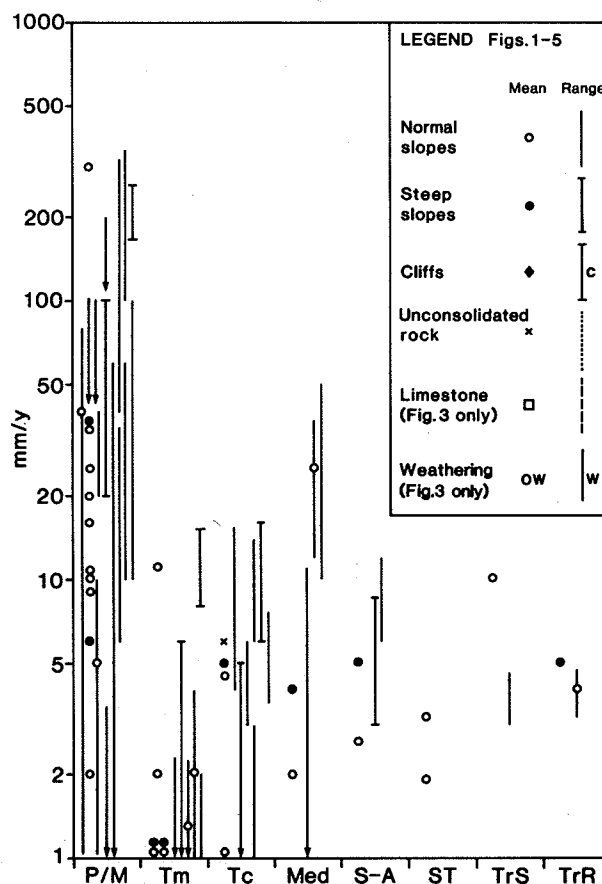


Figure 1. Rates of solifluction (polar and montane climates) and soil creep. Rates refer to linear movement close to the ground surface. Note that scales in Figures 1–5 are logarithmic. For abbreviations of climatic zones, see p. 474.

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) | — | Maximum rate at 25 mm below root mat |
| Temperate maritime | Colluvium | 11° | 1·3:0·4–2·2 | | Six methods | Weardale, England | Anderson, E. W., and Cox, N. J. (1978) | 79A/1206 | Movement to 10–15 cm depth |
| Temperate maritime | Various | 2·5°–24° | | 1·5–2·5 | Three methods | Taunus Mts, Germany | Göbel, P. (1977) | — | Deep creep, to 15 m; rates correlated with soil moisture |
| Temperate maritime | Igneous | Steep | 8–15 | 200 | Inclinometers | Oregon, U.S.A. | Swanson, F. J., and Swanson, D. N. (1977) | 79A/0126 | |
| 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 17y |
| Temperate continental | Clay | 70° | 6–16 | | Inclinometer | Ottawa, Canada | Eden, W. J. (1977) | 78A/1948 | |
| Temperate | Limestone | Steep | 0–5 | | Surface | Hallstatt, Austria | Hausworth, E. K., and | 76A/1992 | 21 y record |

| Climate | Material | Angle | Rate | Rate | Method | Location | Source | Ref. | Notes |
|---|---|---|---|---|---|---|---|---|---|
| continental | Various | 8°–39° | 4–15 | | Buried pillars and tubes | Poland Sudety Mts., Poland | Cielinska, M. (1974) Jahn, A. (1981) | | to 25 cm depth 19 pits at 4 sites; one site 17y |
| 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 Scheideger, 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 terrettes. 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 | Movement Surface | Movement Volumetric | Method | Location | Source | Geo | Notes |
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Table II. Rates of solifluction

| Climate | Rock | Slope angle degrees | Movement Surface mm y⁻¹ | Movement Volumetric cm³ 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 | Frost creep and gelifluction; vegetation hampers solifluction |
| Montane | — | Steep | 37 | | Surface markers | Alps, Switzerland | Gamper, M. (1981) | | |
| 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 cm³ 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 | Badlands | Steep | 2800–10 400 | | — | N. Dakota, USA | Clayton, L., and Tinker, J. R. (1971) | 74A/0370 | Varies with aspect and rock formation |
| | | Normal | 0·03 | | Traps | Beskids, Poland | Czenne, Z. (1970) | 71A/1192 | Under forest; |

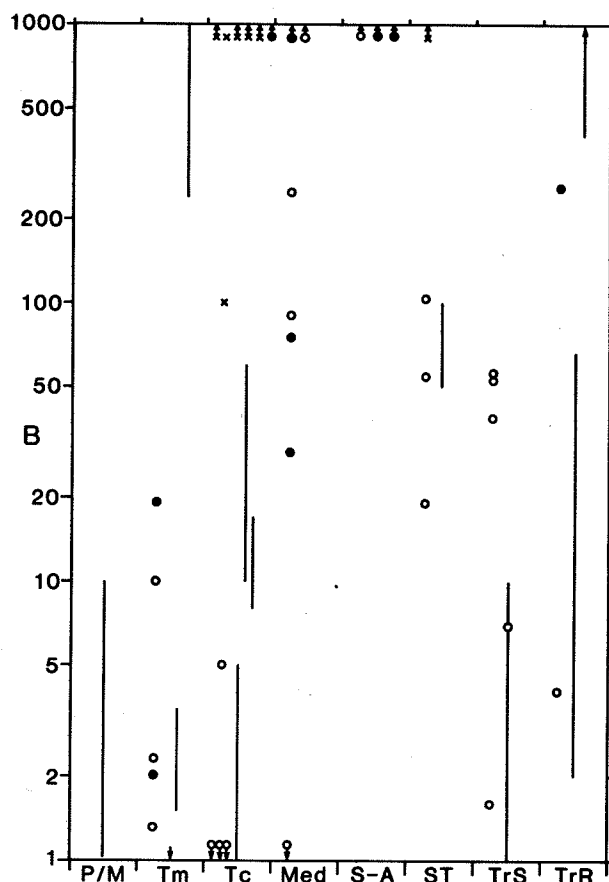| Climate | Material | Slope | Rate | Method | Location | Reference | Campbell no. | Remarks |
|---|---|---|---|---|---|---|---|---|
| | | | | | Poland | | | by vegetation cover |
| continental | | | | | Alberta, Canada | Campbell, I. A. (1974) | 75A/0648 | Slope angle not a major influence |
| Temperate continental | Badlands | Steep | 3750–5000 | Measuring frame | | | | |
| Temperate continental | Badlands | Steep | 2800–10 400 | — | 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 | 7500 | Traps | Catalan Ranges, Spain | Sala, M. (1981) | | |
| | | Normal | 5000 | | | | | |
| Arid | Metamorphic | Normal | 2·6:1·2–6·9 | Traps | S. Israel | Yair, A., and Klein, M. (1973) | | Inverse relation to $\theta$, because coarser debris on steep slopes |
| Semi-arid | — | Normal | 4–5 | Erosion pins | Arizona, USA | Kirkby, A., and Kirkby, M. J. (1974) | 75A/0448 | |
| Subtropical humid | Badlands | Steep | 17 400 | Measuring frame | Hong Kong | Lam, K.-C. (1977) | 78A/0651 | In braided channels 100× faster |
| Subtropical humid | Granite | Normal | 54 | Traps | N.S.W., Australia | Williams, M. A. J. (1973) | 74A/0425 | |
| | Sandstone | | 103 | | | | | |
| Tropical savanna | Granite | Normal | 54 | Traps | N. Territory, Australia | Williams, M. A. J. (1973) | 74A/0425 | |
| | Sandstone | | 56 | | | | | |
| 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 $\mu$ 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*    Notes

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 | 13–29 | Dissolved river load | Devon, UK | Walling, D. E., and Webb, B. W. (1978) | 78A/1175 | |
| Temperate maritime | Carboniferous 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 Michalezyk, Z. I. (1973) | 76A/1100 | |
| Temperate continental | Various | 36–60 | Dissolved river load | Czechoslovakia | Starkel, L. (1962) | 64/0778 | |

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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 = $0.28\,R^{0.66}$, $R$ = 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

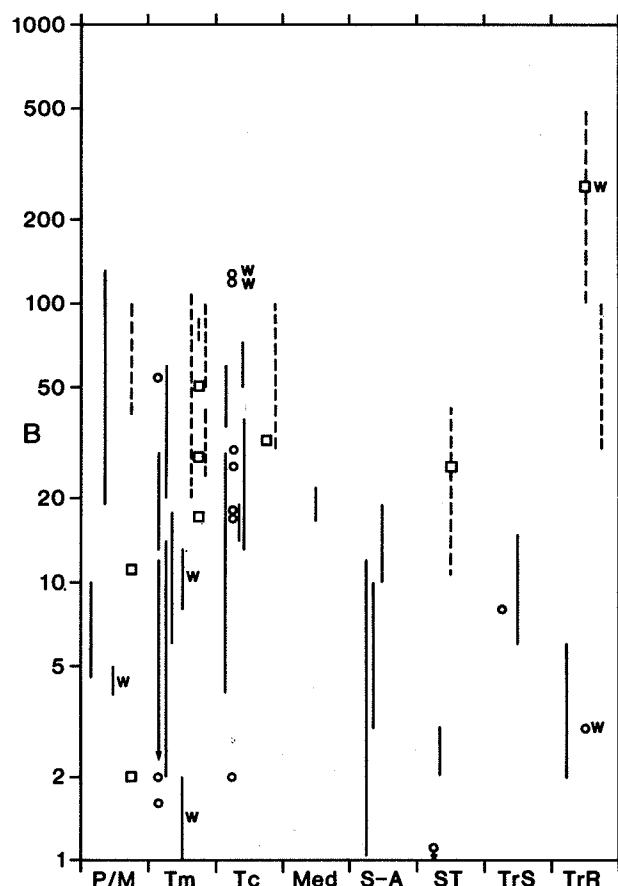| Climate | Rock | Weathering Loss B | Method | Location | Source | Geo. Abstracts No. | Notes |
|---|---|---|---|---|---|---|---|
| Montane | Rhyodacite | 4–5 | Rock tablets | Colorado, U.S.A. | Caine, N. (1979) | 80A/1347 | |
| Temperate maritime | Marble, sandstone | 90:197–210 | Tombstones | Edinburgh, 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 cemetery |
| 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 $3\frac{1}{2}$ 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 | 3900–10000 | 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 | 130000–2600000 | 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 | $5 \times 10^4$ – $2.5 \times 10^8$ | Review | Various: river bank erosion | Hooke, J. M. (1980) | 80A/2745 |

Table IX. Rates of marine cliff retreat

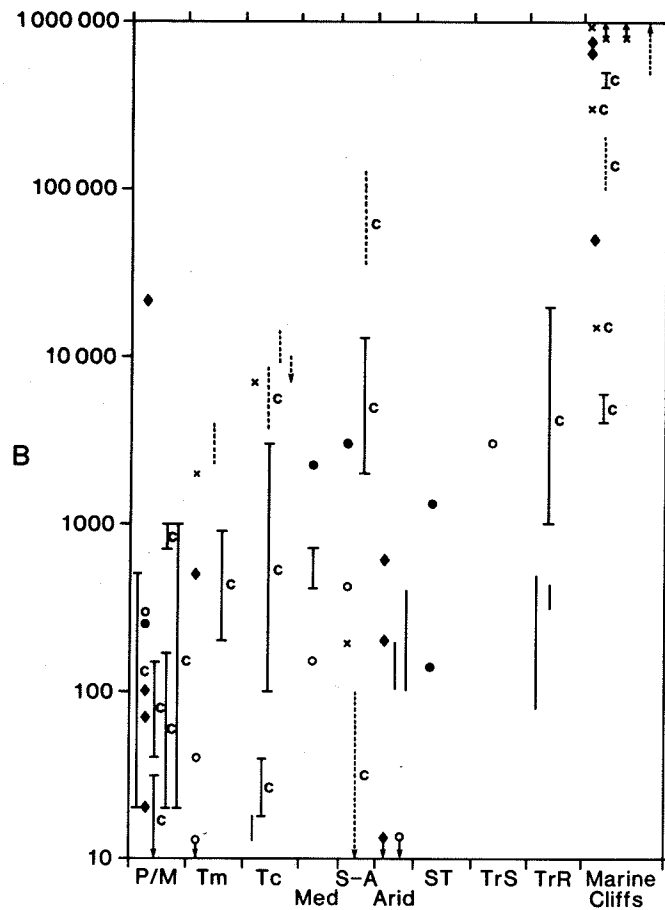| Climate | Rock | Ground loss B | Method | Location | Source | Geo Abstracts No. | Notes |
|---------|------|---------------|--------|----------|--------|-------------------|-------|
| Polar | Unconsolidated | 2 300 000 | Periodic surveying | N.W. Territories, Canada | Kerfoot, D. E., and Mackay, J. 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 | $8 \times 10^6$– $16 \times 10^6$ | 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

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 | Carboniferous/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 | |

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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) | | |
| 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 | Various | Normal | 63 | Sedimentation | Black Sea basin | Degens, E. T. et al. (1977) | 77A/0710 | Man's impact has |

| Climate | Rock type | Slope | Rate | Method | Location | Reference | No. | Notes |
|---|---|---|---|---|---|---|---|---|
| maritime | Calcerous marls | Normal | 30 | reconstruction | France | | | |
| 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 | Various | Steep | 127 | Lake sedimentation | Switzerland | Steiner, A. (1953) | | Over post-glacial |
| Temperate continental and montane | | | | | | | | |
| 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 100y 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 | 3000–17800 | Direct measurement | Kenya | Dunne, T. et al. (1978) | 79A/1068 | Accelerated by over-grazing |
| Subtropical humid | Various | Steep | 153–862 | Reservoir sedimentation | Japan | Yoshikawa, T. (1974) | 74A/2178 | |

Table X—Cond.

| 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 savanna | Various | Steep | 700 | Volume estimate | Himalayas | Curray, J. R., and Moore, D. G. (1971) | 71A/1953 | |
| Tropical rainforest and savanna | 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 y ×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

Pre-man; acceleration 70 to 20 × 40 × 3.5

Lake sedimentation   Papua New Guinea   Oldfield *et al.* (1980)

7·5

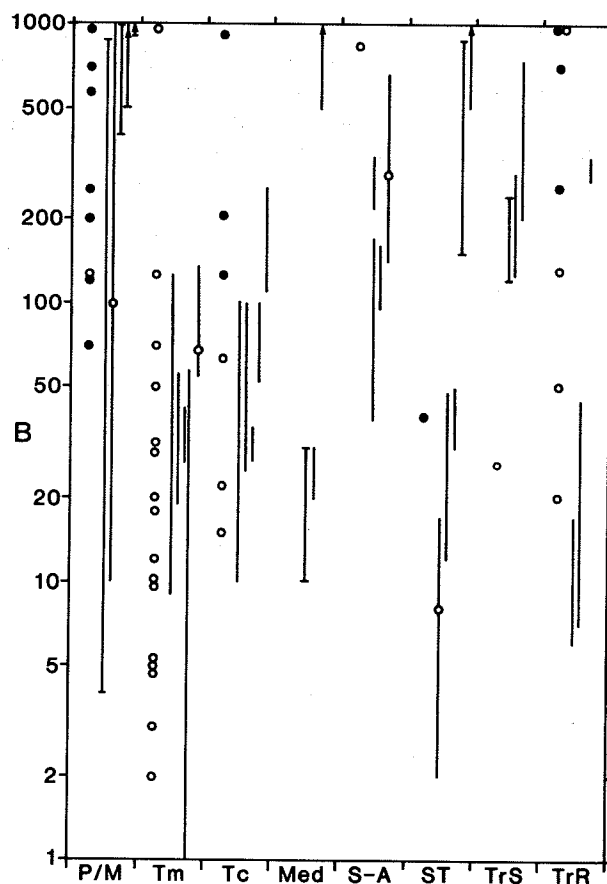Steep

Igneous

Tropical rainforest

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 $5 \text{ mm y}^{-1}$; 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 1000–10 000 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 | 20 000–25 000 | Gabrielyan, H. (1971) | 73A/1888 | |
| Central Europe | −2 000–5 000 | Zuchiewicz, N. (1978) | 79A/1678 | Range from minus 2000 B |
| Sweden | 50 000–500 000 | Morner, N.-A. (1980) | 81A/0540 | Peak in glacio-isostatic uplift |
| California, U.S.A. | 7 600 maximum | Scott, K. M., and Williams, R. P. (1978) | 78A/1794 | |
| California, U.S.A. | 10 000–17 000 | Castle, R. O. *et al.* (1976) | 76A/1520 | Maximum along San Andreas fault |
| California, U.S.A. | 5 000–8 000 | Bandy, O. L., and Marincovich, L. (1973) | 74A/0052 | |
| Japan | 500–2 200 | 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 10 000 y |
| Antilles | 50 | Herweijer, J. P., and Focke, J. W. (1978) | 79A/0737 | |
| Continental platform areas | 4 000–5 000 | Gopwani, M. V., and Scheidegger, A. E. (1971) | 72A/0528 | Review; Maximum 10 000 B |
| World, typical | 7 600 | 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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