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EPISODIC EROSION: A MODIFICATION OF THE GEOMORPHIC CYCLE.(U)
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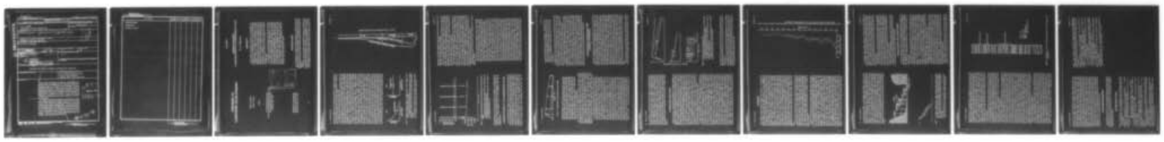

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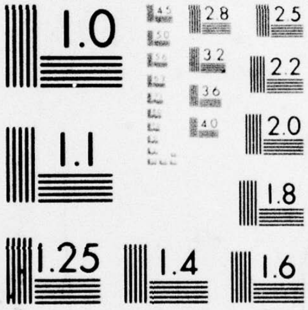

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It is proposed that stream gradients and valley floor altitudes do not change progressively through geologic time, but rather relatively brief periods of instability and incision are separated by long periods of relative stability (grade). Although the climatic and diastrophic history of the Quaternary prevents the identification of unstable periods due to geomorphic controls alone, some field and experimental evidence indicates that such a model is possible. Therefore, a very complex denudational history of a landscape may be geomorphically "normal".

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CHAPTER 4

EPISODIC EROSION: A MODIFICATION OF THE GEOMORPHIC CYCLE

S. A. Schumm

ABSTRACT

Most models of geomorphic evolution are oversimplified and, therefore, they are unsatisfactory for short-term interpretation of landform change. For example, the extrapolation of average denudation rates from a 10-year record to longer periods of geologic time is based on the assumption of progressive erosional evolution which even without the influence of climate change and diastrophism is probably not correct. In fact, the inherent workings of a fluvial system may prevent progressive reduction of a valley floor.

It is proposed that stream gradients and valley floor altitudes do not change progressively through geologic time, but rather relatively brief periods of instability and incision are separated by long periods of relative stability (grade). Although the climatic and diastrophic history of the Quaternary prevents the identification of unstable periods due to geomorphic controls alone, some field and experimental evidence indicates that such a model is possible. Therefore, a very complex denudational history of a landscape may be geomorphically "normal".

INTRODUCTION

It is stimulating to consider the grand changes of a landscape during the millions of years of its erosional evolution. Unfortunately, this overview provides little assistance to those concerned with the short-term behavior of landforms.

The reason that most models of geomorphic evolution are unsatisfactory for short-term interpretation is that they are oversimplified, and this is largely because they are based on very limited information. For example, the extrapolation of average denudation rates from a ten-year record to a thousand or million years of erosional evolution of a landscape produces a model of landscape evolution that is based on an assumption of progressive slow change, which may not be correct (Gage, 1970).

The criticism of the Davis geomorphic cycle in the writings of Penck and John Hack reflect their concern with this simplistic model. Some years ago, Lichty and I (1965) attempted to resolve some of the controversy by considering the landscape during very different spans of time. The time required for the denudation of a landscape was subdivided into cyclic, graded and steady time periods (Fig. 1). Under the category of cyclic time are time spans of geologic duration, that is, the period of time required for the denudational evolution of a landscape. For example, during this period, one expects an essentially exponential decrease of stream gradients, which is a landscape component that reflects changes in the fluvial system. However, cyclic time can be subdivided into graded time and steady time periods. During graded time, average gradient will remain relatively constant, but there will be, through time, fluctuations about this mean. Graded time, therefore conforms to the definition of a graded stream, as expressed by Mackin (1948). During the very short period of steady time, there is no change. When considering a landscape or its components, it is helpful to think in terms of the time spans and how a landscape is altered during the time span under consideration. In short, the period of time referred to as being cyclic or geologic in duration can be represented by the Davis curve showing the erosional evolution of the landscape (Fig. 2). Of course, it seems unlikely that denudation will continue for such an appreciable period of time without interruption by climate change or by isostatic adjustment. So the smooth curves presented by Davis (Fig. 2) and by Schumm and Lichty (Fig. 1a) can be expected to be complicated, when

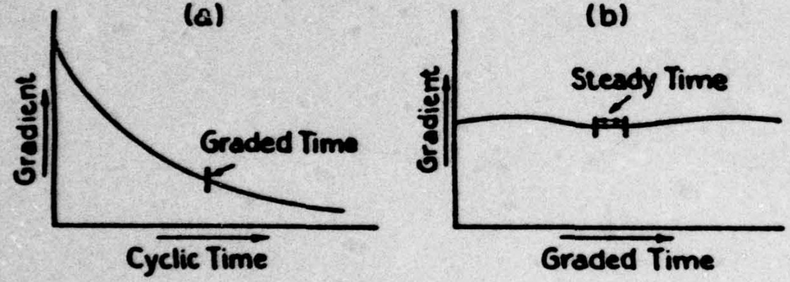

Figure 1. Diagram illustrating change of channel gradient during different time spans (from Schumm and Lichty, 1965).

A. Progressive reduction of channel gradient during cyclic time. During graded time, a small fraction of cyclic time, the gradient remains relatively constant.

B. Fluctuations of gradient above and below a mean during graded time. Gradient is constant during the brief span of steady time.

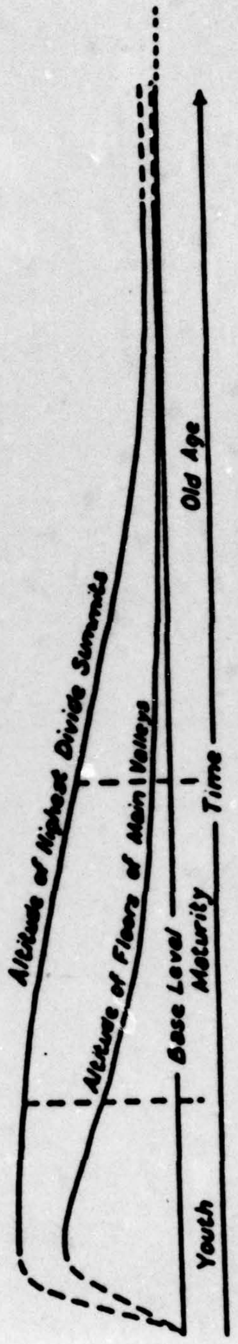

Figure 2. The Davis geomorphic cycle as usually presented.

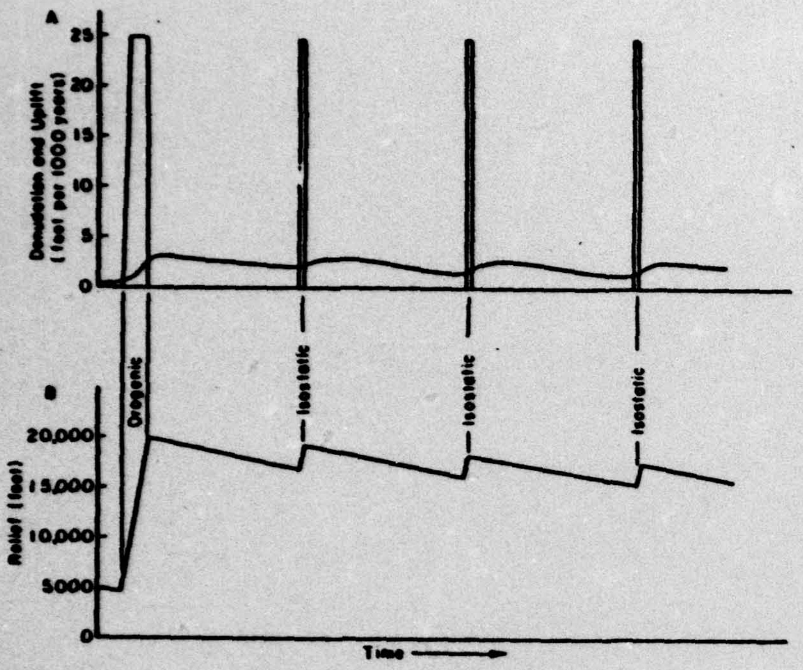

Figure 3. The effect of isostatic adjustment on the geomorphic cycle (from Schumm, 1963a).

A. Hypothetical relation of rates of uplift (25 feet per 1000 years) and denudation (3 feet per 1000 years) to time.

B. Hypothetical relation of drainage basin relief to time as a function of uplift and denudation shown in A.

external forces act on the system (Fig. 3). In addition, it is likely that the workings of the fluvial system itself will prevent progressive reduction of a valley floor or stream gradient, and it is this hypothesis that will be considered here.

COMPLICATIONS OF THE GEOMORPHIC CYCLE

It is understood that a change of an external variable will interrupt the progress of the geomorphic cycle, and changes of stream profile and variations of gradient during graded time are readily understood as reflecting variations of discharge and sediment load (Fig. 1b). Nevertheless, Figure 1 poses a problem. It is difficult to image how the graded time curve (Fig. 1b) can be compatible with the cyclic time curve (Fig. 1a). The progressive reduction of gradient shown on Figures 1a and 2 seems reasonable, but this in turn prevents a graded condition from developing until "old age" (Fig. 2). Conversely, if graded conditions exist then progressive reduction of the valley floor and stream gradient is impossible.

This line of reasoning apparently requires the elimination of either the concept of progressive erosion or grade. However there is an alternative solution. If valley floors (Fig. 2) and stream gradients (Fig. 1a) do not evolve progressively but rather change rapidly, during brief periods of instability that separate longer periods of grade, then a model incorporating both progressive change and grade can be proposed.

One central aspect of landscape denudation that has attracted little interest is that, as a landscape changes, components of the landscape, hillslopes, tributaries, and main channels, will not necessarily be adjusted to one another or be graded. That is, a channel adjusting to uplift may not be ready to cope with the effects of the rejuvenation in the watershed upstream. Hence, an actively eroding system will be continually searching for a stability that cannot be maintained. Interestingly enough, Davis was to some extent aware of this problem. For example, when the diagram illustrating the geomorphic cycle that was prepared by Davis himself is inspected (Fig. 4), it is apparent that part of his scheme is missing in Figure 2.

A description of Figure 4 in Davis' own words is appropriate here (Davis, 1899, pp. 254-255):

> "the base line represents the passage of time, while verticals above the base line measure altitude above sea level. At the epoch 1 let a region of whatever structure and form be uplifted, B representing the average altitude of its higher parts and A that of its lower parts, AB thus measuring its average initial relief . . . The larger rivers, whose channels initially had an altitude A, quickly deepen their valleys, and at the epoch 2 have reduced their main channels to a moderate altitude represented by C. The higher parts of the interstream uplands, acted on only by the weather without the concentration of water in streams, waste away much more slowly, and at epoch 2 are reduced in height only to D. The relief of the surface has thus been increased from AB to CD. The main rivers then deepen their channels very slowly for the rest of their lives, as shown by the curve CEGJ, and the wasting of the uplands, much dissected by branch streams, comes to be more rapid than the deepening of the main valleys, as shown by comparing the curves DFHK and CEGI. The period 3-4 is the time of the most rapid consumption of the uplands, and thus stands in strong contrast with the period 1-2, when there was the most rapid deepening of the main valleys. In the earlier period the relief was rapidly increasing in value, as steep-sided valleys were cut beneath the initial troughs. Through the period 2-3 the maximum value of relief is reached, and the variety of form is greatly increased by the headward growth of side valleys.

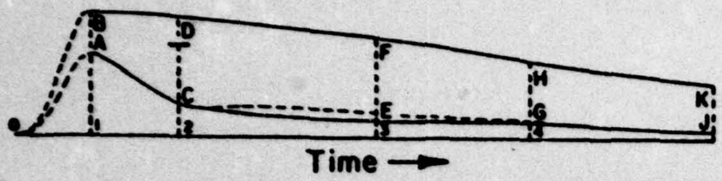

Figure 4. The geomorphic cycle according to Davis (1899).

> During the period 3-4 relief is decreasing faster than at any other time, and the slope of the valley sides is becoming much gentler than before; but these changes advance much more slowly than those of the first period. From epoch 4 onward the remaining relief is gradually reduced to smaller and smaller measures, and the slopes become fainter and fainter so that some time after the latest stage of the diagram the region is only a rolling lowland, whatever may have been its original height."

A few pages further (pp. 260-261) Davis returns to the topic of valley deepening and the effect of sediment load on this process, and he clearly states that downwearing of the valley floor may not be a continuous process. That is, at some stage the main river adjusts by aggradation to the increased quantities of sediment being delivered from upstream, and a valley-fill deposit is formed within the valley. Davis, thus, envisioned a period of aggradation during the progressive erosion of the drainage basin. This concept was stated also in an earlier paper (Davis, 1895, p. 130) as follows:

> ". . . streams proceed to entrench themselves in the slanting plain, and in a geologically brief period, while they are yet young, they will cut their valleys down so close to base level that they cannot for the time being cut them any deeper; . . . When this condition is reached, the streams may be described as having attained a "profile of equilibrium;" or, more briefly, they may be said to be *graded*. It may be noted, in passing, that inasmuch as the work that the stream has to do is constantly varying, it must as constantly seek to assume new adjustments of grade. In the normal course of river events, undisturbed by outside interference, the change in the work is so slow that the desired adjustment of capacity to work is continually maintained. It may be that during the adolescence of river life, the work to be done is on the increase, on account of the increasingly rapid delivery of land waste from the slopes of the growing valley branches; and in this case, part of the increase of waste must be laid down in the valley trough so as to steepen the grade, and thus enable the stream to gain capacity to carry the rest. Such a stream may be said to *aggrade* its valley . . .; in this way certain flood plains (but by no means all flood plains) may have originated. Aggrading of the valley line may often characterize the adolescence of a river's life; but later on, through maturity and old age, the work to be done decreases, and degrading is begun again, this time not to be interrupted."

The deduction of Davis that deposition will naturally follow initiation and presumably rejuvenation of a drainage system was a very astute one, and one that he illustrates by the dashed line CEG in Figure 4. This idea seems to have been ignored; nevertheless, the possibility that deposition takes place naturally within the drainage system is of great importance.

In summary, it appears that an uplifted drainage system will have difficulty in disposing of all the sediment delivered to its major channels from minor tributaries and interfluve areas, and sediment will be stored within the system. There is, of course, a reduction of slopes and stream gradients as well as a widening of the main valley in a downstream direction, which creates a situation whereby sediment delivered from upstream may be stored in the downstream parts of a drainage system. For example, there is a very dramatic downstream increase in the area available to receive deposition within even small drainage basins, as valleys widen downstream (Hadley and Schumm, 1961). That is, within any natural drainage basin there are many places where sediment can be stored permanently or temporarily.

GEOMORPHIC THRESHOLDS AND COMPLEX RESPONSE

Recently I discussed two geomorphic concepts that have potential for aiding in the development of an understanding of the complexity of the landscape; these are geomorphic thresholds and complex response (Schumm, 1975). For example, when a small experimental drainage basin was rejuvenated, the system responded not simply by incising, but by hunting for a new equilibrium by incision, aggradation, and renewed incision. This was referred to as the *complex response* of the system. The concept of *geomorphic thresholds* suggests that there can be changes within the fluvial system that are not due to external influences but rather they are due to geomorphic controls inherent in the eroding system. Field and experimental studies demonstrate that when sediments are stored within a fluvial system they become unstable at a critical threshold slope, and erosion takes place. This seems to be a reasonable explanation for the distribution of some arroyos and gullies in the West (Patton and Schumm, 1975), and it is also a partial explanation for the different morphological characteristics of alluvial fans, that is, the presence or absence of fan-head trenches (Weaver and Schumm, 1974).

When the influence of external variables such as isostatic uplift is combined with the effects of complex response and geomorphic thresholds, it is clear that denudation, at least during the early stage of the geomorphic cycle, cannot be a progressive process. Rather, it should be comprised of episodes of erosion separated by periods of relative stability, a complicated sequence of events. Much of this complexity is the result of a delayed transmission of information through the system. That is, channel changes that take place near the mouth of a drainage basin following incision are responding to the conditions at that time and location. Therefore, the channel is not prepared for the changes that its incision induces within the system upstream; hence downcutting is followed by deposition when the upstream response occurs (Fig. 4).

LANDSCAPE EVOLUTION

When the concepts of geomorphic thresholds and complex response are applied to landscape evolution the model becomes as summarized by Figure 5. Figure 5a is essentially a modification of the left side of the Davis scheme shown in Figures 2 and 4 (youth and early maturity), but the progress of denudation is interrupted by periods of isostatic adjustment. As in Figures 2 and 4, the upper line of Figure 5a represents divide elevations and the lower line valley-floor elevations. The divide elevations probably change as shown by Figure 5a. That is, only major external influences affect the divides, and they are subjected to a relatively uniform downwearing. However, if the valley floor is considered in greater detail over a shorter span of time (Fig. 5b), a stepped pattern of valley floor reduction emerges, as a result of storage and flushing of sediment from the valleys. This model ignores variations due to external influences, and it shows a system that is in dynamic metastable equilibrium (Chorley and Kennedy, 1973).

A steady state equilibrium involves fluctuations about an average, but a metastable equilibrium occurs when an external influence carries the system over some threshold into a new equilibrium regime. The effects of external variables on equilibrium systems are expected, but in the case of landscape denudation the dynamic metastable equilibrium may reflect the response of the system to inherent geomorphic thresholds (Schumm, 1973), in this case, the accumulation of sediment to an unstable condition. When a geomorphic threshold is crossed, the drainage system will be rejuvenated, and the complex response will come into play (Fig. 5c). Figure 5c shows periods of instability separated by longer periods of dynamic equilibrium or grade. Because periods of erosion are followed by periods of deposition, the bedrock floor of the valley is reduced in a steplike manner through time as shown by the dashed lines. Hence, separating the periods of erosion will be periods of deposition and storage of alluvium. In addition, during these periods of relative stability, channel pattern may change from straight to increasingly sinuous, as the nature of the sediment moved through the channel changes (Schumm, 1963b). Hence, sinuosity may also increase to a condition of incipient instability when a large flood can cause an abrupt shortening of the river course of the type documented by Fisk (1944) for the Mississippi River. This type of event could also play a role in the establishment of a period of valley erosion.

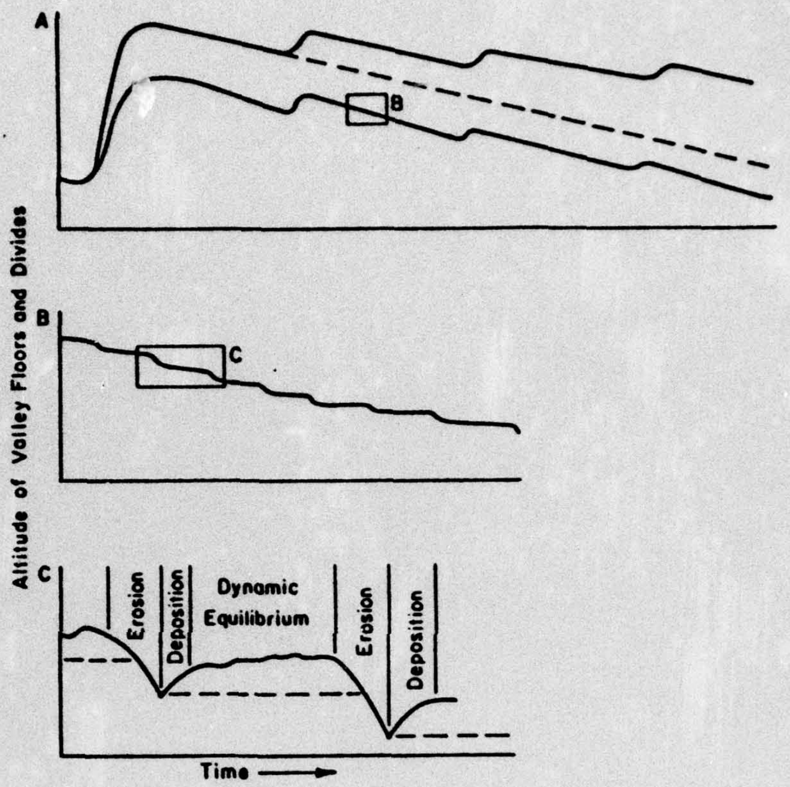

Figure 5. Modified concept of geomorphic cycle.
A. Erosion cycle, as envisioned by Davis (dashed line), following uplift, and as affected by isostatic adjustment to denudation.
B. Portion of valley floor in A above, showing episodic nature of decrease of valley-floor attitude.
C. Portion of valley floor in B above, showing periods of instability separated by longer periods of dynamic equilibrium.

If, in fact, this type of episodic erosion takes place many of the details of the landscape, small terraces, and recent alluvial fills, do not need to be explained by the influence of external variables because they develop as an integral part of system evolution. The Davis curve of Figure 2 averages out these variations during cyclic time (Fig. 1a).

EVIDENCE

The reader's obvious response to Figure 4 is "prove it." In view of the climatic history of the last few million years it may be impossible to demonstrate that the details of landscape are not due to climatic fluctuations or to tectonism. In fact, it is extremely difficult to find locations where one can with confidence view the results of an uninterrupted evolution of the landscape rather than the response of the landscape to climatic and tectonic changes. Nevertheless, the evidence is suggestive that, when a drainage system is rejuvenated, incision takes place, and relatively soon thereafter, depending on the size of the system considered, deposition follows, and the complex response occurs, as detected in the experimental studies described by Schumm and Parker (1973). During these experimental studies, following rejuvenation sediment yield from the drainage system decreased rapidly, but this decrease did not continue to an essentially uniform or average value; rather sediment yield fluctuated through time (Fig. 6). These variations of sediment yield occurred during each experiment and under essentially uniform experimental conditions. For example, the quantity of water delivered to the drainage system was constant, and there were no further changes of base level.

The variations of sediment yield occurred during the normal uninterrupted erosional evolution of a very small drainage basin. Additional experiments demonstrate that periods of low sediment yield occur when sediment is stored in the upstream valleys. When sediment storage causes the gradients of the valley floor to exceed a critical threshold slope, this material is flushed out to produce the periods of high sediment yield. The erosion of the valley floors in the experimental studies should follow the scheme as outlined in Figures 5b and 5c.

Further tests of this idea can be obtained in situations where rejuvenation of a basin is so great that progressive downcutting of the stream is expected. It is well established in the geomorphic literature that a major reduction of base level will cause a progressive downcutting and readjustment of the stream gradients until a new graded or equilibrium situation has been developed. However, where such an event has occurred, terraces and evidence of pauses in the erosional downcutting are found, but these are usually attributed to some external influence, such as variations in climate, the rate of base level change, or variations in the rates of uplift of the sediment source area. However, recent studies in Douglas Creek drainage basin of western Colorado support the idea of discontinuous downcutting. The investigation of the recent erosional history of this valley (R. Womack, 1975, unpublished M.S. Thesis, Colorado State University) shows that modern incision of the valley fill began after 1882. Yet, there are four surfaces now present below the two pre-1882 surfaces (Fig. 7). These surfaces are unpaired, discontinuous terraces that elsewhere have been explained by the *shifting of a channel laterally across the valley floor, during progressive*

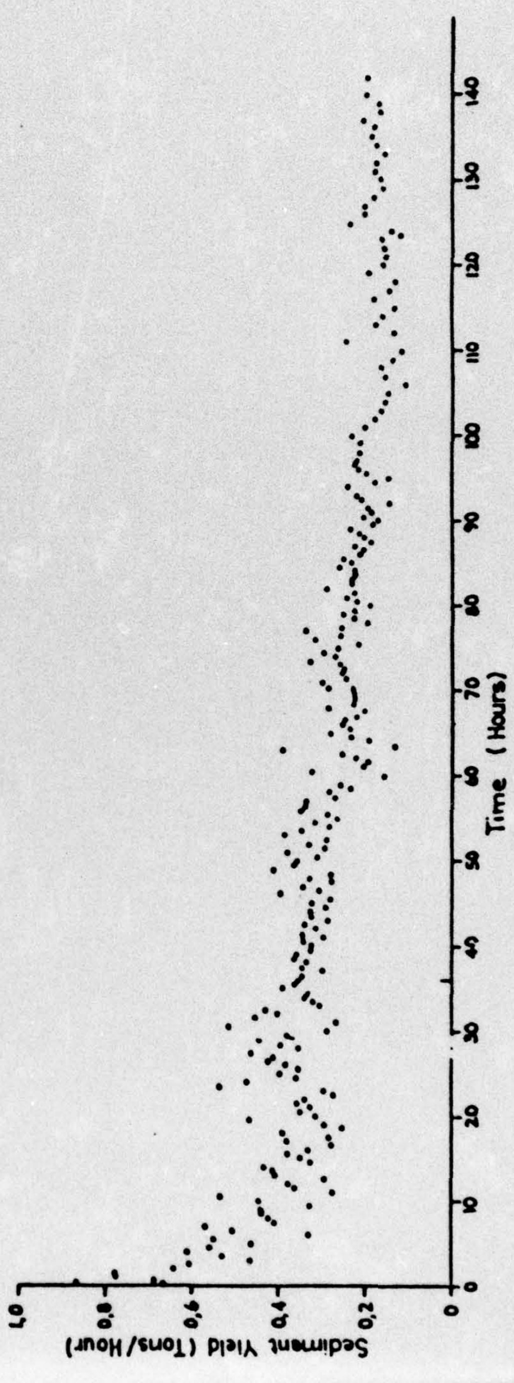

Figure 6. Sediment yield from DERF following rejuvenation of drainage network at time 0. Secondary peaks of sediment production occur at about 30, 50, 75 and 97 hours (Parker, R. S., 1975, unpublished Ph.D. dissertation).

downcutting (Davis, 1902). In the Douglas Creek Valley, however, downcutting was discontinuous. In fact, during pauses in downcutting there was deposition. The denudation scheme as sketched on Figure 5c portrays the sequence of events in this 400 square mile drainage basin in western Colorado. That is, during incision of the main channel, there is rejuvenation of tributaries and a progressive increase in sediment yield from upstream. Sediment loads become so great that downcutting ceases and deposition begins. Deposition continues until it is possible for the channel to incise again and to continue the downcutting process. Multiple surfaces of this sort can be identified on photographs of the Rio Puerco area, and elsewhere. Probably the sequence of events in these areas was similar to that of Douglas Creek.

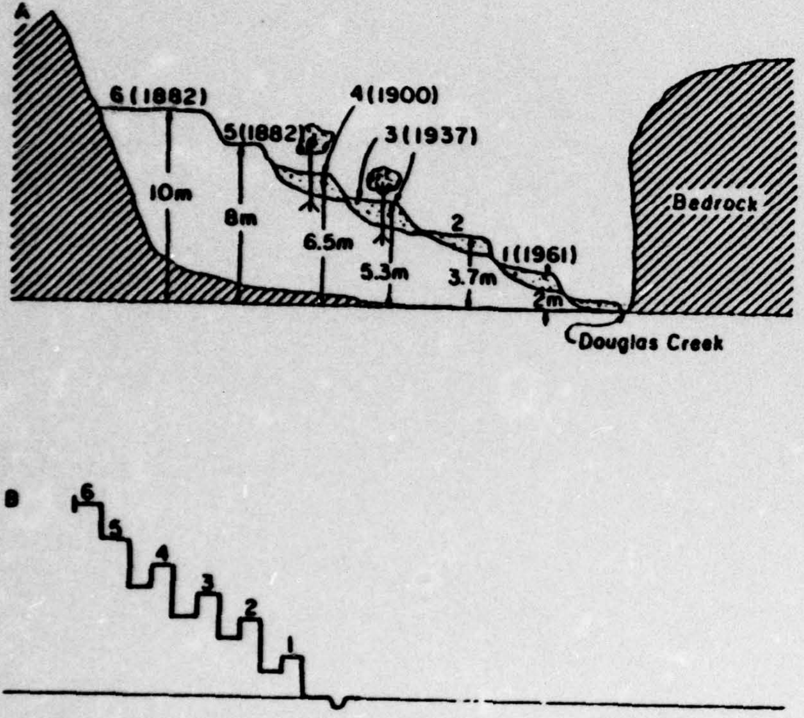

Figure 7. A. Sketch of Douglas Creek valley showing erosion surfaces formed since 1882. Age of surface is based on tree-ring dating and historical data. Note burial of trees by deposition. Surfaces 5 and 6 were present before modern erosion began after 1882 (after Womack, 1975, unpublished M.S. thesis).
B. Summary of behavior of Douglas Creek. Vertical segments indicate incision or deposition, horizontal segments periods of relative stability.

The Douglas Creek situation appears to conform to the observations of Born and Ritter (1970) who have mapped six discontinuous and unpaired terraces at the mouth of Truckee River, where it enters Pyramid Lake in Nevada. A reduction of the water level in Pyramid Lake reduced the base level of the lower Truckee River, but instead of simple downcutting commensurate with the lowering of the base level, the channel in fact paused as many as six times.

Gage (1970) cites an example of rapid deposition, which caused aggradation of from 10 to 80 feet in the Waiho River of New Zealand. This glacier-fed river then proceeded to clear the deposited sediment over a period of a few weeks. The erosion produced a flight of 10-foot terraces. Gage attributed this and similar events to 10-year weather patterns, and he cautioned that if some of these terraces were preserved they could easily be mistaken for surfaces of considerable antiquity.

Other examples of multiple unpaired terraces can be cited that may have formed as a result of rapid but episodic incision similar to that which occurred in the Douglas Creek Valley (Davis, 1902; Small, 1973).

CONCLUSIONS AND DIRECTIONS

The major conclusion is that a very complicated erosional evolution of a landscape can be expected, and the erosional evolution will be complicated even though there are no external influences affecting the system. Richard Hey (1972) has reached similar conclusions on a theoretical approach to channel incision.

This model of landscape evolution may seem to pose problems for the interpretation of some landscape details, but of course the usual appeal to climate fluctuation or tectonics is no solution. In fact, one need not attempt to explain all of the details of a landscape as a result of climate change or distrophism because some of the complications are inherent in landscape evolution. To one concerned with river stability and erosion control this model may be of considerable aid, because it suggests that it is possible to recognize unstable components of the landscape based on the identification of geomorphic threshold slopes, and to take measures to prevent further development of the instability (Patton and Schumm, 1975).

In geologically and geomorphically homogeneous regions the high variability of sediment yield and runoff characteristics of drainage basins may also be explained by this model, as illustrated by the variations of sediment yield from the experimental watershed (Fig. 6). That is, even within the same geomorphic region, similar drainage basins need not be producing comparable quantities of sediment. In effect, the revised model explains why the attempt to relate geomorphic variables to hydrology has been successful but less satisfying than one would like.

Some evidence to support an episodic model of at least the early stages of landscape evolution has been presented based on experimental studies and limited field data. The field data are restricted to the semi-arid and arid regions of western United States and high sediment producing areas elsewhere. The applicability of the model to perennial streams and the humid regions is unknown. In addition, a major difficulty with regard to the field evidence is that it was obtained from relatively small drainage systems (less than 400 square miles), where changes take place at rates sufficiently rapid to be recorded. In large drainage systems the progression of erosion will be sufficiently slow that it will be impossible to detect changes in sediment-yield variations and in valley slope and stream gradient through the life span of any one individual.

To find convincing evidence of the ideas put forth here it seems necessary that the geomorphologist must scrutinize the records of depositional events. The stratigraphic record is complex and fragmentary, and this in turn may be considered to be a natural result of the erosional development of the landscape as described here. Nevertheless, there should be sequences of rocks that, when analyzed, will provide information on the rate and variability of the erosional denudation of the landscape.

Apparently what is required are investigations of the type suggested by Mutti (1974) who concluded from his study of deep-sea fan deposits that an understanding of these features must come from the study of the geologic record rather than the few cores and profiles of modern deep-sea fans. This is true also of an attempt to evaluate the erosion cycle of a fluvial system. The complexities of erosional evolution through time will be preserved for the most part in the depositional basin, whereas the evidence of these events will be destroyed by the denudation of the landscape itself. It seems appropriate therefore to close this discussion with consideration of a topic that has concerned stratigraphers for some time, that is, cyclic sedimentation. A great deal has been written on this subject, not, of course, all related to fluvial processes. The symposium volume edited by Merriam (1964) and the book by Duff, Hallam and Walton (1967) adequately review the problem. The concern, of course, is whether or not such cycles actually exist, and if they do, the reason for them. It appears from the previous discussion on the behavior of fluvial systems that the development of cyclic sedimentation is inevitable in fluvial sedimentary deposits.

Cycles of several dimensions should be found within a fluvial depositional unit (Fig. 8). Referring to Figure 5, which shows the progress of the erosion cycle through time, one can substitute sediment yield for elevation or relief on the abscissa of that figure. The curves then show sediment produced by the fluvial system through time. There should be at least five fining upward cycles of decreasing magnitude in the deposits associated with this erosional evolution. The primary cycle is related to denudation following uplift, with maximum sediment production at the beginning of the erosional event and a progressive decrease in quantity and size of material through time to yield a massive fining upward sequence (Figs. 2 and 4). Interruptions of this,

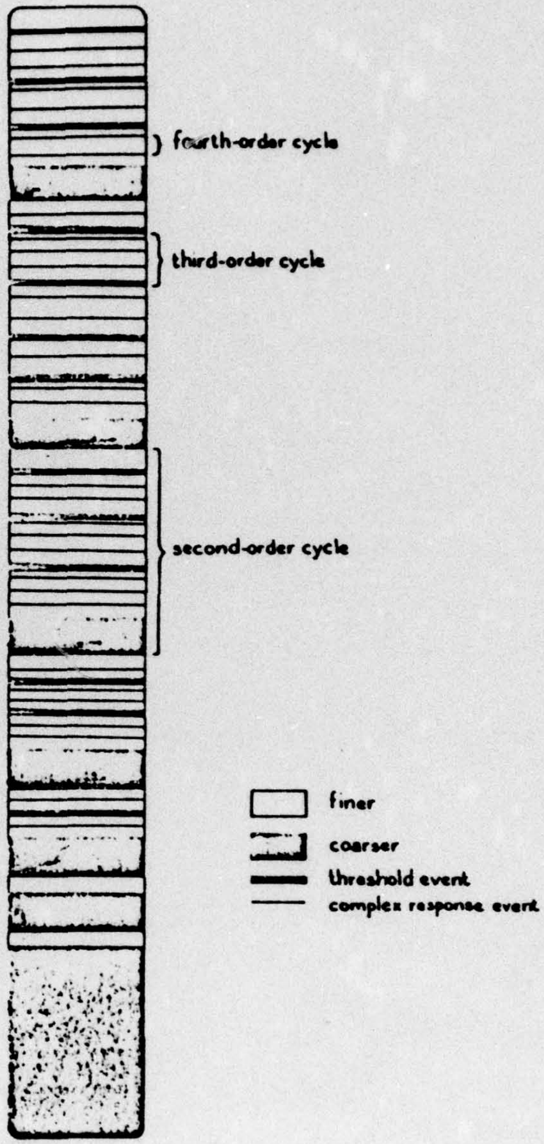

Figure 8. Diagrammatic model of primary sedimentation cycle with higher order components.

however, due to isostatic adjustment produce higher sediment yields from the source area (Figs. 3 and 5a). Therefore, within the primary cycle associated with tectonics, there are second-order cycles associated with isostatic adjustment and perhaps major climatic change. Between these events third-order cycles are related to the exceeding of geomorphic thresholds (Fig. 5b). These third-order cycles will be of much smaller dimension, and yet they should be important for the concentration of heavy minerals and the development of channeling in fluvial deposits. Fourth-order cycles will be related to the complex response of the fluvial system to any of the above changes, either tectonic, isostatic, climatic, or geomorphic threshold (Fig. 5c). These cycles of smaller dimension will result from the attempt of the system to adjust to changes related to the primary, secondary, and tertiary cycles. Finally, fifth-order cycles will appear that are related to the seasonality of hydrologic events or to major flooding, and in the stratigraphic record these will appear as thin fining-upward depositional units.

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