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EVOLUTION AND RESPONSE OF THE FLUVIAL SYSTEM, SEDIMENTOLOGIC IMPLICATIONS

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ABSTRACT

A fluvial system ideally has three main components: 1) a drainage basin, the sediment and water source area, 2) a river, the conduit which removes the waste of the drainage basin, and 3) a site of sediment deposition in a piedmont or coastal zone.

The nature and quantity of sediment produced from the source area determines the morphologic character of the river, and a river can be classified into five patterns dependent on type of sediment load. The 1) straight and the 2) sinuous-thalweg patterns reflect relatively low values of sediment transport, of bed-load to total-load ratio, and of stream power. The 3) meandering pattern reflects relatively low to moderate values of sediment transport, of bed-load to total-load ratio, and of stream power. The 4) meandering-braided transitional pattern and the 5) braided pattern reflect relatively high values of sediment transport, of bed-load to total-load ratio, and of stream power.

Throughout geologic time fluvial systems have had complex erosional and sediment-production histories as a result of external and internal influences. The external variables that most significantly affect the fluvial system are tectonic, eustatic and climatic. The internal variables are geomorphic. The response of the fluvial system to changes in these controls is complex involving both erosion and deposition.

The morphologic character of a river and its associated sediments change, as the character of the sediment delivered from the source area changes. The character of sedimentary deposits (piedmont, deltaic or near-shore) reflect the geology, morphology and erosional history of the source area as well as the type of river transporting the sediment. Abrupt changes in amount and type of sediment reflect not only the complexity of the erosional evolution of the area, but also the dynamics of the sediment producing and transport zones of the fluvial system.

INTRODUCTION

The sedimentologist and stratigrapher observe in the sedimentary record a complex history of the erosional evolution and dynamics of the fluvial system. The geomorphologist, on the other hand, views a complex assemblage of landforms. He attempts to determine, by study of the landforms and the erosional processes acting on them, the mode of geomorphic evolution and the effects of changing environmental conditions on the erosional processes and the landforms themselves.

The sedimentologist and stratigrapher have great temporal freedom because they view the results of landform evolution through vast periods of time. The geomorphologist, on the other hand, has spatial freedom, and he can study the present variations of landscape morphology and the different processes of erosion and deposition that are occurring under different climatic and geologic controls. Clearly the observations of the sedimentologist should aid the geomorphologist in the interpretation of landscape evolution because the record lies in the sedimentary deposits. Of course, a fuller understanding of the erosional and transportation processes acting on the landscape will also provide a sound basis for the interpretation of fluvial and fluvially-influenced sedimentary deposits.

The geomorphologist describes and classifies landforms and explains their character with the aid of empirical equations that relate the erosional and transportation forces to the morphology of that landform. In addition, he must consider other types of landforms that might have formed when conditions were very different, as during pre-vegetation times on the earth's surface. Therefore, both the sedimentologist and geomorphologist are interested in paleolandscapes or what Hans Cloos (1953, p. 48) has referred to as subterranean landscapes. Cloos visualized the character of the now deeply buried Precambrian Witwatersrand fluvial-fan surface, and one can indeed fancy panning for gold in the Precambrian streams of the Witwatersrand or floating down a Morrison Formation channel looking for likely locations of future uranium deposits. Undoubtedly most geologists at some state in their career have considered the advantages of a time machine which would deliver them to a critical site on the paleolandscape. Unfortunately, such means of performing research are not available and we must resort to our imagination and the scientific method.

The purpose of this paper is to discuss the fluvial system and its components in order to relate the dynamics of this geomorphic system to its depositional results, both now and in the geologic past. It is clear that the very nature of the fluvial system will produce sediments that show great variability through time and in space. For example, the great variability of modern river patterns indicates that both braided and meandering river sediments

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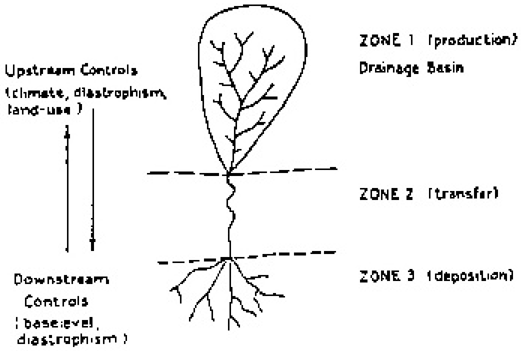

FIG. 1.—Idealized sketch of the fluvial system (from Schumm, 1977).

should frequently be found in close proximity in the rock record, as a paleoriver abruptly alters its pattern or as the pattern changes in a downstream direction.

THE FLUVIAL SYSTEM

For reasons of simplicity and convenience, the fluvial system is divided into three parts that are referred to as Zones 1, 2, and 3 (Fig. 1). The uppermost zone is the drainage basin or watershed from which water and sediment are derived. It is primarily the zone of sediment production, although sediment storage occurs there in important ways. Zone 2 is the transfer or transportation zone, where major streams move water and sediment from Zone 1 to Zone 3, which is the sediment sink or zone of deposition. Obviously sediments are stored, eroded and transported in all of these zones. Nevertheless, within each a single process is usually dominant, and it is convenient to discuss the fluvial system in this manner. In fact, the outline of this paper will follow this organization.

Figure 2 indicates in a very simple way the characteristics of the three zones. Each zone can be considered to be composed of two basic parts, the morphologic system (the landforms that make up each zone) and the cascading system (the energy and materials flowing through that zone).

There is little value in describing the morphologic system without consideration of the cascading system, and Table 1 relates the morphology and hydrology of the fluvial system to the controlling variables, which produce the morphologic and cascading characteristics of Zone 1 and which, in turn,

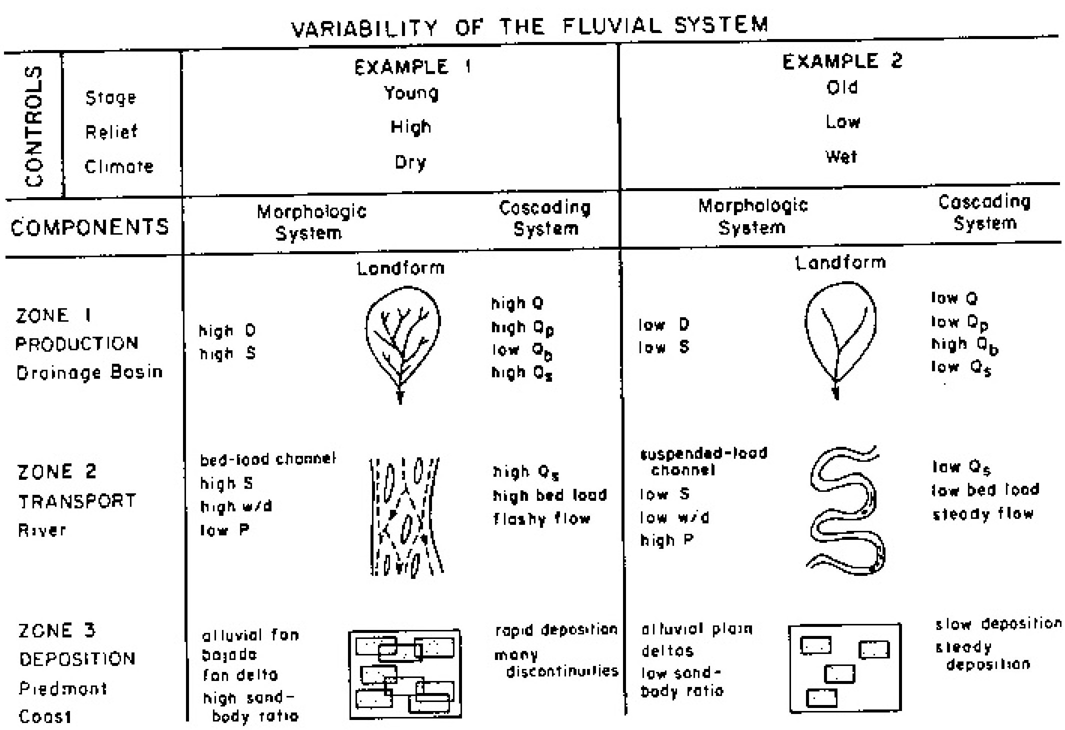

FIG. 2.—Two examples of very different fluvial systems, showing the variability of the morphologic and cascading components of the models in the three geomorphic zones: D, drainage density; S, gradient; w/d width-depth ratio; P, sinuosity; Q, water discharge; Qb, base flow; Qp, peak discharge; Qs, sediment load.

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TABLE 1. – FLUVIAL SYSTEM VARIABLES (FROM SCHUMM AND LICHTY, 1965)

Drainage system variables
1. Time
2. Initial relief
3. Geology (lithology, structure)
4. Climate
5. Vegetation (type and density)
6. Relief or volume of system above baselevel
7. Hydrology (runoff and sediment yield per unit area within Zone 1)
8. Drainage network morphology
9. Hillslope morphology
10. Hydrology (discharge of water and sediment to Zone 2 and 3)
11. Channel and valley morphology and sediment characteristics (Zone 2)
12. Depositional system morphology and sediment characteristics (Zone 3)

significantly influence Zones 2 and 3. The variables of Table 1 are arranged in a sequence that reflects increasing degrees of dependence insofar as this can be done for the fluvial system. Time, initial relief, geology and climate (variables 1 through 4) are the dominant independent variables that influence the progress of the erosional evolution of a landscape and its hydrology. Vegetation type and density (variable 5) depends on lithology (soil) and climate (variables 3 and 4). As time passes, the relief, or the volume of the drainage system remaining above base level (variable 6) is determined by the factors above it in the table, and relief in turn significantly influences runoff and sediment yield per unit area within the drainage basin (variable 7). Runoff acting on the soil and geologic materials produces a characteristic drainage network morphology (variable 8, drainage density, channel shape, gradient and pattern) and hillslope morphology (variable 9, slope angle, length, and profile form). These morphological variables in turn strongly influence the cascading system, the volumes of runoff and sediment that are eventually discharged from Zone 1 (variable 10). It is the volume and type of sediment and water discharge and flow character that to a major extent determine channel morphology and the nature of the fluvial deposits that form in Zones 2 and 3 (variables 11 and 12).

In Table 1 only upstream controls are listed, but the fluvial system can also be significantly influenced by downstream base-level variations (Fig. 1). Lowering of base level will rejuvenate the drainage system, and the effect on Zones 1 and 2 will be significant with a feedback to Zone 3 of greatly increased sediment production and a change of sediment characteristics. For further discussion of these variables and their influence on the drainage basin, see Schumm (1977).

To the sedimentologist the most important aspects of Zones 1 and 2 are the "normal" erosional evolution of the system, as well as the response of the fluvial system to climate change and to variations in relief due to tectonic activity. The complex Zone-1 landscape is composed of a number of landform elements, drainage divides, hillslopes, flood plains, and channels, and the response of this complex landscape to change will not be simple. Recent geomorphic investigations both in the field and in the laboratory show that the response of this complex assemblage of landforms will in itself be complicated. In addition, the traditional conception of the progressive lowering and erosional evolution of the landscape is probably incorrect (Schumm, 1976, 1977). Therefore, before proceeding to the discussion of the three zones of the fluvial system and to the manner in which the interrelationships between Zones 1, 2 and 3 affect the depositional system of Zone 3, three relatively new geomorphic concepts, which relate to the complexity of landform evolution must be introduced. They are concepts of geomorphic thresholds, episodic behavior and complex response (Schumm, 1973, 1976, 1977, 1979).

Geomorphic thresholds—Various natural phenomena do not change progressively; in fact, they may change abruptly. A good example is the change in the sediment movement with increasing velocity of flow over the surface of a sand bed. At some threshold velocity sand begins to move. At increasing velocities there are threshold conditions at which the bedforms change from ripples to dunes and then to antidunes.

There are also geomorphic thresholds of landform stability above which there is an abrupt and dramatic change in the landforms. The changes can take place as a result of both intrinsic and extrinsic threshold conditions. Extrinsic thresholds are those encountered when there is a progressive increase in the forces exerted on a landform, and at some value of this force failure occurs, as in the above sediment transport example. Intrinsic thresholds are the result of evolution of landforms to a condition of relative instability; for example, the accumulation of sediment in a valley or on an alluvial fan to an inclination that results in failure or erosion of that material. A geomorphic threshold, therefore, is a threshold of landform stability that is either exceeded by forces generated by an intrinsic change of the landform itself or by a progressive change of an external variable (Schumm, 1979). This concept will be made clearer later during a discussion of the channel patterns in Zone 2, but obviously the crossing of an erosional threshold will produce a pulse of sediment into Zone 3.

If the pages that appeared in a recent volume on fluvial sedimentology (Miall, 1978) are an indication, the concept of geomorphic thresholds at least has been welcomed by sedimentologists as an addi-

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tion to their interpretive options (Heward, 1978; Minter, 1978, p. 805; Nami and Leeder, 1978, p. 439).

Episodic behavior and complex responses—Related to the concept of geomorphic thresholds is the episodic behavior of landforms. For example, a single rejuvenation covered episodic downcutting that produced multiple terraces in northwestern Colorado (Schumm, 1977). The terraces tend to be unpaired and discontinuous, but they indicate that, during the erosion of the valley fill, downcutting and aggradation alternated repeatedly (Womack and Schumm, 1977). In areas of steep relief and high sediment transport the incision of a stream sets in motion large quantities of sediment that can overwhelm the transporting capacity of the channel, and periods of aggradation interrupt the degradational processes. The reverse situation was observed during the development and growth of an experimental alluvial fan (Schumm, 1977, pp. 255–264). The fan head was steepened by a maximum deposition at that location, and episodes of fan-head trenching and reworking of the fan head resulted. The growth of the fan, although predominantly a depositional event, was interrupted by periods of incision. Episodic behavior appears to be a response to rapid deposition and erosion, which follow a major geomorphic, climatic or tectonic disruption. Episodic behavior should produce a series of fining-upward deposits in Zone 3, as pulses of sediment reach the depositional zone.

Although episodic behavior is certainly complex, the term complex response is used to describe the response of a channel or drainage basin to a change of much smaller magnitude (Schumm, 1973, 1977). In this case, a slight rejuvenation of a channel will cause incision that is followed by deposition. This cycle is followed by another cycle of erosion and deposition of lesser magnitude, as the channel hunts for a new condition of grade or stability. The changes are of much less magnitude, as compared to episodic behavior, because the magnitude of the adjustment is less, and, therefore, the quantity of sediment mobilized is much less. Nevertheless, sediment is exported from Zone 1 causing aggradation and degradation in Zone 2 with associated channel changes.

The effects in Zone 3 may be small, but, nevertheless, they will add to the complexity of the fluvial deposits unless the distance of transport is sufficiently long that a damping effect attenuates and obscures the sediment pulse.

It is probably that episodic behavior and complex response are most common in the early stages of the erosional development of a landscape and where sediment production is great. In humid regions of low relief, where there is an abundant water supply, it is less likely that episodic erosion or deposition will occur or that threshold conditions can exist, but during pre-vegetation times episodic behavior could have been normal.

The geomorphic concepts of thresholds, complex response and episodic behavior, lead to a different model of landscape evolution (Schumm, 1977). It has been proposed that rather than a progressive lowering of the valleys in Zone 1, at least in the early stages of the erosional development, the system will be in dynamic metastable equilibrium and that the behavior of the system will be episodic (Fig. 3). Experimental studies and studies in higher relief areas elsewhere support this model. Of course, any such episodic variations of sediment discharge from Zone 1 will have a significant influence on the channels of Zone 2, and on the nature of the materials being delivered to Zone 3. In short, the complexity of landform evolution will yield a complex sedimentary record in Zone 3.

COMPONENTS OF THE FLUVIAL SYSTEM

Zone 1

The morphology of Zone 1 can be as different as the range of variables acting upon it. Consider, for example, the changes of drainage density or texture, as geologic materials vary from highly erodible shales and siltstones to crystalline rocks or as climate varies from semiarid to humid or as relief varies from high to low. In each case drainage density, and the number and length of channels, will decrease. Figure 2 summarizes the variability of a fluvial system under the influence of only three controls; stage or time, relief, and climate. Only two examples are shown in Figure 2. Example 1 is a young, high-relief, dry-climate drainage basin. Example 2 is an old, low-relief, humid-climate drainage basin. These three variables act in the same direction so they can be lumped for our purposes.

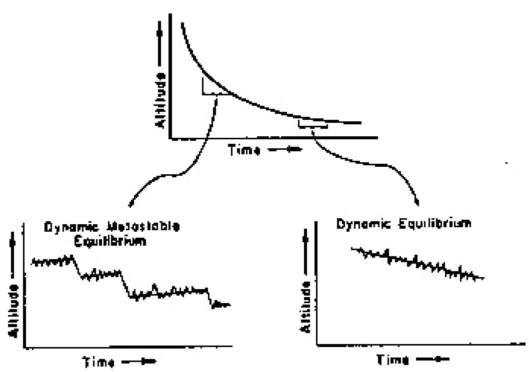

Fig. 3.—Erosional evolution of Zone 1 valley floors under early conditions of dynamic metastable equilibrium and episodic behavior and under later conditions of dynamic equilibrium (from Schumm, 1977, Fig. 4-18).

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There is a continuum of drainage basin, channel and depositional environments depending upon the variables listed in Table 1, but on Figure 2 only the end members of this continuum are shown. Figure 2 reviews both the morphologic and the cascading system characteristics for each of the three zones. For the youthful, high-relief, sparsely-vegetated drainage basin the drainage density (D) will be high, and both hillslope inclination and stream gradient (S) will be steep. A well-developed drainage network will result in high discharge (Q), high peak discharge (Qp), relatively low base flow (Qb), and high sediment production (Qs). The well-developed, fine-textured drainage network will rapidly move water and sediment from the basin and deliver it to Zone 2. In Zone 2 the high sediment load, the high bed load, and the flashy nature of the discharge will produce a bed-load channel of steep gradient, large width-depth ratio, low sinuosity (P) and braided pattern. Avulsion and thalweg shift will be common. Downstream (Zone 3) the large quantity of coarse sediment may form an alluvial fan, bajada, or fan delta. Deposition will be rapid and the sedimentary deposit will contain many discontinuities and a high sand-body ratio (Allen, 1978).

At the other extreme is Example 2, an old, low-relief, humid, well-vegetated drainage basin that has a low drainage density (D), low slopes, and low discharge (Q). A high percentage of precipitation infiltrates, or is lost to evapotranspiration. Peak discharge (Qp) will be relatively low, and groundwater will be abundant, leading to high base flow (Qb). Sediment loads will be low. In Zone 2 the result is a suspended-load channel, which transports relatively fine sediments at a low slope in a low width-depth ratio channel with high sinuosity. The meandering channel is subject to shift and cutoffs. Discharge will be relatively steady, although during major precipitation events large floods will move through the valley. In Zone 3 the fine sediment and the steady nature of the flow will cause slower rates of deposition, and there will be a low sand-body ratio and an alluvial plain or delta will form.

A change of climate can transform Example 1 to Example 2 or vise versa or to some intermediate stage. The result of this is that the character of the sediments delivered to Zones 2 and 3 will change and significant channel adjustments will result (Schumm, 1977).

Without tectonic interruptions through geologic time, the erosional evolution of a landscape should result in a transition from Example 1 to drainage basins and channels to those of Example 2 (Fig. 2). As the relief of the drainage basin is reduced during the erosional evolution, drainage density will decrease, slopes will decline, sediment load and sediment size will decrease. The result will be a transition from a braided to a meandering channel in Zone 2 and to finer grained, more uniform deposits in Zone 3.

The relationships displayed in Figure 2 are straightforward, and they are well known; therefore, there is little value in further discussion.

Zone 2

Rivers exhibit an astonishing diversity which can be related to the variations of water discharge and sediment load, as well as to the presence of bedrock outcrops, man's activities, and tectonic influences. A simple means of classifying alluvial channels is by pattern. Five basic channel patterns exist (Fig. 4): straight channels with either migrating sand waves (pattern 1) or migrating alternate bars with sinuous thalweg (pattern 2), two types of meandering channels, a highly sinuous channel of equal width (pattern 3a) and channels that are wider at bends than in crossings (pattern 3b), the meandering-braided transition (pattern 4) and a typical braided-stream (pattern 5). The relative stability of these channels in terms of their normal erosional activity and the shape and gradient of the channels, as related to relative sediment size, load, velocity of flow and stream power, are also indicated on Figure 4. It has been possible to develop these patterns experimentally by varying the gradient, sediment load, stream power, and the type of sediment load transported by the channel (Schumm and Kahn, 1972).

The types of rivers observed on the earth's surface can be placed within these five general categories. However, within the meandering stream group there is considerable range of sinuosity (1.25 to about 3.0). In addition, in the braided stream category there are bar-braided and island-braided channels. Islands are vegetated bars. There are also multiple-channel patterns termed anastomosing, anastomosed, or anabranching channels (Schumm, 1977, p. 155; Smith and Smith, 1980).

Alluvial channels have also been classified according to the type of sediment load moved through the channels as suspended-load, mixed-load, and bed-load channels. Water discharge determines the dimensions of the channel (width, depth, meander dimensions), but the relative proportions of bed load (sand and gravel), and suspended load (silts and clays) determine not only the shape of the channel but width-depth ratio and channel pattern. A suspended load channel has been defined as one that transports less than 3% bed load and a bed-load channel as one transporting more than 11% bed load. The mixed-load channel lies between these two (Fig. 4).

Figure 4 suggests that the range of channels from straight through braided forms a continuum, but experimental work and field studies have indicated that the pattern changes between braided, meandering and straight occur abruptly at river-pattern

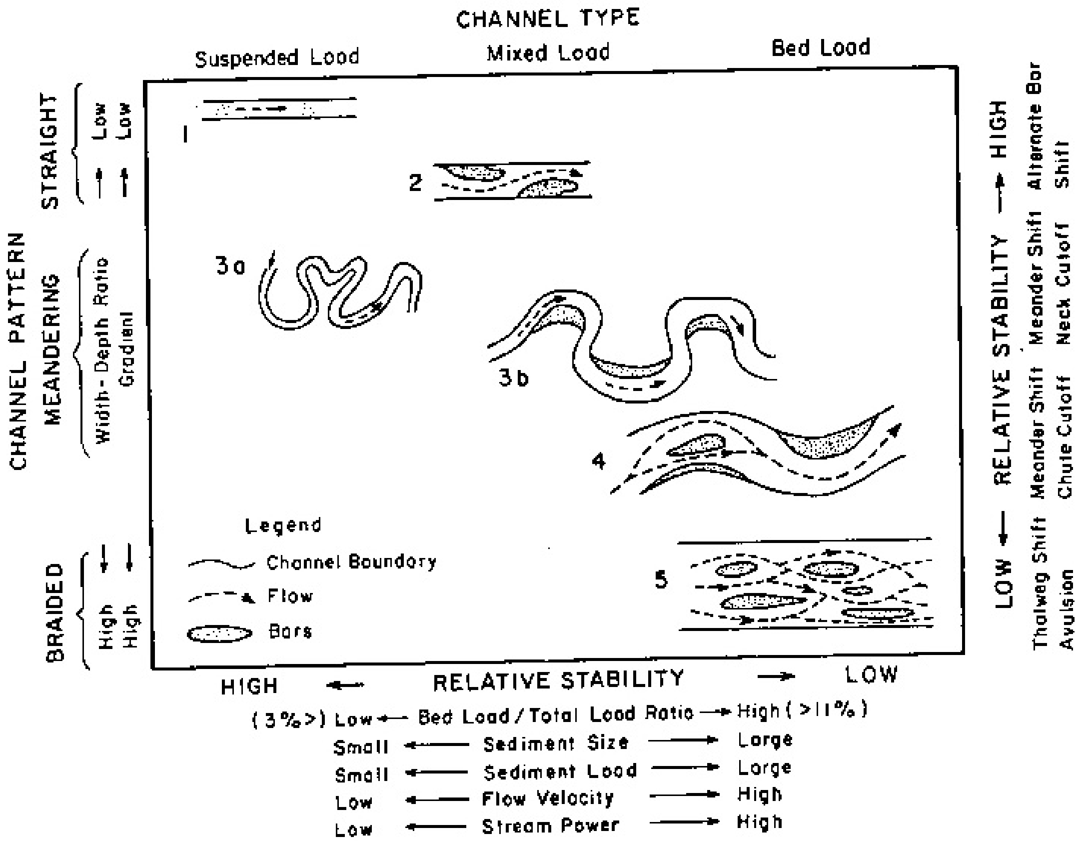

FIG. 4.—Channel classification based on pattern and type of sediment load with associated variables and relative stability indicated (from Schumm and Meyer, 1979).

thresholds (Fig. 5). The pattern changes take place at critical values of stream power, gradient and sediment load (Schumm and Kahn, 1972).

Although the five patterns of Fig. 4 involve all three river types, there are five basic bed-load channel patterns (Fig. 6a) that have been recognized during experimental studies of channel patterns (Schumm, 1977, p. 158).

These five basic bed-load channel patterns can be extended to mixed-load and suspended-load channels to produce 14 patterns that could have existed during geologic time (Fig. 6). As indicated above, patterns 1–5 are bed-load channel patterns (Fig. 6a), patterns 6–10 are mixed-load channel patterns (Fig. 6b), and patterns 11–14 are suspended-load channel patterns (Fig. 6c). Figure 7 shows how the pattern thresholds change with increasing valley slope, stream power and sediment load for each channel type.

The different bed-load channel patterns (Fig. 6a) can be described as follows: Pattern 1) straight, essentially equal-width channel, with migrating sand waves. These patterns are rare today, but they may have been more common in the past, Pattern 2) alternate-bar channel with migrating side or alternate bars and a slightly sinuous thalweg, Pattern 3) low-sinuosity meandering channel with large alternate bars that develop chutes, Pattern 4) transitional meandering-thalweg braided channel. The

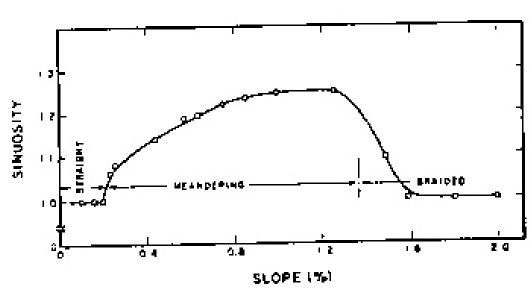

FIG. 5.—Relation between flume slope and sinuosity during experiments at constant water discharge. Sediment load, stream power, velocity increase with flume slope and a similar relation can be developed with these variables (from Schumm and Khan, 1972).

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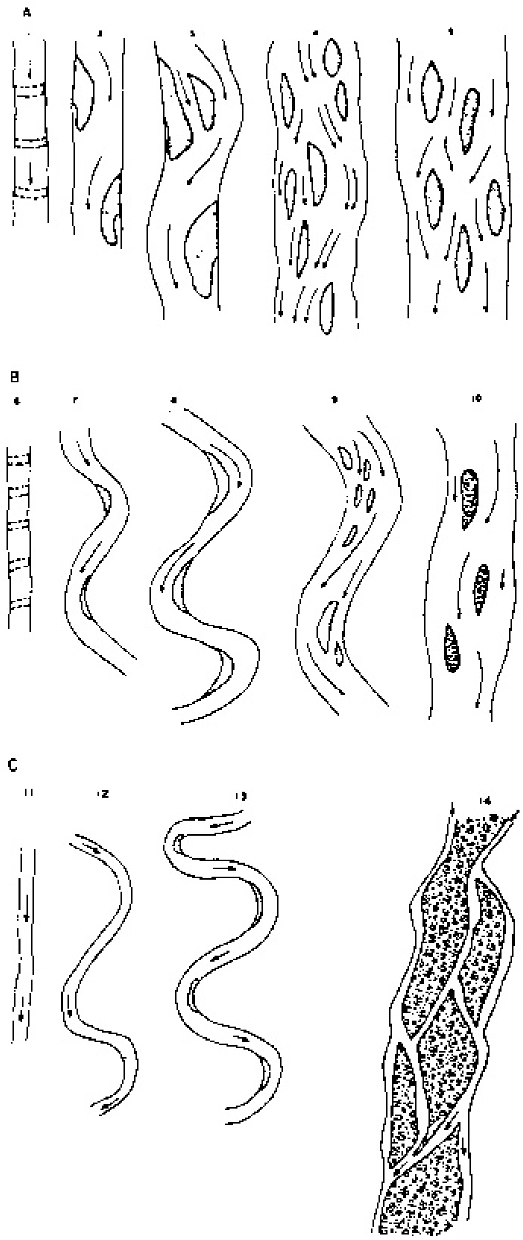

FIG. 6. — The range of alluvial channel patterns.
a. bed-load channel patterns
b. mixed-load channel patterns
c. suspended-load channel patterns

large alternate bars or point bars have been dissected by chutes, but a meandering thalweg can be identified. Pattern 5 is a typical bar-braided channel.

As compared to the bed-load channel pattern, the five-mixed load patterns (Fig. 6b) are relatively narrower and deeper, and there is greater bank stability. The higher degree of bank stability permits the maintenance of narrow-deep straight channels (Pattern 6), and alternate bars stabilize because of the finer sediments, to form slightly sinuous channels (Pattern 7). Pattern 8 is a truly meandering channel, wide on the bends, relatively narrow at the crossings, and subject to chute cutoffs. Pattern 9 maintains the sinuosity of a meandering channel, but with the larger sediment transport the presence of bars gives it a composite sinuous-braided appearance. Pattern 10 is a braided channel that is relatively more stable than that of bedload channel 5, and in fact, it may be a transitional pattern between the bar-braided pattern 5 and a narrow, more sinuous channel (Pattern 8). Under present conditions it is an island-braided channel.

Suspended-load channels (Fig. 6c) are narrow and deep. Suspended-load Pattern 11 is a straight, narrow, deep channel. With only small quantities of bed load, this type of channel will have the highest sinuosity of all (Patterns 12 and 13). The steepest suspended-load channel (Pattern 14) will anastomose. Bars will not form because bed-load transport is so low, but multiple channels will develop to produce the anastomosing pattern that is characteristic of some alluvial plains. The anastomosed channels may be kilometers in length. Therefore, the intervening vegetated areas are not simply islands of the Pattern-10 type. On a smaller scale, a very similar appearing pattern develops when, as a result of reduced flood peaks and annual discharge there is a metamorphosis from bed-load pattern 4 and 5 to a single channel pattern (e.g. Patterns 7 and 8).

The most common of the above patterns are bed-load Patterns 4 and 5, mixed-load Patterns 7 and 8, and suspended-load Patterns 11, 12 and 13, which are actually the patterns of Figure 4. I believe that although all of the patterns of Fig. 6 could have been common in the past, the stabilizing effect of vegetation, especially hardy pioneer species such as willows and cottonwoods, will convert Patterns 2 and 3 to Patterns 7, 8 and 9. The closure of side channels will convert Pattern 14 to Patterns 12 and 13. Rivers may undergo a metamorphosis during which the channel morphology changes completely; that is, a suspended-load channel (Pattern 12) could become braided (Pattern 5), or a braided channel (Pattern 5) could become meandering (Pattern 8 or 12), etc., when there is a sufficiently great change in the type of sediment load transported through that channel. Therefore, the change from one type of channel pattern to another should be relatively common in fluvial sedimentary deposits, as the nature of the sediment moved through the system changes from the proximal to the distal part of Zone 3 (Morton and Donaldson, 1978).

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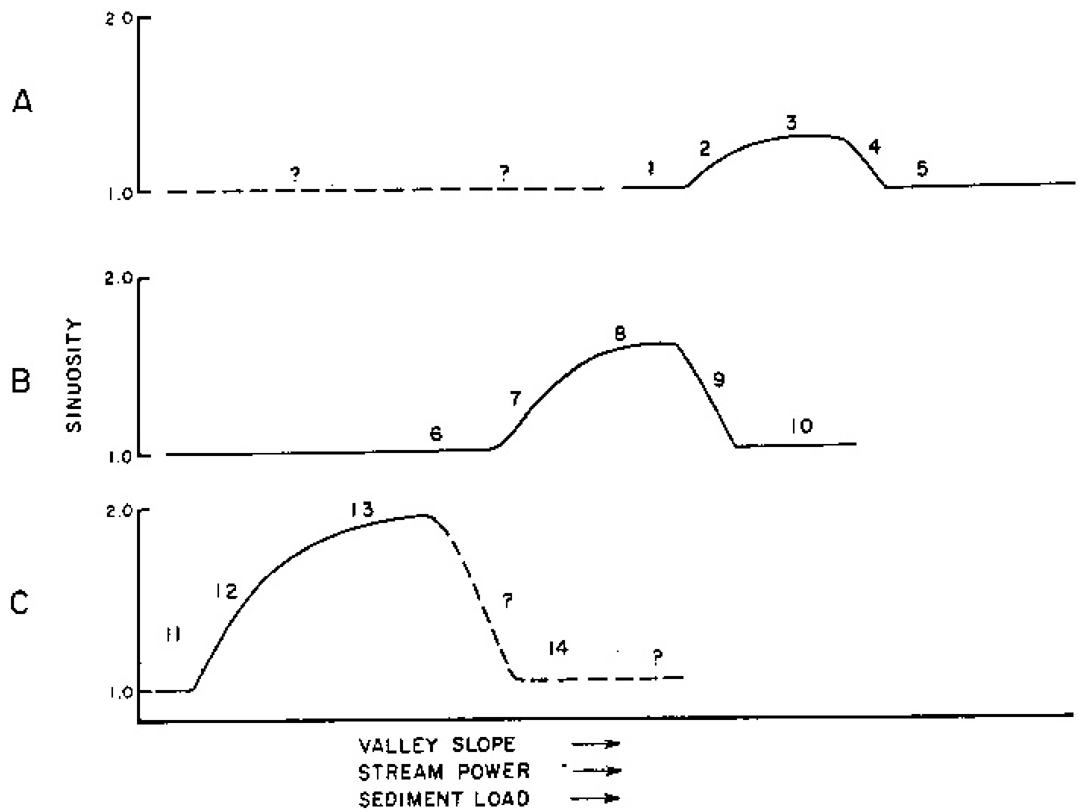

FIG. 7.—Relative effect of valley slope, stream power, or sediment load on river pattern thresholds for: a) bed-load channels, b) mixed-load channels, and c) suspended-load channels. Numbers indicate locations of the channel patterns of Fig. 6.

Changes of valley-floor gradient provide another explanation of downstream pattern variations. For example, it is possible to follow a river in a downstream direction and to find that the influence of tributary sediment contributions to the main channel may change the channel from a suspended-load Pattern 3 to a bed-load Pattern 5 (Fig. 4). In addition, variations in the valley floor slope such as those in the Mississippi River valley have influenced sinuosity, as the river adjusts its pattern to maintain a constant gradient over the changing valley-floor slope (Schumm, et al, 1972).

Variations of valley floor slope can be the result of several influences. Tectonic activity may change the slope of the valley floor and have its effect on the channel pattern (Adams, 1980). In addition, a high-sediment-transporting tributary may build a fan-like deposit in the valley, which will persist even after the tributary sediment load has decreased. When the main river crosses this fan, pattern changes will result, as the river maintains a constant gradient. Tributaries to the Jordan River have developed fan-like deposits in the valley, and the valley floor of the Jordan valley undulates as a result. The Jordan River, as it approaches one of these convexities, straightens as it crosses the upstream flatter part of the fan and then it develops a more sinuous course on the steeper downstream side of the fan (Schumm, 1977, p. 140).

The sedimentologist should not be surprised when he finds extreme variations in fluvial deposits such as those between braided channels and meandering channels within the same stratigraphic unit. There are abundant reasons for abrupt vertical and longitudinal variations as outlined above. Needless to say, any changes in sediment delivery, either in quantity or type from Zone 1, will cause channel metamorphosis, or more subtle changes will occur depending on the magnitude of the variations in sediment load and discharge in the source area.

It is equally important to realize that those channels that lie near a pattern threshold may change their characteristics dramatically with only a slight change in the controlling variable. For example, some rivers that are meandering and that are near pattern thresholds become braided with only a

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small addition of bed load (Schumm, 1979). It is, therefore, possible to find a consistent and uniform pattern of fluvial deposition through time as a river, which lies far from a threshold, behaves in a predictable fashion. On the other hand, another river, because of its position near a threshold, may cross this threshold many times during its history. The result could be a fluvial deposit showing the characteristics of braided and meandering streams alternating abruptly and frequently.

Changes in stream patterns from meandering to straight or to braided produce a dramatic change in the quantity and the type of sediment that will be moved through Zone 2 and Zone 3. A noted above, the episodic behavior of Zone 1 can strongly influence the channels of Zone 2, and pattern changes within Zone 2 can have equally great effects on deposition in Zone 3.

Zone 3

Piedmont deltaic and even deep-sea fan deposits should reflect the geology, morphology and erosional history of the source area as well as the type of river transporting the sediment to Zone 3 (Fig. 2). Abrupt changes in the amount and type of sediment in Zone 3 reflect not only the complexity of the erosional evolution of Zone 1, but also the dynamics of the rivers of Zone 2. Figure 2 suggests the character of the sedimentary deposits that result from the two different drainage basins. When the sediment supply is large and sediment size is coarse, alluvial fans and fan deltas develop. At the other extreme, when sediment supply is small and fine-grained, broad, flat, alluvial plains and deltas are characteristic. As noted above, similar differences through time result, as landforms are reduced during erosional evolution of the fluvial system. Similar changes take place over shorter periods of time, as climatic change modifies vegetative cover and the volumes of water and sediment that leave the source area. The effect of these changes and others can be relatively gradual or abrupt.

On Figure 8 an attempt has been made to show the nature of sedimentary deposits that are associated with bed-load, mixed-load and suspended-load channels. Each example is positioned with reference to an idealized stratigraphic section that shows the effects of tectonic, isostatic, threshold, and episodic-behavior and complex-response events (Schumm, 1977). The stratigraphic column portrays the complexity that is inherent in the fluvial sedimentary record. It is a hierarchy of fining-upward cycles that represent rejuvenation events of different magnitudes; tectonic, isostatic, threshold, and complex-response episodic-behavior events.

Bed-load channel deposits will be associated with alluvial fans, fan deltas, braided streams (Fig. 2) and proximal alluvial-plain deposition. Mixed-load channel deposits will contain significant amounts of

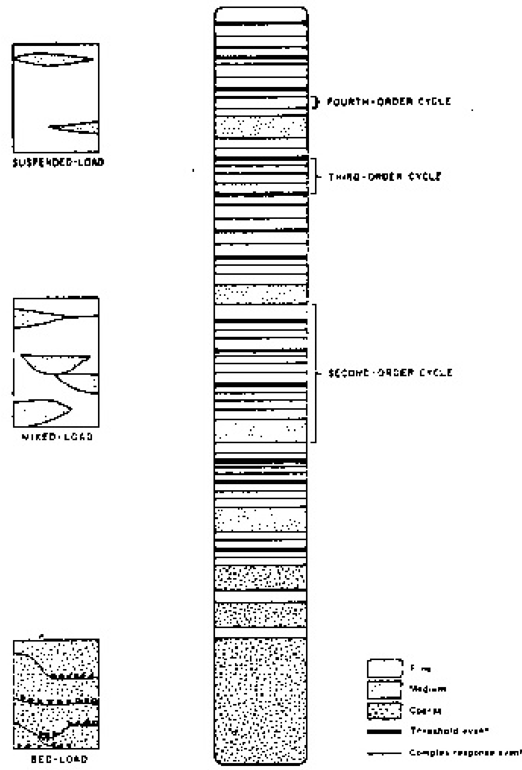

FIG. 8.—Diagrammatic model of a major fining-upward cycle that is related to uplift and the erosional evolution of the landscape. The major cycle is composed of second, third and fourth order cycles that relate to isostatic adjustment (2nd order cycle) geomorphic thresholds (3rd order cycle) and episodic behavior and complex response events (4th order cycle).

During the primary cycle all three types of channels will be functioning and the deposits associated with each are shown at appropriate places. In reality this simple and idealized model will be complicated by climate change and additional tectonic activity and even large hydrologic events (after Schumm, 1977, Fig. 9–4).

fine sediments. The sand bodies will be interconnected to a large degree, and in an alluvial plain continuum the mixed-load deposits will be found in the mid-plain position. Suspended-load channel deposits contain relatively small amounts of sand and gravel, which may appear to be randomly distributed, as coarse sediments were flushed episodically into the depositional site. They will comprise the distal sediments of an alluvial fan or plain.

If marine influences are negligible, the differences in deltas that are usually attributed to longshore drift and wave action can also be the result of the type of sediment delivered to the coast. Bed-load streams will produce fan-deltas, whereas suspended-load streams will produce birdsfoot deltas.

In addition to the effects of Zones 1 and 2, sediment accumulation may result in episodic aggradation. Rapid accumulation of sediments at one locality may result in channel avulsion and renewed incision, such as the reworking of fan heads during episodic growth of an alluvial fan (Schumm, 1977). Thus, in Zone 3 there should be changes in the nature and quantity of sediment deposited through time. With channel avulsion there will be changes in space, and the crossing of channel-pattern thresholds will produce changes with time.

Episodic deposition can be important in placer formation (Schumm, 1977). The reworking of previously deposited sediments containing small quantities of heavy minerals can result in their concentration. Coarser sediments will also be concentrated to form armor layers, and zones of higher permeability.

SUMMARY

Everything about the fluvial system reflects instability and variability in process and rate. The quantity of sediment and the type of sediment derived from Zone 1 will depend on the geologic and climatic characteristics and tectonic history of area. A revised model of landform evolution indicates the erosion may be episodic, the model being based on dynamic metastable equilibrium rather than dynamic equilibrium (Fig. 3). If so, the resulting variations in channel patterns in Zone 2 and the resulting variation of quantity and type of sediment delivered to Zone 3 will result in a very complex depositional history (Fig. 8).

In Zone 2 rivers may change their morphology and their ability to transport sediment, as a result of variations in discharge and hydrologic events in Zone 1. Under these circumstances, when the channel is near a pattern threshold, abrupt changes in the channel morphology will yield significant variations in the quantity and types of sediment delivered to Zone 3.

Channel patterns will vary through time and longitudinally along the channel, depending on variations in valley slope and tributary contributions. It is no wonder that the depositional record is complex, considering the complexity of the erosional evolution of Zone 1 and the sensitivity of the channels in Zone 2 to upstream sediment production and to down-stream variations in base level.

All the geomorphic evidence indicates that the manner and rate of sediment deposition in Zone 3 must vary through time. It is only under the conditions of low relief, uniform and invariable climate and uniform geology that a slow progressive accumulation of sediment in Zone 3 will take place. The most unusual circumstance should be episodic aggradation.

Variations of sediment delivery to Zone 3 are a result of episodic denudation in Zone 1 and of channel metamorphosis and abrupt channel pattern changes in Zone 2, as geomorphic thresholds are exceeded. Geomorphic studies can explain the great variability of the Zone 3 deposits, but as yet they are unable to permit prediction, except in the broadest terms, of what will occur next in a given sequence or what will occur laterally in the sequence.

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