Landscape sensitivity and change

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ABSTRACT. The general concepts generated by modern studies of geomorphological processes are examined in terms of their utility for models of long-term landform evolution. The work is summarized by four fundamental propositions of landform genesis. These include the idea that each set of environments is represented by constant processes and characteristic landforms which tend to persist over time. 'Geomorphological' time is divided into the time taken to attain this characteristic state and the time over which it persists. The systems and forms are subject, over 10^2–10^5 years, to perturbations caused by high magnitude–low frequency events, environmental change and internal structural instabilities which initiate change. The responses to these impulses are complex and include damped, sustained and reinforcing changes taking place by ubiquitous, linear or diffusive propagation which reflect the sensitivity of the landscape to change. This sensitivity is dependent on the path density of the process and the strength of the coupling between the system components and has two end members, mobile-sensitive systems and slowly responding-insensitive areas. Some of the results include the concepts of (1) relief and pattern persistence; (2) stagnancy of development and the hypothesis of unequal activity; (3) convergence of form; (4) the concept of transient forms; (5) stability-instability phases and episodic landscape evolution, which together form a coherent framework for long-term landform evolution.

> Davis's great mistake was the assumption that we know the processes involved in the development of land forms. We don't; and until we do we shall be ignorant of the general course of their development.
>
> LEIGHLY, 1940

INTRODUCTION

ONE of the most appealing features of the contemporary fashion for process studies is that we are beginning to understand the mechanics of process and associated landform changes in 'man-sized' areas and 'human' time scales. It is worth pausing, however, to consider Stoddart's (1978) complaint that we are 'increasingly encapsulated in (our) small drainage basins and pollen profiles' and to recognize that the challenge of extrapolating the short-term record of measurable processes to the relatively unknown time span of, say, 100–10 000 years and beyond still remains.

There are many approaches to this challenge. There has been an impressive increase in detailed information about past changes in climate, sea-level, rates of uplift and continental movements, which enables more accurate reconstructions of fluctuations in environmental controls. There has been an accumulation of data on the rates of operation of geomorphological processes. The description of landforms has become more objective and precise and the use of statistical techniques has improved the description of relationships between processes and between forms and processes. There is a better understanding of the dynamic basis of geomorphology which has led to the development of deterministic and stochastic modelling techniques and the adoption of the methodology of realist science.

The purpose of this paper, however, is to review some of the more general concepts which have been generated by the process-form studies and to consider whether they yield a coherent conceptual basis for studies of long-term landform evolution. These ideas are stated as a series of fundamental propositions of landform genesis.

CONSTANT PROCESS—CHARACTERISTIC FORM

A basic proposition is that:—

> *For any given set of environmental conditions, through the operation of a constant set of processes, there will be a tendency over time to produce a set of characteristic landforms.*

These ideal forms are specified by the external variables of rock type, structure, energy inputs, climate, biotic activity and the boundary conditions provided by tectonic deformation, isostatic movements and base level change which together define process domains of geomorphological activity. Each domain is characterized by a set of forces whose variation through time can be described by magnitude and frequency distributions and by a set of materials which resist the forces to varying degrees, the interaction being complicated by feedback controls and sediment yield responses. These find expression in a uniform, repetitive assemblage of landforms which portray an essential unity of landscape and a strong interdependence of process and form.

The regularity of form has been demonstrated for many years but its description first gained real impetus from the work of Horton (1945) and later morphometrists. Their concern for the topological properties of rivers led to the demonstration of an astonishing degree of regularity in networks and in the arrangement of contributing areas. Strahler (1952) initiated objective and precise studies of form properties and later Leopold and Maddock (1953) convincingly demonstrated the 'all-pervading unity' of river channels in terms of the association between channel properties and discharge.

Regularity of form and pattern, in its turn, has long been used to infer process, for example, the convexo-concave hill-slope couplet has been accounted for in terms of the respective domains of soil creep and slope wash (Gilbert, 1909). Hack's (1957) study of the Shenandoah Valley, and Carson's (1971) attempt to relate characteristic forms to weathering properties are also typical of this approach.

Several authors have examined the interdependence and balance between system attributes, and the basic tenet has been shown to be useful in the study of river profiles (Gilbert, 1877; Davis, 1899; Mackin, 1948), channels (Leopold *et al.*, 1964), patterns (Langbein and Leopold, 1964; Holmes, 1964; Woldenburg, 1966), sediment transport (Tanner, 1962; Allen 1974), beaches (Tanner, 1958), cliff systems (Cambers, 1976; Brunsden and Jones, 1979), soil systems (Nikiforoff, 1959), weathering (Miller, 1961; Yaalon, 1976), hill-slope profiles (Scheidegger and Langbein, 1966) and alluvial fans (Hack, 1965; Denny, 1967; Bull, 1977). Thus overall the concept of constant process producing characteristic form is proving a powerful paradigm for process studies.

There are also serious attempts (e.g. Peltier, 1950; Skempton, 1957; Wilson, 1960, Fournier, 1960; Corbel, 1964; Schumm, 1965; Strakhov, 1967; Kirkby, 1976) to identify the controls and processes which would provide characteristic domains. Some of these attempt to specify process domains on the basis of an intuitive understanding of the relationship between the processes and simple climatic parameters. The present shift toward the examination of much more elaborate variables (Fig. 1) emphasizes that the basic idea of control by environmental domains is at the centre of the constant process—characteristic form argument.

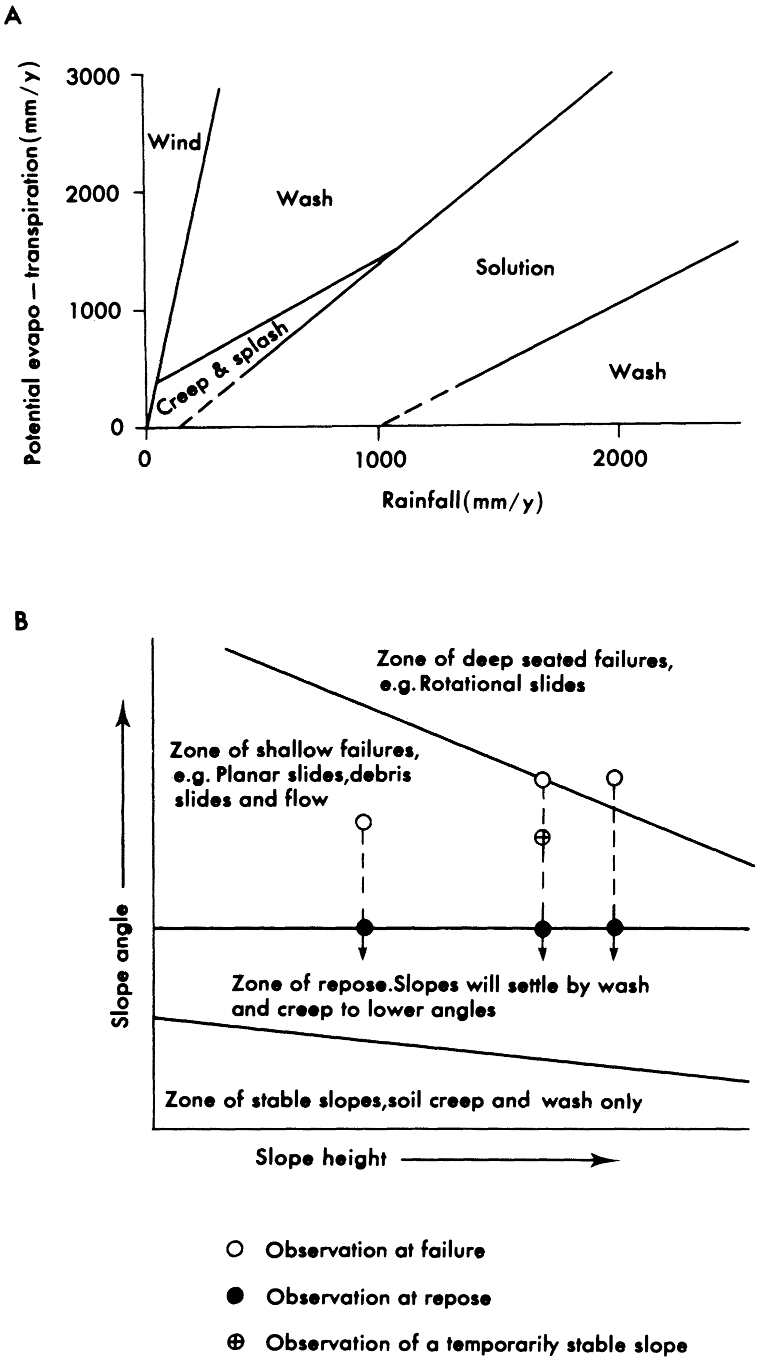

FIGURE 1. Process-domains identified with respect to climate for hillslope processes by Kirkby (1978) and with respect to slope morphology for mass movement processes by Skempton (1953)

The idea of process domains is complemented by Wolman and Miller's (1960) assertion that work done by a process depends not only on the magnitude of the applied force, but also on the frequency of application and by Wolman and Gerson's (1978) ideas on formative events. The data used in these analyses gave further support to the idea that there is a particular frequency at which most of the geomorphologically effective work is done. This view had already been strongly established by Leopold and Maddock's (1953) argument that the bank-full discharge was the event of greatest geomorphological importance for channel development. The association of a characteristic form with events of particular frequency or magnitude is also common in hydraulics in the idea of the domains of different bedforms (Allen, 1970) as used by Dury (1964) in river and valley meander studies and by Starkel (1972 a and b) in his studies of formative events on Himalayan hill-slopes.

Great success has been achieved in utilizing the concept for theoretical modelling. There are limitations but the characteristic form solution provides a mathematically more tractable goal than alternative time-dependent solutions. The work of Jeffreys (1918), Scheidegger (1960), Culling (1963) and Kirkby (1971) on hill-slopes, the characteristic fluvial process models of Lane (1937) and Engelund (1974) and the limit equilibrium models of soil mechanics should all be mentioned in this context. The new-found ability to simulate these mathematical constructs (Ahnert, 1976; Armstrong, 1976) should lead to the lowering of technical restrictions on the range of feasible solutions.

The conceptual revolution which enabled the characteristic form proposition to gain acceptability was the shift from closed-system to open-system thinking. Strahler (1950) and Culling (1958) both pointed out the need for a shift away from approaches which adopted a progressive reduction of available energy for doing work through time, to one in which there was a constant flux of energy and matter to which the forms are adjusted. This theme has been extensively developed by Chorley (1962) and represents a major change in our perception of the problems of long-term development and the way we attempt to solve them.

Perhaps the most fundamental change required with respect to long-term development is the need to adopt an attitude to time which lays stress on the period required to attain characteristic form (relaxation time) and the length of time over which the characteristic form persists (characteristic form time), since this will identify the ability of the system to adjust in relation to the frequency of any impulse of change.

The importance of this approach to time should not be lightly disregarded, for it is the most distinctive difference between models of open systems which are self-regulatory and studies of closed systems in which time itself is regarded as a controlling variable. For example, G. K. Gilbert's philosophy, which is generally regarded to be the forerunner of the characteristic form idea, was summarized by Davis (1926) in his assessment of Gilbert's work almost as a matter of disbelief:

> The absence of the important physiographic factor, time, from Gilbert's reports is . . . perplexing. He must have known perfectly well that the existing conditions of drainage systems as well as the existing forms of the land surfaces are the product of erosional processes acting upon structural masses through longer or shorter periods of time; yet his account of streams and of land forms is much more concerned with their existing status than their evolutionary development from an earlier or initial status into their present status.

As Chorley (1962), Smalley and Vita-Finzi (1969) and Baker and Pyne (1978) have pointed out, rather than searching for endforms in which entropy attains a maximum and thus basing the concept on the Second Law of Thermodynamics, the Gilbert approach utilizes the First

Law—the conservation of energy and mass—to study selectively systems in which entropy and information content remain constant for longer or shorter periods of time according to the stability of the environmental specifications.

The actual length of time over which conditions remain steady is the subject of much recent research on environmental change (for recent reviews see Goudie, 1977; Bowen, 1978) and we are beginning to obtain a more precise scale of reference. Data on the 'time of attainment' for different systems, however, is scarce. Examples include Hutchinson's (1967) study of London Clay, Welch's (1970) study of Athabasca moraines, Brunsden and Kesel's (1973) investigation of degradation of Mississippi bluffs and Hutchinson and Gostelow's (1976) study of changes at Hadleigh cliff. These studies, all for 'soft' rocks, indicate a 10–10^4 year period for the attainment of a characteristic slope value. Weathering and soil development studies also indicate that, on the scale of the soil profile or catena, an orderly balance between soil solutions and minerals can be achieved in 10–10^3 years. As with many other geomorphological systems, initial rapid change is succeeded by an exponential change towards very slowly changing values (Fig. 2).

The time needed for adjustment appears to be of similar order of magnitude to that needed for changes to the external controlling variables, such as climate or base level (e.g. post-glacial time), so that the characteristic form concept seems to be a valid and applicable position to adopt as a basis for landform change studies, at least for the less resistant systems.

Despite the apparently well-founded nature of the characteristic form proposition, and despite discussions of its validity for long-term retrodiction or prophesy (Hack, 1960, 1965, 1975; Holmes, 1964; Howard, 1965; Schumm and Lichty, 1965; Gerasimov, 1970; Melhorn and Flemal, 1975), there have been remarkably few attempts to apply it systematically to the study of

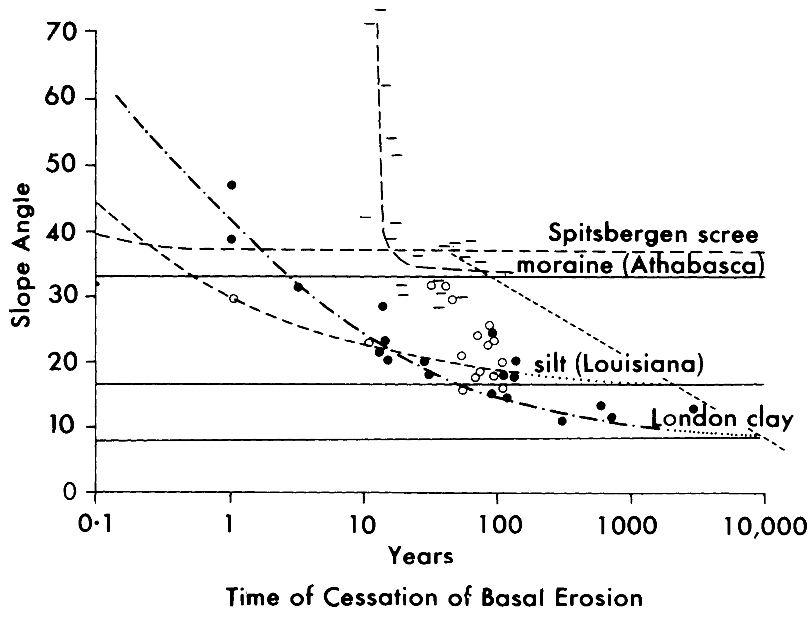

FIGURE 2. The exponential change of slope angle through time is demonstrated by the records of the Athabasca moraines in Canada (Welch, 1970) the Mississippi bluffs at Port Hudson, Louisiana (Brunsden and Kesel, 1973) clay cliffs throughout the London Basin (Hutchinson, 1967; Hutchinson and Gostelow, 1976) and Spitzbergen (general data).

the denudational history of an actual region and only lip-service has been paid to its suitability for the understanding of the British landscape (Challinor, 1930; Bowen, 1967; Worssam, 1973).

The most comprehensive use of the concept is expressed by Tricart and Cailleux (1965) who, founding their studies on the seminal works of the continental geomorphological tradition (Tricart and Cailleux, 1965, pp. 45–6), quite unequivocally state that 'the fundamental unity of nature and the narrow interdependence of its various elements are at the base of the concept of morphoclimatic equilibrium' in which the idea of 'climax' systems, 'forms of equilibrium', a tendency of forms to persist, and the 'concept of landform stability' are the essential elements in the interpretation of palaeoclimatic systems, present systems and the basis of rational land management in the production of future systems.

TRANSIENT BEHAVIOUR

A second basic proposition is that:

> *Geomorphological systems are continually subject to perturbations which may arise from changes in the environmental conditions of the system or from structural instabilities within. These may or may not lead to a marked unsteadiness or transient behaviour of the system over a period of* 10^2–10^5 *years.*

Basic attacks have been made on the constant process-characteristic form proposition on the grounds that geomorphological controls rarely remain constant for a sufficient period of time to enable the characteristic form to evolve. In particular it is argued that a few very large events may produce substantial, long-lived landscape change. The debate centres around the question as to whether this transient behaviour is the norm rather than the exception. The usual way of incorporating this neocatastrophism and environmental change is through the magnitude and frequency concept, by adopting larger areas and longer time periods. A more recent view is that the conceptual and technical base for future work might be provided through catastrophe theory. Another procedure is to regard transient behaviour as a logical extension of the characteristic form case and attempt to model it. In such circumstances systems theory provides the general methodology, and stability analysis of the mathematical models provides a technical base.

The potential success of this approach might be judged from the related fields of hydraulics where analysis of unsteady flow conditions, dating back to the early 'fifties', has revolutionized the subject (Ven Te Chow, 1959; Yevjevich *et al.*, 1975). Recently Parker (1976), Ponce and Mahmood (1976), Kirkby (1976) and Thornes (1979) have adopted similar strategies with respect to braided streams, meanders, drainage density and sedimentation respectively. It is worth noting, however, that only a few authors have directed attention to the wider landscape implications (e.g. Chorley and Kennedy, 1971; Smith and Bretherton, 1972) and that a conceptual approach to transient behaviour is now required if we are to make progress in long-term evolutionary studies (Thornes, 1977).

THE INITIATION OF CHANGE

External shocks to the system may be thought of either as pulsed or ramp inputs. In the former, the imposed disturbance is short in relation to the time scale being considered and is followed by a return to or near to the initial state of the system. This kind of change is typical of extreme, episodic events. Normally such disturbances are spatially as well as temporally restricted in effect. In the ramp type of disturbance the changes in inputs are sustained at the new level as a result of permanent shifts in the controlling variables or boundary conditions. These exogenous ramp disturbances may cause a shift from one process domain to another and may be applied synchronously over a wide area to yield uniform spatial response.

In addition, change can be initiated internally through the progressive operation of the normal inputs by exceeding certain critical levels. These thresholds occur as transitions between the conditions necessary for different process domains or as structural instabilities within a domain.

Pulsed inputs (low frequency–high magnitude formative events)

One of the most notable results of recent process studies is the increasing emphasis being placed on the role of extreme (catastrophic?) events on landform change and the morphogenetic balance (Wolman and Miller, 1960; Starkel, 1963, 1976; Beaty, 1974; Selby, 1974; Wolman and Gerson, 1978).

In this review it is impossible to give a complete summary of the concepts of frequency and magnitude in geomorphology or to mention all of the work carried out. Nevertheless, it is essential from the viewpoint of long-term landform change to note the following points:

(i) The morphological impact of extreme events varies in different climatic and epeirogenetic zones according to the relative efficiency of more frequent events. It is also a function of reinforcing or restorative processes which determine how long the resulting landform or deposit persists and thus becomes a diagnostic element of the landscape assemblage.

(ii) It follows that the importance of a large event in landform evolution depends on the extent to which it produces unique results in terms of differences in magnitude or kind from more regular occurrences (Fig. 3).

(iii) When the average values of disturbing stresses are low but the variation about the mean is large, then the landscape is likely to be dominated by large events, large storage and abrupt discontinuities, scars and variations in relief. A more regular and smoother form might be expected to occur where the variation of perturbations about the mean magnitude of stress is less. This probably applies along a traverse from temperate and humid areas to more arid regions and within any environment from higher to lower scales of landscape components.

The significance of these observations is that extreme events can and do change the main trends of landscape evolution and therefore must be regarded as an essential part of landscape genesis and our models of that genesis. At present, however, we do not know the extent to which the characteristic or repetitive forms of a landscape are caused by extremes, though we can be fairly certain that the stable, constant forms are produced by the more frequent events. Intuitively, it seems likely that it is those landforms and deposits which depart from the average which are produced by the extreme event. Thus in interpreting the landscape we must be very careful that we do not too readily ascribe their origin to different equilibrium conditions (e.g. to a previous periglacial environment); they may in fact merely represent an accumulation of extreme event phenomena (Thornes, 1976a; Starkel, 1976).

There are two very good examples of this principle. First, from studies of arid, semi-arid and sub-tropical mountain channel systems (Schick, 1974; Brunsden *et al.*, 1979) it has been discovered that flood events can have a formative influence on such features as overall valley form, flood terraces and alluvial fan accumulations (see also Gage, 1970; Born and Ritter, 1970, Womack and Schumm, 1977; Pullar, 1965; Grant, 1965) and that, at least for low terrace forms, classical concepts of stage, rejuvenation or climatic change may be quite out of place.

Secondly, the interpretation of complex areas of degraded landslides, such as those

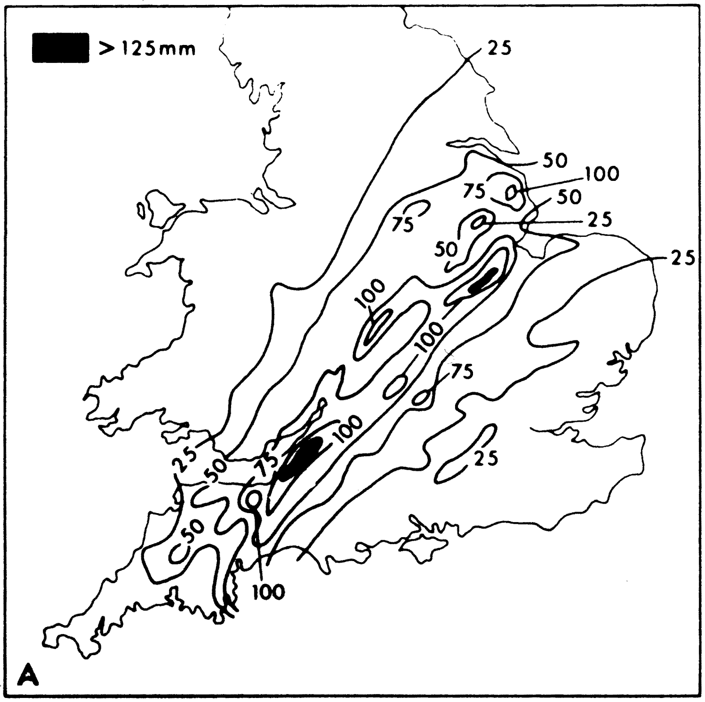
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FIGURE 3. An extreme rainfall event was registered in 1968 over central Britain as shown by the isopleths (Newson 1975) (a). Dramatic floods occurred across the Mendip Hills as seen in Cheddar Gorge (b). A year later only a few signs of this flood were visible in the landscape. Some parts of the system recovered very quickly, as in Cheddar Gorge a few days after the event (c). (Photographs: copyright N. Barrington, gratefully acknowledged)

occurring beneath many of Britain's escarpments, should not necessarily be seen as being a legacy of palaeo-conditions such as higher groundwater conditions of the Late Glacial period (Skempton and Weeks, 1976; Hutchinson and Gostelow, 1976; Chandler, 1976; Brunsden and Jones, 1972). A common interpretation is that the Late Glacial is a likely period for slope failure and this is supported by a few radiometric dates (e.g. the Sevenoaks landslides of 12 200 B.P.). The occasional records of more recent failures are then often explained as being related to the Little Ice Age deterioration of climate, forest clearance, highway construction or other causes. All this is logical, quite reasonable and widely accepted. We merely note that there exists the alternative possibility that they may all be extreme climatic event forms, *some* of which may have occurred during late-glacial, Little Ice Age, forest clearance or recent times (e.g. 1640 at Leith Hill, 1968 at Ide Hill on the Lower Greensand escarpment). In view of the latter dates the dated record of 12 200 B.P. at Sevenoaks may reflect the occurrence of an extreme saturation event (Thornes, 1976b) rather than distinctive (Late Glacial) morpho-equilibrium specifications.

Ramped inputs including changes and fluctuations in environmental specifications

One of the outstanding achievements of environmental science has been to document changes of climate, vegetation, land use and base level which have occurred over the last two million years. If we are allowed, for the sake of this discussion, to adopt fairly loose limits on what constitutes a reasonable environmental specification for a given morphogenetic equilibrium, then we have to accept that over the 10^3–10^4 time scale there will be distinct variations in the level of energy input to geomorphological systems. A few examples will suffice to illustrate the point but the reader should turn to the reviews and cited references of Tricart and Cailleux (1972), Goudie (1977) and Bowen (1979) for comprehensive information.

Most of the geomorphological unsteadiness is caused by shifts of climate and by the associated vegetation changes such as advances or retreats of desert, grassland and forest. Although much of the evidence is derived from palaeobotanical, palaeoclimatic and human prehistorical studies some remarkable reconstructions of geomorphological conditions have also been made. These include the studies of pluvial and aeolian phases in the desert regions of India, Australia, Arabia and elsewhere (e.g. Singh, 1971); the massive shifts of Himalayan rivers (Goudie, 1977); neo-glacial advances and the retreats of the hypsithermal periods (Denton and Porter, 1970); phases of alluvial cutting and filling due to either climatic or land-use fluctuations (Bryan, 1940; Vita-Finzi, 1969; Butzer, 1972; West, 1972; Cooke and Reeves, 1976); changes in river discharge (Goudie, 1972) and the remarkably well-documented glacial and mass movement events of the Little Ice Age (neo-glaciation) (Fig. 4) (Grove, 1972).

All indicate that even over as short a period as 500 years (e.g. taking the Little Ice Age as centring on the seventeenth to eighteenth centuries) there can be a real unsteadiness of input behaviour. The mass movement records are particularly important observations (Starkel, 1968; Hutchinson and Gostelow, 1976), for they indicate that not only do responsive sub-systems such as glacier snouts, sand dunes and stream channels react to these inputs but also that major formative changes can take place in less responsive elements of the landscape such as hill-slopes.

It is perhaps equally important to mention the rather more continuous but nonetheless significant changes associated with the fluctuations of the relative level of land and sea. Although

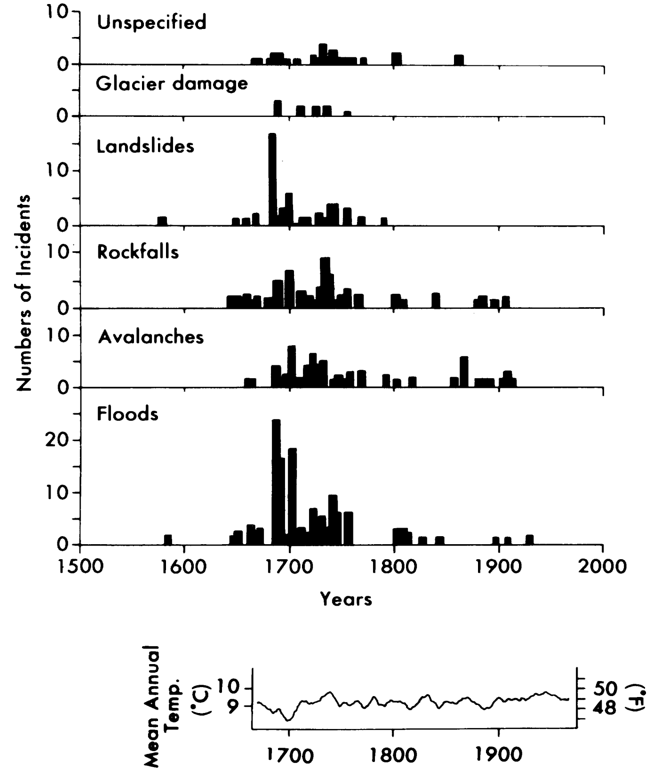

FIGURE 4. An example of geomorphological unsteadiness caused by a temporary shift in value of climatic parameters is illustrated by the well-documented case of the Little Ice Age in Norway (Grove, 1972). The climatic curve is after Manley (1974).

it is impossible here to give a full review it is worth reminding ourselves that there have been remarkable changes of sea level, and of the position of the coastline which exert a continuing influence on the relief-energy available for morphological change. The change in sea level over the last 10 000 years has had a stabilizing effect on many drainage basins, controlled the growth of extensive flood-plains and shoreline accumulations and, conversely, led to continuous erosion of many coastal cliffs. In addition, uplift and subsidence rates due to tectonic or isostatic forces have led to considerable disparities between denudation and increasing elevation so that, in some areas of the world, there is a continuous source of dynamic instability.

THRESHOLDS

The third type of unsteady behaviour is expressed in the widespread recognition (see Howard, 1965; Chorley and Kennedy, 1971) of the existence of thresholds of systems behaviour (Fig. 5a). This work was initiated at the beginning of the century and culminated in such recent works as Schumm's study of channel incision (Schumm, 1973) and Kirkby's investigation of drainage density (Kirkby, 1978). There appear to be at least three types:

(i) Those which lead to rapid changes in the rate of operation of processes within a given domain (Hjulström, 1935).
(ii) Those which separate unstable and stable system states within a given domain. These are associated with those processes which show pronounced maxima or minima as a controlling factor changes (Kirkby, 1978).
(iii) Those which separate two or more process domains (Leopold and Wolman, 1957).

In any of these cases the transition may be viewed as a simple line, such as the discriminant function between braiding and meandering, in two dimensions. In fact the threshold is usually a complex surface in at least three and often in many dimensions.

The general importance of thresholds and their definition with respect to processes is now well known and we are aware not only of some critical values and their definition, but also of their importance in systems management. Less consideration has been given, however, to the ways in which a knowledge of thresholds can assist our interpretations of long-term landscape change. One way of approaching this problem is to attempt to model fundamental structural instabilities by catastrophe theory and then to trace typical time paths across the topological space so defined. Some of these paths will be more probable than others but provided the space is adequately defined many possible cases can be envisaged (Thornes, 1979).

It is clear from this review that we need to define the nature and magnitude of the changes which will move a system to a new equilibrium state. If we could achieve this it would enable us to locate ourselves on the space–time manifold and travel across it in a manner dictated by changes in the control variables. Until we can model the fundamental behaviour of these manifolds we do not know how much variation the system can tolerate before change occurs. If we cannot chart accurately the controls of landform change then we cannot make progress in the field of climatic geomorphology.

Besides these shifts in the relative dominance of one process or another, changes also occur with a shift from a negative to a positive feedback situation. A good deal has been learned about these situations in the last twenty years and particularly in the last ten years. The shift from negative to positive feedback was especially recognized by Erhart (1955, 1956) in his concept of biostasy and rhexistasy in which conditions of morpho-biological constancy are interrupted by periods of natural instability on a continental scale. Similarly the K-cycle concept of Butler (1959, 1967) attempts to view systematic long-term changes as periodic shifts from dynamically stable equilibrium forms by rapid change involving positive feedback.

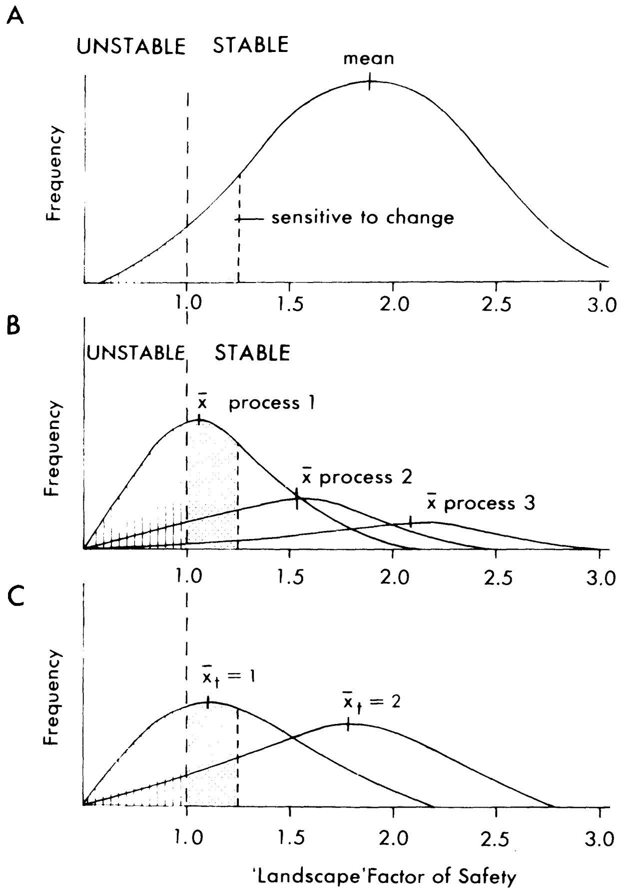

FIGURE 5. The concept of failure at a threshold represented by a safety factor of unity. In any landscape the majority of components are likely to be stable according to the frequency distribution of a chosen morphological characteristic (A). Different distributions for each process will yield different distributions of the safety factors (B). These will also vary through time (C). Those components nearest to a factor of safety of one will be those most sensitive to change.

In recent years the initiation of change has received more attention, most notably in formulating the *conditions* under which a specified model of an environmental system will shift from a stable to an unstable state. The great problem for long-term landform development is to know which of the types of change (pulsed, ramped or structural, and they are not mutually exclusive), was responsible for past changes. There can on the other hand be no doubt that our capacity to model long-term developments is greatly enhanced by our appreciation that change is not merely initiated by changes in the external variables.

COMPLEX RESPONSE

The response to perturbing displacement away from equilibrium is likely to be temporally and spatially complex and may lead to a considerable diversity of landform.

This important proposition seems almost trivial and yet, with notable exceptions, there have been few studies of the various ways in which different geomorphological systems can respond to the same impulse. Most studies faced with the need to explain complex landscapes have chosen instead to explain them as the effect of multiple and complex causes.

The most obvious type of response is the simple, lagged, stabilizing response in which an impulse is damped out and the previous state is restored. Studies of floods (Schumm and Lichty, 1963; Burkham, 1972), of slopes (Brunsden and Kesel, 1973) and mass movements (Hutchinson and Gostelow, 1976; Brunsden and Jones, 1979, Fig. 2), all tend to indicate a typical first-order exponential decay toward a characteristic form. Other processes which probably follow similar relaxation paths include the impact of deforestation and urban development on sediment yield; changes in flow characteristics, bed forms and channel infills; and the adjustment of a shore following a hurricane or storm surge.

Some impulses yield a sustained response at a new level of geomorphological activity. This kind of change is readily studied in the laboratory or theoretical model and there are many historical case studies. Examples are provided by the dumping of mining debris, the long-term effects of reservoir construction or the permanent changes of coastal geometry induced by protective works. Sustained response also includes those adjustments which follow from significant changes of climate, rock type or base level.

Here too there will be an initial period of rapid adjustment followed by a slower move toward the new characteristic state. On closer inspection, however, the response sometimes appears to be stepped. Carson and Petley (1970) for example, suggested that the long-term response of hill-slopes to uplift, of either the pulsed or ramp type, would be a reduction of angle by a jerky path dictated by particular stages in the weathering of the regolith.

A third type of response, which has become better known both deductively and through process observations, is *reinforcement* by positive feedback (Schumm, 1976; Twidale, 1976), in which one change leads autocatalytically on to another. Two important examples are the generation of curves in rivers and the development of streamheads, both of which are at the core of many of the long-term changes we wish to study. Another, of widespread importance, is the sequence in which progressive induration of soils leads to reduced infiltration capacity, to increased relative run-off for a given storm magnitude, to the exceeding of critical erosion thresholds, to gully incision and the production of a two-storey landscape which under other conceptual approaches might be attributed to rejuvenation or climatic change! Conversely, there is Schumm's (1976) model of rejuvenation in which complex and progressive changes in channel incision, alluvial infilling, headwater responses and terrace production yield similar stepped landscapes from quite different complex response sequences.

The knowledge that ultimately such changes must be checked is not at issue. What is more important is that by the time they have been checked they will have left indelible and irreversible imprints on the landscape which constitute an important part of the historical record but which are difficult to explain by conventional ideas.

In addition to the varying patterns of temporal response, landscape complexity arises from the way in which impulses are propagated spatially through the landscape. There are three basic patterns of spatial response. First, a change may be *ubiquitous* owing to the application of a widely distributed process which, in geological terms, changes instantaneously. Weathering is one such response (e.g. to climatic change) and it is an important example of a ubiquitous response which, under certain conditions, may be a limiting factor to further change.

Secondly, change is normally propagated linearly along the sensitive erosional axes such as zones of jointing, shearing, 'weak' rocks, or river channels. The 'subsequent stream' hypothesis or the two-stage concept of tor evolution (Linton, 1955) are good examples of this idea.

Thirdly, several models of landscape change (e.g. King, 1957; Bjerrum, 1971; Brunsden and Jones, 1976, Fig. 6) argue for the propagation of changes as *diffuse* waves of aggression away

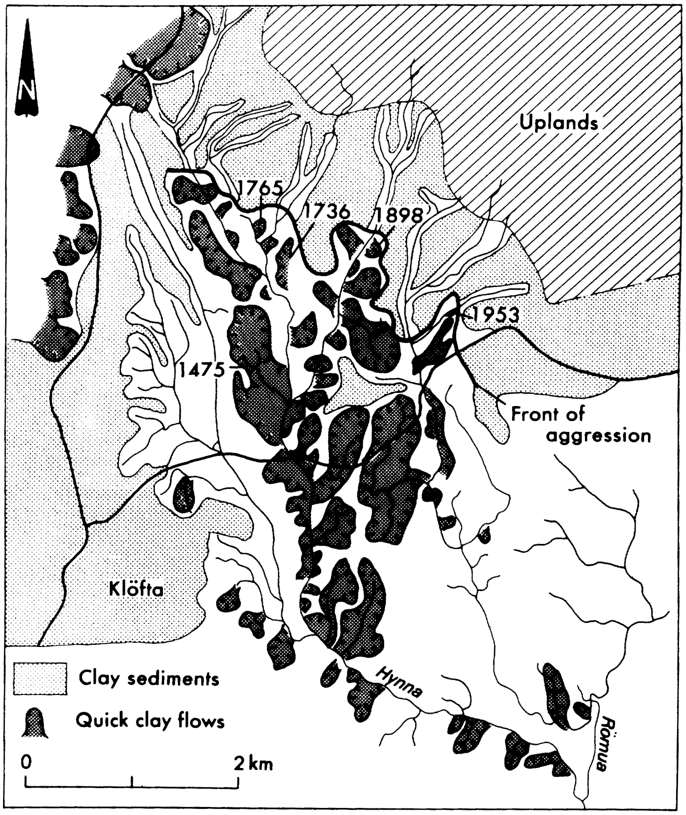

FIGURE 6. The propagation of change as a diffusing wave was illustrated by Bjerrum, 1971, for the development of quick clay flows on the Hynna river. In mapping the limit of failure as a 'front of aggression' he demonstrated how the age of landslides reflected the diffusive mechanism

from the river channels or linear axes of change. This theme of slope-channel coupling, which is so important to long-term development, has still not been studied in detail, though there have been many attempts to model it (e.g. Young, 1963; Culling 1965). These characteristic responses, damped, sustained and reinforcing taking place by ubiquitous, linear or diffusive propagation, reflect the sensitivity of the landscape to change and go a long way toward assisting an understanding of landscape diversity and complexity of response.

SENSITIVITY TO CHANGE

> *Landscape stability is a function of the temporal and spatial distributions of the resisting and disturbing forces and may be described by the landscape change safety factor here considered to be the ratio of the magnitude of barriers to change to the magnitude of the disturbing forces.*

The sensitivity of a landscape to change is expressed as the likelihood that a given change in the controls of a system will produce a sensible, recognizable and persistent response. The issue involves two aspects: the propensity for change and the capacity of the system to absorb the change.

The propensity for change may be cast in terms of the analogy from rate process theory in chemical kinetics. The state occupied by a geomorphic system can be thought of in terms of a stone resting on a stream bed which is rough, exponential in form and higher in the headwaters. Particles in the headwaters have greater propensity for movement than those at the downstream end for they have greater potential energy; they are, relatively speaking, less stable. In any given location, the particle is surrounded by other particles which form barriers to be crossed. Some even occupy hollows which they have to leave if they are to occupy progressively more stable locations further downstream (Fig. 7). The propensity for change of the state of a particle (i.e. its position) depends on the distribution of lift forces available to move it out into the main flow in relation to the barriers to that movement. In time and space, both the distribution of barriers and the applied forces are variable, so the sensitivity of the channel bed to change also varies. The same principle may be applied at the scale of a river valley in which the channel is equal to the stone and the interfluves the barriers, or it may be applied in the abstract to geomorphological systems, where the stone represents a combination of state variables, the hollows a number of metastable conditions and the base the ultimate stability.

We may characterize shifts in sensitivity through time by assuming a constant distribution of disturbing forces but an evolution of the barriers (as in the stepped weathering regolith model of Carson and Petley, 1970). Alternatively we may assume a relatively constant distribution of barriers with changes in the distribution of disturbing forces (as for example in a change in the frequency of high-magnitude events). In practice both are varying through time. It is important to note that changes may occur which produce higher barriers (Fig. 8) so that larger events are required to initiate change (e.g. induration). The ratio of the mean magnitude of the barriers to the mean magnitude of the disturbing forces is known in engineering parlance as the safety factor (> 1·0 equals stable). Although this concept is generally applied to limit equilibrium situations, such as the stability of hill-slopes against landslides, it is also applicable to a whole landscape.

Since both the barriers and the disturbing forces have statistical distributions, the safety factor itself will have a distribution (Fig. 5A) which differs for each kind of process (Fig. 5B) and with time (Fig. 5C). This defines those parts of the landscape closest to a factor of safety of unity and therefore those most likely to change. Because there are different thresholds for each process in a complex landscape there will be a multitude of possible responses to any impulse. This is especially true if the factor causing change affects more than one process at different rates and

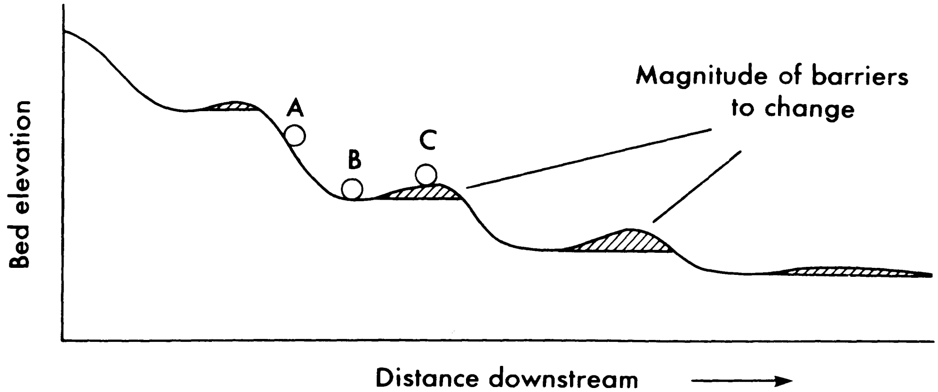

FIGURE 7. The two-dimensional analogy of states in a dynamic system showing unstable (a) and metastable (b) conditions and the notion of barriers to change

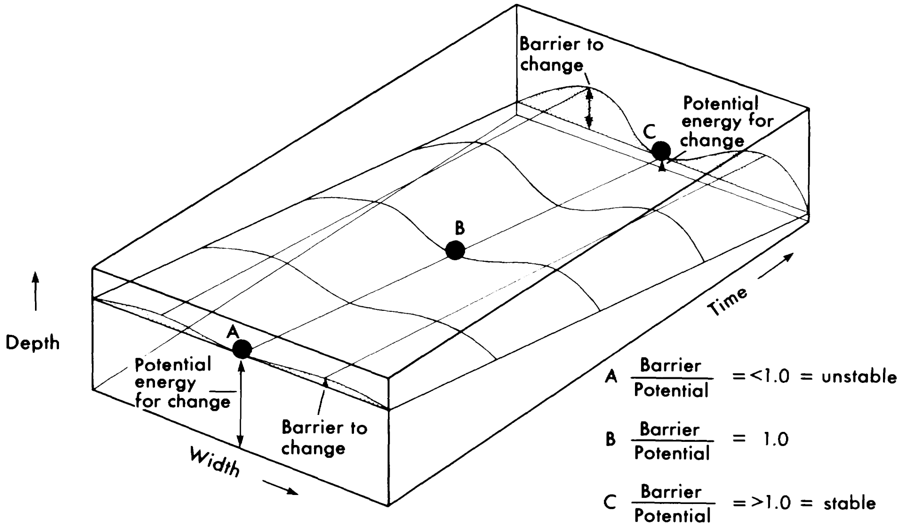

FIGURE 8. Through time the systems become more entrenched in furrows in the space-time manifold. The barriers to change become greater and more energy is required for a change from one equilibrium state to another.

with varying reaction and relaxation times. A project for future research will be to map these safety factor distributions as a predictive aid to landform change studies.

Additionally, geomorphologists have concentrated on the distributions of the disturbing forces (change of climate, base level, land use, etc.) but an enormously important development of recent years has been the recognition that the barriers to change are much more complex than hitherto suspected. A common view is that resistance should be defined by 'rock resistance' as measured by weathering rates, strength and erodibility, or as 'morphological resistance' in terms of flat slopes, low relief or closeness to base level. Recent process studies emphasize, however, that attention should also be given to the ability of the system to absorb and store energy, water and materials, and thereby reduce the effect of an impulse. In addition it is worth noting that if a 'harsh' environment precedes a more gentle one then it is likely that some forms will be produced which are morphologically 'too flat' to be altered in the new system. As far as the new state is concerned they are 'over-adjusted' and therefore remain unchanged for very long periods. This principle—the acceptance (persistence) of previous system states—is perfectly illustrated by the present dominance of low-angle periglacial slopes in the English landscape which are so flat that they have become resistant forms and barriers to further change.

Once change has been initiated, the rate of change determines the relaxation time or time of attainment of a new characteristic form or, conversely, the persistence of the characteristics of the former state. Usually in most landscapes a mixture of the two conditions together with transient forms exists. This is mainly controlled by the capacity of the various components of the landscape to actually transmit an impulse. This capacity is dependent on the *path density* of the process and the *strength of the coupling* between the system components. For example, if the path density is high (e.g. high drainage density) then effects may be propagated in all directions quickly and ubiquitously. Similarly, it is a common fact that in headwater areas there is a strong slope-channel coupling and close interdependence of variables, whereas downstream, with the development of a flood plain and high storage, a lack of slope-channel coupling prevents contact between the channel-led impulse and the hillslope and promotes linear alterations along the main axes of change. There therefore exists in the landscape a wide spatial variation in the response characteristics to change. We may identify two main end members:

(i) Mobile fast responding subsystems which have a high sensitivity to externally generated pulses; react quickly and relax to new system states with facility; they are relatively sensitive to climatic variations and act as energy filters, removing the main impulse and passing on only minor changes to contiguous subsystems. These areas are morphologically complex because they are not only subject to rapid change and therefore exhibit transient forms, but they are also capable of rapid restoration and achievement of new stable states. In other words they may be expected to include mixtures of characteristic and transient forms.

(ii) Slowly responding, insensitive areas, such as interfluves or plateaux where the ratio of stress to resistance rarely exceeds unity; they lie far from the boundary changes, and changes are rarely propagated inwards because of low path density, high storage capacity or intermediate buffering. These areas are characterized by low concentrations of flows of energy, water and materials. They are passive, insensitive to external effects (such as climate) and therefore change but slowly.

There are a number of consequences of this range of sensitivity. First, in the insensitive areas, morphoclimatic characteristic forms are rarely produced unless the environmental conditions remain constant for long periods. The landscapes are thus a 'palimpsest of systems . . . whose history is superimposed' (Chorley and Kennedy, 1971). Secondly there must be a persistence of relief and pattern in which the interfluves suffer from a general stagnancy of development (Crickmay, 1959). This 'principle of erosional probability' or 'hypothesis of unequal activity' defines the existence of enormous areas of great antiquity ($2–200 \times 10^6$ years), poor dissection and polygenetic mantles, such as the plains of Africa (King, 1960) or Australia (Twidale, 1976). Thirdly, the idea also implies that the mobile elements must be remarkably persistent in location despite their great activity because they cannot overcome the barriers to change (Potter, 1978). Rivers such as the Mississippi have remained roughly in their present position (with minor oscillations about their mean position) throughout one-sixteenth of the earth's history and it must be assumed that only major changes such as continental rifting, plate tectonics, tectonic arching (e.g. the Congo), glaciation (e.g. the Thames) or marine transgression are capable of altering the fundamental locational patterns.

Fourthly, in the relatively insensitive areas, there will be a persistence of basic, geologically-controlled relief elements and the landforms will be dominated by lithological resistance. If the rates operate sufficiently rapidly there will be a move, through a mode of continuous evolution, towards a form characteristic of the lithology, such as cuestas, hogsbacks or inselbergs. This is likely to occur whatever the morphoclimatic condition, leading to a convergence of form which transcends climatic boundaries.

Fifthly, some areas which typically do not exhibit adjustments to continuous but relatively insignificant perturbing forces over long periods of time preserve the effects of large changes for extremely long periods and may even be dominated by landforms entirely produced by large events (e.g. mass-movement complexes, lava flows and floodplains). Smaller changes will on the other hand only be registered in very sensitive areas, such as the current channels, areas of high drainage density or areas of overland flow. This variation in sensitivity leads to a filtering effect where only the very large events, or the integration through a threshold of many small events, can be preserved in the stratigraphic record. In the insensitive areas the smaller changes do not exceed the barriers. In the sensitive areas they do, but the high mobility means that the effects are quickly damped. This accounts for the apparent complexity of contemporary processes and environments (such as the behaviour along the margins of ice sheets and glaciers) when compared with the apparent simplicity of the stratigraphic record.

The sensitivity of landforms to both internally and externally generated changes can also be thought of in terms of a transient-form ratio, expressed as:

$$TF_r = \frac{\text{mean relaxation time}}{\text{mean recurrence time of events}}$$

each of which is a function, of course, of the rate of operation of the corresponding processes, and not of time itself, which is an artifact. The river channel illustrates this idea. A short overbank discharge may lead to major change, and several months might be required to return to a characteristic form in steady-state condition. If the ratio is greater than unity, the forms will be predominantly transient. Conversely if the ratio is less than unity, the characteristic forms will tend to prevail (Fig. 9). In the former cases there will be a poor correspondence between the agents of process or even the processes themselves and the resulting landforms. The dimensionless nature of the ratio means that it applies to all time scales and provides an alternative way of scaling time to the divisions suggested by Davis (1899) or by Schumm and Lichty (1965). In practice these divisions do not exist. It is more realistic to accept that both transient and characteristic forms normally co-exist in the same landscape because of variations in landscape

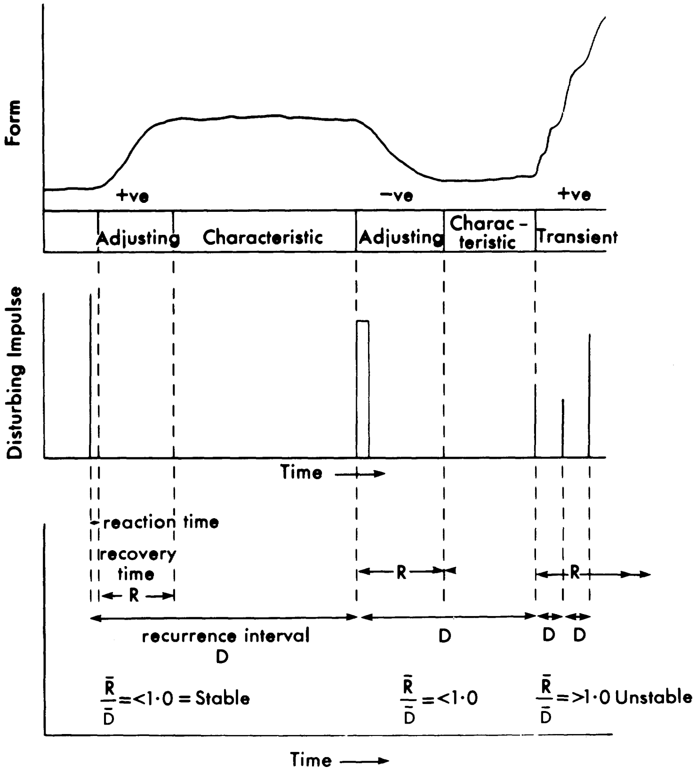

FIGURE 9. Diagrammatic representation of conditions of stability and instability according to the ratio of mean relaxation to recurrence times

sensitivity at all scales. Neither is there need to adopt a neo-catastrophist view to account for this reality since the extreme event is only extreme in terms of the relaxation processes and can be conceptualized with all other events through a transient-form ratio.

CONCLUSIONS

From a theoretical point of view, the investigation of long-term changes should involve the establishment of the characteristic response to fixed distributions of barriers and forces of change (e.g. Culling, 1963; Kirkby, 1971) using calibrations from contemporary process studies. This might be matched by an evaluation of the relative sensitivity of different parts of the environmental system (the geomorphological regions) to changes in the distributions expressed as a map of erosional probabilities. Sometimes these would fall below the previous distribution, resulting in overadjustment and persistence of the prior form. If these regional models are exposed to realistic changes in the environmental controls the results may then be compared with those known from historical sequences.

From a historical-genetic point of view our knowledge of the nature of impulses to changes, intrinsic threshold controls, barriers and responses suggests that landscape change will be episodic and not continuous. Landscape evolution may thus be viewed as a series of short adjustments between constant process-characteristic form states. The reconstruction of denudation chronologies must therefore concentrate on:

(1) the identification of sequences of process domains;
(2) the evaluation of the sequence and magnitude of environmental controls capable of causing changes, especially where morphological instabilities in the forms of thresholds are known to exist;
(3) the relaxation paths and times required for the establishment of characteristic forms within these domains and
(4) the extent of progression along these paths before another pulse of change arrived.

As noted earlier the episodic change viewpoint is that adopted by Erhart, 1955 (biostasy–rhexistasy), Butler, 1959 (K-cycles), Tricart and Cailleux, 1965 (landscape stability) and Schumm (episodic erosion), the change from stability to instability sometimes being marked by a morphological and sedimentological discontinuity.

Above all, however, the idea of episodic change should be compared with Gilbert's (1880) model for Lake Bonneville which was described as exhibiting not 'a continuous growth of form but an oscillation of events often in broken sequence', or a history of 'stages of equilibrium upset by sudden discontinuous events' (Baker and Pyne, 1978). It is also implicit in Ager's (1973) opinion that evolution 'has been a very episodic affair, with short happenings, interrupting long periods of nothing much in particular'. Because of the varying sensitivity of the landscape it is evident that this is a spatial as well as a temporal dictum.

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