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Rates of Operation of Geomorphological Processes

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MODERN GEOMORPHOLOGY seeks to provide data that are quantitative and as accurate as possible. To this end attention is usually directed to the measurement of form rather than process, partly because form must be defined before process can be understood and partly because there is commonly great difficulty in measuring the rates at which processes operate. Yet the latter are very important and have been so often the implicit subjects of controversy that an attempt to assess the order of accuracy with which they may be estimated may be of some value. Various categories of measurements and their probable accuracies are discussed in general terms below before their special application to marine erosion is considered.

Measurements of velocity

The velocities of transporting agents, such as rivers, wind and glaciers, may be directly measured, though with considerable difficulty in the case of ice, where good points of reference may be distant or absent. But, as the transporting agents form only one aspect of the process of denudation, little may be learned directly about rates of denudation from measurements of the velocities of transporting agents.

Measurements of annual rates

Annual losses or gains due to erosion or deposition may be measured and such rates extrapolated over varying periods of time. The uses and dangers of this method are excellently illustrated from a variety of examples. It is possible to measure the rate of lateral migration of a free meander in alluvium by systematic mapping, but the rate observed cannot be extrapolated indefinitely because sooner or later the meander would be cut off. This intervention of another process or another aspect of the same process is one of the main objections to extrapolation: the other is the slowing down of the process concerned. A rate of chemical rotting of rock of about one inch per year has been observed on Sugar Loaf Mountain, Rio de Janeiro:[1] this would be equivalent to the rotting of a mountain the size of Everest from its summit to sea-level in the duration of the Pleistocene period if such a rate were to be maintained. In another sphere the rate of river down-cutting is probably seriously and progressively retarded when the

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stream reaches grade: further degradation of the bed awaits a decrease in load calibre, which in turn probably demands a decrease in the angle of slope of the valley sides.

Not all processes, however, bring themselves to a standstill. The clearest exception is solution. If the average content in solution and the total discharge from a permeable bed can be calculated, it is possible to estimate the average annual loss of rock, though whether this is mainly from the surface or from the sides of joints underground is not to be ascertained readily if at all. It is always difficult to infer rates of downwearing from measurements of load discharged by the drainage pattern, because of this problem of knowing where the erosion is taking place. However, provided that the accumulation of a thick layer of residue does not insulate the rock from the effects of percolating acid water, there is no need to assume that the rate of solution slows down. Thus, peneplanation on limestones may, as was clearly recognized by Baulig,[2] be a more rapid process than on other types of rocks. If it were possible to calculate an average rate for the denudation of a limestone region, it would seem far safer to extrapolate such a rate over a long period than it is for most other short-period geomorphological measurements.

Thus, average annual rates of erosion, if it is possible to measure them at all, vary in their suitability for long-term predictions, though with most of them such predictions are dangerous.

Measurements from the dates of known events

A number of possibilities offer themselves here, for example, the use of datable enclosures of land. C. T. Smith[3] has the interesting idea of measuring rates of soil creep on arable land from differences in height on either side of hedges across a slope. This example admirably illustrates the difficulties which may arise. There is the historical difficulty of establishing the date of enclosure and the probability of the land having been under the plough more or less continuously since. There are the difficulties arising in attempting to convert depths of soil into volumes of creep. Finally, one has to admit that the rate of soil creep is not only a function of the slope and the climate, but also of the rate of weathering of the rock, which itself may be partly controlled by the rate of creep!

The application of a similar type of method on a broader time scale is that suggested by Birot and Joly[4] for measuring the rate of erosion at the feet of steep-sided hills in Morocco. Many such hills are coated with desert varnish, which can be dated by comparing the age of inscriptions covered by the varnish with that of those cut into it. Although prehistoric inscriptions cannot usually be dated as accurately as historical events, the degree of precision attainable is very high when compared with that resulting from some of the cruder methods suggested below. When the varnish has been dated the amount of material eroded from the foot of the hill since that period may be estimated by projecting the varnish-covered slope downwards as shown in Fig. 1.

Similarly, it would be possible to arrive at a rate of weathering of datable monuments, especially the undercutting at their feet.

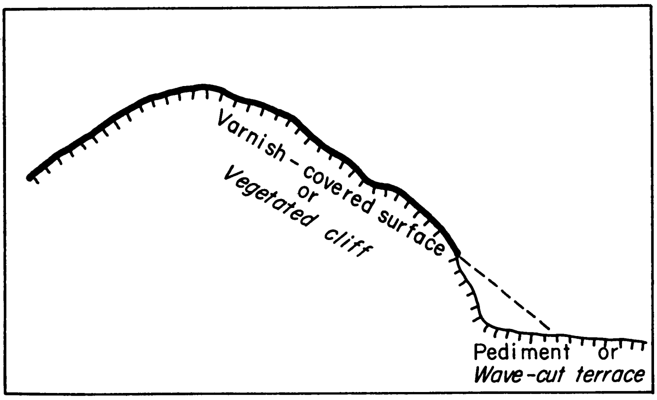

Fig. 1.—Method of assessing recession of foot of inselberg in Morocco, or hog-back cliff in Britain.

Measurements against a long-period time-scale

Changes in radioactive minerals provide scales against which measurements may be made. Two such scales are available: the radiocarbon method provides, with refined techniques,[5] a short time-scale back to a maximum of about 70,000 years before the present (B.P.), although few dates earlier than about 30,000 B.P. have been determined. Long-term scales are provided by the uranium–lead, rubidium–strontium and potassium–argon ratios used in dating mainly igneous rocks and certain types of uranium-rich sediments.[6] Unfortunately, owing to the possible errors inherent in these methods, most of the Pliocene and Pleistocene periods, both critical for the assessment of the rates of geomorphological processes, cannot be accurately dated, except by the potassium–argon method. I am very grateful to Dr. J. A. Miller, who is at present working on the last method in the Department of Geophysics at Cambridge, for informing me that he has recently dated oceanic basalts of an age of 2–3 million years by the potassium–argon method, though the degree of accuracy is not certain. Theoretically, it should be possible to date rocks even younger than this, though not as yet, sediments. Dr. Miller is actively engaged on this problem at present and the dating of more events in the Pliocene and possibly Pleistocene periods may thus become feasible in the near future.

Even within the period covered by radiocarbon dating, it is not easy to measure erosion, for the dating requires a study of vegetable deposits and it is usually very difficult to correlate deposits with erosion forms. The following example may be envisaged. A stream falling over the lip of a corrie has effected no erosion since the glacier shrank to within the corrie, a state of affairs photographed by Lewis in Skye.[7] In the vicinity, perhaps on lower, flatter ground, it may be possible to analyse the vegetation succession shown in a peat bog by means of pollen analysis and to pick out a phase of cold steppe vegetation representing the Late Glacial, which can then be dated by radiocarbon. Some assumption has then to be made connecting the vegetation succession in the peat bog and the initiation of stream erosion over the lip of the corrie, for example that the latter occurred in the Late Glacial. If there is a vegetable deposit in the corrie, it would, of course, be possible to infer more accurately the period at which the corrie was abandoned by the glacier. Thus, it may be possible to arrive at a period of years in which one particular stream has effected no erosion, but general conclusions are difficult to infer because of variations in rock resistance and stream size.

On a more extended scale the uranium–lead method has provided dates for the major geological periods against which it is sometimes possible to measure cycles of erosion.[8] Baulig's work on the Central Plateau of France,[9] for example, suggests that a post-Hercynian cycle was completed in the Jurassic, a period of approximately 30 million years. The evidence of a cycle is usually, however, merely a series of approximately accordant summits held to represent an erosion surface, in the interpretation of which there is room for differences of opinion. For example, the accordance of summits in Wales has been variously attributed to an arid cycle, a series of partial peneplanations, a marine cycle and to pure chance. However, even if a statement of no greater precision than that an unspecified cycle ran its course in 20–50 million years can be made, one has made a great advance over pure guessing.

Measurement in terms of various Quaternary divisions

For the period between the end of lead dating and the beginning of carbon dating a number of indefinable units are available, such as glacial and interglacial periods and the vegetation zones recognized in pollen analysis. Approximations to the lengths of some of these may be possible and hence an assessment of erosion rates made. This is discussed more fully in relation to marine erosion below.

Measurement of the relative rates of different processes

A simple example would be the formulation of river activity in such terms as: while a river was cutting down 30 feet it swung laterally half a mile across its valley. Even though this is only a statement about relative rate, it is still insufficient for generalization, for the relative rate will depend upon, among other things, whether the stream is graded, whether it is swinging in a confined valley or across an alluvial flood-plain and finally whether the part of the valley concerned is typical of the whole valley or is an area of particularly pronounced lateral erosion.

Yet such relative rates may be the only possible measures of certain important geomorphological processes, as, for example, the rate of development of subsequent streams, some notions about which may be inferred from areas of fairly recently superimposed drainage. If (Fig. 2) contours can be reconstructed on the surface from which the drainage

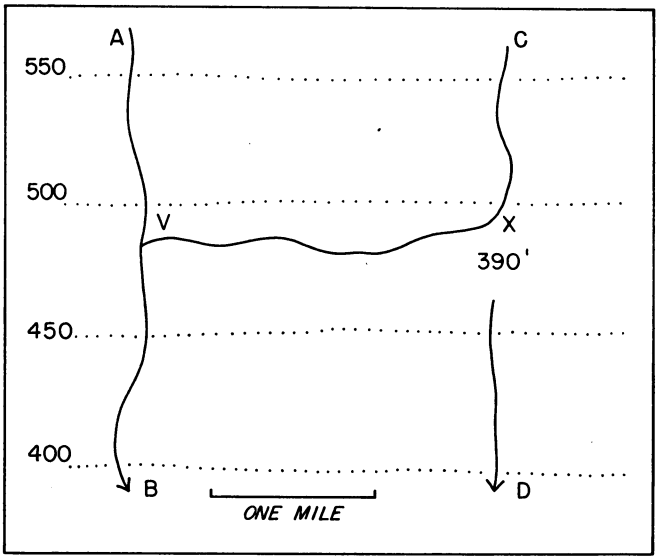

Fig. 2.—Method of inferring relative rates of erosion by consequent and subsequent streams.

has been superimposed, it may be possible to formulate a relationship of the following sort. While consequent stream CD was cutting down from 470 feet to 390 feet at X, the subsequent tributary, VX, of consequent stream AB cut back 2 miles along a weak bed to capture the upper part of CD. In this example the subsequent eroded back 1 mile while the consequent was cutting down 40 feet, but the variation of factors involved is probably so great that it is dangerous to generalize. Apart from the fact that it is rare to find an area of superimposed drainage in which the surface can be reconstructed with sufficient accuracy (although this can be done in those parts of the Hampshire Basin described by Wooldridge and Linton[10]), the following difficulties have to be met:

(a) The rate depends upon the relative resistance of the hard beds cut across by the consequents and the soft beds etched out by the subsequents. In the Hampshire Basin there is a great difference between the two.

(b) The argument depends upon the assumption that the subsequent stream is not merely etching out a valley filled with unconsolidated sediment in a partially but not completely planed landscape.

(c) It is assumed that there has been no significant modification of the wind gap at X since the capture took place.

(d) There are the usual provisos about relative sizes of consequent and subsequent streams, about the effect of heights above base-level, about the possible underground diversion of water through permeable rocks and so on.

Yet although such variations ensure that each example is unique, it may be possible in areas of similar structure to find enough examples all producing rates of the same order so that the calculation is not necessarily valueless though its results need to be applied with care.

Application to coastal geomorphology

Measurements of the velocities of various marine currents may be made but are of no direct application in assessing rates of erosion. Both sedimentation and recession of unconsolidated Quaternary cliffs have been directly measured or calculated from series of dated maps and some surprising rates obtained. Maximum sedimentation rates of about 1 cm. per year have been recorded in salt marshes by Steers:[11] extrapolated this means 20 metres of deposition in the last 2000 years if the rate were maintained. Similarly, direct measurements of cliff recession are available for unconsolidated Pleistocene coasts: rates of 2 to 5 metres per year have been recorded in Holderness and almost 30 metres per year on the unconsolidated ash coasts of Krakatoa.[12] These figures admirably illustrate the dangers of long extrapolations, for in 30 million years, an "average" length for a cycle, they would produce eroded surfaces respectively 40,000–100,000 and 600,000 miles wide!

The erosion of hard rock coasts is much more difficult to assess, for no annual rates can be determined except perhaps in the softer hard rocks such as chalk. The approach must be indirect and with reference to a longer time-scale. As an approximation one might sum the widths of all the marine terraces from the 650-foot early Pleistocene downwards. This might produce a figure of the order of 2 miles on the moderately resistant chalk of the South Downs dip-slope and the length of time involved might be estimated at half a million years, i.e., an annual rate of recession of about a quarter of an inch. It might be argued that this figure is too low, as this is not an example of continued marine erosion but of the sea being set to work afresh again and again. On the other hand, the rate of marine erosion at one level must fall off drastically with the width of terrace cut, if it does not stop entirely as some believe, so that even had the sea continued at one level it probably would not have eroded a greater width. All that one can do is to hope that the two possible errors cancel each other out.

Another way of approaching the same problem is to try to fix the time limits for any particular terrace and so to measure the average annual rate of cutting at least in the early stages of marine erosion. This is a very difficult problem, though a preliminary approach might be made in the following manner. Marine terraces are often attributed to certain interglacial periods, but how long is an interglacial period and for what proportion of that length did the sea stand at the elevation at which the terrace was cut? If it be assumed that the Pleistocene consisted of some preliminary climatic fluctuations followed by four glaciations and that the interglacials were equal in length, it is possible to take 50,000 years as an approximation to the length of an interglacial. This at least agrees fairly closely with Penck's original estimate of the length of the Last Interglacial,[13] which is that most suited to a discussion of the present problem. But obviously sea-level rose and fell in this period and it is difficult to determine how long it stood at the "25-foot" level to cut the narrow terrace, usually attributed to the high sea-level of this interglacial in southern Britain. An approach may be made, however, in the following way. By studying the changes from freshwater to brackish Mollusca and back again in the deposits of this interglacial, the time-planes at which the sea-level rose above and fell below present sea-level may be established. On the Continent these Last Interglacial deposits are usually found in the Low Countries and adjacent areas, where, unfortunately, warping has occurred. However, it has recently proved possible to show at Selsey, Sussex and Stone, Hampshire, that sea-level in the Last Interglacial rose above its present level in Zone *f* and that, near Arromanches in Normandy, it fell back below this level in Zone *i*.[14] These zones are pollen zones representing periods of readily definable vegetation but of uncertain length of time. Thus, there are three pollen zones available for the sea to rise from present sea-level to 25 feet, cut a terrace, and fall back below present sea-level—or perhaps only two zones if the apparent lack of Zone *h*[15] proves to be general in Britain. Although it is impossible to date interglacial pollen zones directly, it is probably true that they are of similar length to the comparable Post-glacial pollen zones which can be dated by radiocarbon methods. On this assumption the period of time from Zone *f* to Zone *i* is of the order of 5000 to 10,000 years, so that it seems reasonable to allow 5000 years at a maximum for the stillstand and terrace cutting at 25 feet. The ensuing terrace is narrow and its exact width reduced by later erosion of the front, but 100 yards is probably a reasonable maximum figure for its original width. This gives an annual rate of recession of the cliff of two-thirds of an inch, a figure which seems comparable with that derived from a general consideration of terraces below 650 feet O.D. especially as one would expect a somewhat higher rate for the development of a single terrace. The number of assumptions and estimates made ensures, however, that this figure, which can refer only to the early stages of marine erosion, is no more than a crude approximation. Indeed, work at present being done by R. G. West and the present writer suggests that there may have been oscillations of sea-level in the middle of the Last Interglacial so that it may not be possible to assume a simple rise to a maximum and a subsequent fall of sea-level. However, in view of the incomplete nature of this work, which concerns the unstable region of East Anglia, this should only be taken as yet another possible complication.

The problem might also be approached by using the data for the Post-glacial period. It has been established that the eustatic rise of sea-level was finished about 5500 years ago,[16] so that all that remains to be done is to measure the width of the terrace cut by the waves at present sea-level. One can rarely be sure, however, that the wave-cut terrace apparently conforming with modern sea-level is not an earlier one slightly modified by present wave action. Alternatively, one might project the profile of hog-back cliffs (e.g., in North Devon or parts of the Cardigan Bay coast) in order to obtain a possibly surer estimate of the amount of wave erosion related to present sea-level (cf. Fig. 1). It is probably true to say that the apparently present-day wave-cut terrace does not often exceed 150 yards and is usually much less, while that in front of hog-back cliffs is probably always less than 80 yards. With the amount of time available these figures give recession rates of 1 inch and ½ inch per year, so that by a variety of methods the derived rates of recession in hard rocks range from ¼ inch to 1 inch per year. There is, of course, always the possibility of local cliff collapse giving rates vastly in excess of this for short periods.

Although a few possible methods of assessing approximately the rapidity of operation of certain processes have been outlined, there are many processes for the estimation of which no obvious method presents itself and others about which such estimates involve so many assumptions as to make them little more than guesses. Yet the question of the long-term rate of operation of process is of great importance to geomorphology. The limits to the gathering of knowledge in this field are severe, yet by the use of increasingly accurate dating and detailed zoning of the Pleistocene, as well as by reference to historically datable events, it may become possible to learn more about the rates of operation of process in the very early stages of the erosion of a landscape. Even very crude estimates are valuable, for they enable one to test the plausibility of certain ideas put forward: for example, if it were stated that a certain area was peneplained, uplifted and a second cycle of erosion started all in the Pleistocene period, one might be excused for regarding such a statement with some suspicion.

Another problem which might be approached is the formation of the isostatically upwarped "25-foot" beach of western Scotland. This is usually correlated, on the basis of its height, with marine deposits mainly in eastern Scotland, where the deposits can be shown to have been laid down between the time of formation of the submerged forests in a mild part of Post-glacial time and the end of the Neolithic period. This Post-glacial "25-foot" beach of Scotland is thus not to be confused with the apparently unwarped beach of southern Britain at approximately the same elevation but dating from the Last Interglacial, which was considered above. For the formation of the beach deposits of eastern Scotland there is thus available at a maximum a period of 2000 to 3000 years and probably much less. This seems far too short for the formation of the "25-foot" marine terrace of western Scotland, which is eroded into some of the hardest rocks in these islands, especially as:—

(a) it is found not only in very exposed places but also in some of the most sheltered;[17]
(b) no comparable erosion has been effected in the probably longer period since the formation of the terrace;
(c) the rates of erosion of much softer rocks in southern Britain, derived above, do not seem to be compatible with the presumed Scottish ones.

The test is only one of consistency. It does not show that the Scottish beach cannot have been formed at this period. It suggests further work: either a re-investigation of the correlation of the beach deposits of eastern Scotland with the rock wave-cut terrace of western Scotland, or a re-appraisal of the rates of marine erosion—or both. In this questioning of hypotheses lies the possibility of closer approach to truth in geomorphology.

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