CHAPTER 1

The Alluvial Fan Problem

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Abstract

The 'alluvial fan problem' is defined as the difficulty of formulating a general model of alluvial fan development. The paradigm concept provides a useful framework for evaluating trends in alluvial fan research. The predominant paradigm since the early 1960s has been the fan dynamics paradigm, in which the major research question of the paradigm was to determine the process involved in long-term fan development. Equilibrium and evolutionary approaches in the fan dynamics paradigm were proposed to explain fan development. Difficulty in successfully applying time-independent equilibrium concepts to the alluvial fan problem required the integration of equilibrium and evolutionary approaches. Reconciliation of these two competing concepts was achieved by considering the time span over which equilibrium is viewed. The resulting integrated approach to the fan dynamics paradigm involves the investigation of depositional processes in different environments and the historical analysis of long-term fan evolution.

Field data collection and laboratory fan models have been essential components of fan research. Fluvial theory in geomorphology has benefited from emphasis on empirical data collection; however, field site selection has been spatially biased, favouring the arid to semiarid regions of the American Southwest.

Introduction

It is not unusual in geomorphology for difficult questions related to the origin and formation of geomorphic features to be regarded as 'problems'. The 'pediment problem' (Oberlander, 1974) and the 'arroyo problem' (Cooke and Reeves, 1976; Graf, 1983) are examples of the treatment of questions in this manner. The 'alluvial fan problem' discussed in this paper is defined as the difficulty of establishing a general model of alluvial fan development. The formation of alluvial fans has attracted the attention of geomorphologists since the exploratory surveys of the American West in the late 1800s, yet the alluvial fan problem has generated significant interest only since the early 1960s. Assessment of the progress towards resolution of the alluvial fan problem is accomplished by discussing the development of paradigms in alluvial fan research. The purpose of this paper is to review the trends in alluvial fan research by focusing on research paradigms and to examine the influence that research on alluvial fans has had in the development of fluvial theory.

The significance of alluvial fan research within

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the general field of geomorphology is threefold. While there may have been a shift of interest in the past several decades to process studies at the expense of the study of landforms, research on alluvial fans serves to stress a fundamental goal in geomorphology—to understand the significance of process–form relationships. Second, the investigation of the processes responsible for the construction of alluvial fans helps to improve understanding of sediment transport in other fluvial systems, particularly in arid and semiarid environments (Bull, 1968). Third, the geomorphic response of fan morphology to changes in fluvial processes, tectonic activity, climate, and drainage basin variables are concerns common to the science of geomorphology as a whole.

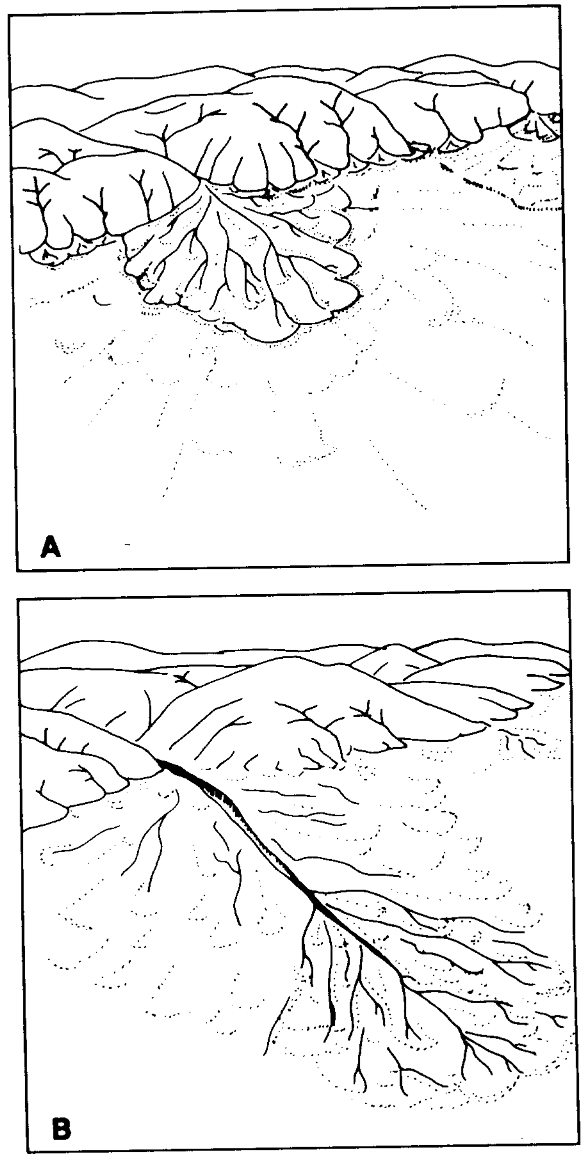

Figure 1.1. Two phases in the development of alluvial fans under the influence of tectonic uplift (A) Area of deposition adjacent to the mountain front; (B) Area of deposition shifted downfan due to stream channel entrenchment. (Reproduced by permission from Bull, 1968)

Alluvial Fans

An alluvial fan consists of stream deposits, the surface of which forms a segment of a cone that radiates downslope from the point where the stream emerges from the mountain area (Bull, 1963, 1968) (Figure 1.1). Some authors have used the term 'alluvial cone' to describe small fans steeper than 20 degrees that are formed by both fluvial deposition and mass wasting (Bull, 1977), while others have used it as a synonym for an 'alluvial fan' (Knopf, 1918). This paper will restrict the use of the term alluvial fan to features deposited by fluvial processes and debris-flow processes (thereby excluding other forms of mass wasting). An alluvial fan may consist of debris-flow deposits, water-laid sediments, or both. The highest point on the fan, where the stream leaves the confines of the mountain, is the fan apex. The overall radial profile of an ideal alluvial fan surface (longitudinal profile) is concave, while the cross-fan profile (parallel to the mountain front) is convex. In plan view the deposit is typically fan shaped, with contours that are convex outward from the mountain front (Bull, 1977).

Fans often have stream channels that are incised into the fan surface. The particular case known as 'fanhead trenching' generally is deepest at the fan apex and progressively decreases downfan until the stream channel and the fan surface intersect. This point on the fan surface is called the intersection point (Wasson, 1974).

Alluvial fans may coalesce along a mountain front to form a depositional piedmont called an alluvial apron or bajada (Eckis, 1928). Coalescent fans are frequently mistaken for pediments. However, alluvial fans are distinguishable as depositional features, while pediments are erosional landforms. Pedimented landscapes commonly contain bedrock knobs that protrude for the ramplike erosional surface, whereas alluvial fans with such knobs projecting through the surface are seldom observed. Doehring (1970) provided a method for discriminating between fans and pediments using topographic map analysis. In general, a fan may be distinguished from a pediment when the thickness of the deposit is greater than 1/100 of the length of the landform (Bull, 1977).

While the term 'alluvial fan' was first coined by Drew (1873) in reference to features in the upper Indus basin, Surell (1841, from Bull, 1977; Anstey, 1965) appears to have been the first to discuss fans. Alluvial fans are commonly found in arid and semiarid regions with tectonically active mountains where there is an abundant supply of sediment, but their occurrence is by no means limited to such environments. Alluvial fans also occur in humid–temperate, subtropical, arctic, and alpine environments (Table 1.1).

Table 1.1 Alluvial fan studies in non-arid environments*

Study area	References
Australia	Wasson, 1977a,b
Canada	
Alberta	Winder, 1965
	McPherson and Hirst, 1972
	Roed and Wasylyk, 1973
	Kostaschuk *et al.*, 1986
British Columbia	Ryder, 1971a,b,
	Church and Ryder, 1972
Northwest Territories	Leggett *et al.*, 1966
Costa Rica	Kesel, 1985
Greece	Schroeder, 1971
Honduras	Schramm, 1981
Iceland	Boothroyd and Nummedal, 1978
India	Drew, 1873
	Gole and Chitale, 1966
	Mukerji, 1976
Japan	Murata, 1931a,b; 1966
	Yazawa *et al.*, 1971
	Matsuda, 1974
	Iso *et al.*, 1980
	Saito, 1980
New Zealand	Carryer, 1966
Poland	Rachocki, 1981
Sweden	Hoppe and Ekman, 1964
United Kingdom	Wells and Harvey, 1987
United States	
Alaska	Anderson and Hussey, 1962
	Boothroyd, 1972
	Ritter and Ten Brink, 1986
Colorado	Blair, 1987
Virginia	Kochel and Johnson, 1984

*From Nilsen and Moore (1984), with additions.

Paradigms

KUHN'S PARADIGM CONCEPT

Before considering the trends in alluvial fan studies, it is valuable to review Kuhn's (1970) perspective on the sociology of science, because it provides a useful conceptual framework for examining trends in scientific research. According to Kuhn, the development of science is characterized by long periods of problem-solving when knowledge is accumulated in a steady manner, interrupted periodically by brief episodes of intellectual crisis. The practitioners of a science share a common approach and philosophy to research and use an agreed-upon methodology (Gregory, 1985). Kuhn defined a paradigm as 'universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners' (Kuhn, 1970: viii). The paradigm defines whether or not specific research is relevant to the current view of the science. 'Normal science' is research based upon past scientific achievements reached within the domain of the current paradigm that form the foundation for subsequent investigations (Kuhn, 1970). The objective of researchers is to solve problems that are identified within the theoretical framework provided by the paradigm in a manner that accumulates generalizations and extends the range of the theory (Johnston, 1983). By working within the structure of the paradigm, practitioners of normal science are provided with (1) an accepted body of knowledge, (2) a general indication of the problems that remain to be solved, and (3) a methodology designed to solve those problems (Johnston, 1983).

As normal science proceeds, occasional anomalies surface that are not in keeping with the assumptions of the paradigm. Minor changes in the paradigm may be necessary to assimilate these discrepancies, but if anomalies persist and accumulate, normal science will be interrupted by an intellectual crisis. At this time some scientists will search for a new paradigm that is able to account for the anomalies. The successful outcome of this 'extraordinary' research presents an alternative paradigm to the scientific community, which, if accepted, marks a scientific revolution whereby the prevailing paradigm is replaced by a new one.

Although Kuhn's work has stimulated criticism (Shapere, 1964; Masterman, 1970; Watkins, 1970) and interest in alternative approaches (Popper, 1970; Lakatos, 1970), his philosophy appears to have particular relevance to the historical development of geomorphology (Graf, 1983).

PARADIGMS IN GEOMORPHOLOGY

Following the early exploratory surveys of the American West, the science of geomorphology experienced a period of normal science dominated by the Davisian concept of landscape evolution which continued until the early 1950s (Tinkler, 1985). While Davis viewed landforms as a function of 'structure', 'process', and 'stage', he placed primary emphasis on stage. Consequently, the investigation of process was virtually ignored (Hart, 1986). Dissatisfaction with Davis's evolution paradigm led to an intellectual crisis in geomorphology. Alternatives (Penck, 1924; King, 1953, 1962; Büdel, 1977) and criticisms (Strahler, 1950) accumulated until a scientific revolution occurred and the evolution paradigm was replaced. Although the search for an alternative to the evolution paradigm had begun early with the work of Leighly (1932), Horton (1932), Hjulström (1935), and Bagnold (1935, 1937, 1941), the shift to a new process paradigm was delayed until Horton published his influential paper in 1945.

A new period of normal science emphasized equilibrium concepts and a quantitative approach to the investigation of surface morphology and process using principles developed in physics (Tinkler, 1985). Research under this process paradigm continued until the early 1970s when geomorphology appeared to enter another crisis period which persists to the present. Problems that are solvable by the equilibrium approach appear to be fewer and some researchers have recognized the advantage of integrating useful aspects of the Davisian and equilibrium approaches (Schumm, 1977). A new conceptual framework emphasizing spatial- and temporal-dependent solutions has been advocated and appears promising for new theory development (Kennedy, 1977; Graf, 1983).

Although paradigms usually pertain to scientific disciplines, it is also important to consider paradigms at the smaller scale of the specialized research field. The development of paradigms in alluvial fan studies generally followed events in the broader science; however, significant differences can be observed which makes the analysis of paradigms at the smaller scale a reasonable proposition. The following section reviews the pre-paradigm period that emphasized description and classification. Next, a more elaborate review is provided of the paradigm of fan dynamics, which is concerned with process and fan development. The third section discusses an approach that combines useful parts of equilibrium and evolutionary hypotheses which illustrate the relevance of the alluvial fan problem to research conducted in the paradigm of fan dynamics. The objective of these sections is to analyse the prevailing paradigms in alluvial fan studies and their influence on the progress of fan research. It is recognized that organizing intellectual history according to paradigms is a subjective exercise at best; nevertheless, it is a useful way to make sense of a seemingly random collection of information and to gain some 'knowledge of the nature of intellectual debate' (Hart, 1986:199). Because paradigms provide the means for answering specific research questions, the goal here will be to identify how paradigms failed or succeeded in resolving the fundamental research questions associated with the paradigm. Finally, fan research is evaluated in the context of fluvial theory development.

Pre-paradigm Research

While the broader field of geomorphology was growing quickly during a Davisian period of normal science, interest in alluvial fans as subjects for research was developing quite slowly. The number of researchers and studies lacked the 'critical mass' necessary to develop a well-defined paradigm for alluvial fans. This period was characterized by lack of a common methodology and literature, resulting in relatively disjointed research efforts. Interest was generally confined to the geologic description of fan deposits, the establishment of fan classification criteria and terminology, and speculation about the depositional processes that form alluvial fans. Few researchers collected quantitative data on surface processes or morphology.

The dominance of Davisian concepts in geomorphology had a relatively limited impact on alluvial fan studies, yet it was through Davis's ideas that the alluvial fan problem was first addressed by the consideration of evolutionary stages (Eckis, 1928). Eckis proceeded under the notion that fans indicated conditions of youth in the geographic cycle, and are therefore only temporary features. He further suggested that trenching signalled maturity and the eventual destruction of the fan, and noted that the significant factors to be considered in the trenching of fans are tectonic uplift, climatic change, reduced sediment load, base-level change, and 'dissection in the normal course of the cycle' (Eckis, 1928:237). Eckis proposed that the last factor, trenching due to the progressive downwearing of the stream profile above the fanhead, was responsible for fan entrenchment in the San Gabriel Mountains of southern California. Evolutionary change was conceptualized in a closed system which neglected periodic inputs of energy due to tectonic uplift.

Following the work of Eckis, Blackwelder (1928) recognized the importance of debris-flows in fan construction and Chawner (1935) described the sediments deposited following a major flood on an alluvial fan in Los Angeles County. In 1952, Blissenbach found that a close relationship exists between the rates of change of particle size and surface slope. He later summarized the current knowledge about fan sedimentology and morphology (Blissenbach, 1954).

Although this period exhibited some of the characteristics of the evolutionary paradigm in the broader field of geomorphology, the work of two researchers (Eckis, 1928; Blissenbach, 1954) was hardly sufficient to be described as a paradigm for alluvial fan research. The concern with fan evolution was but a small component of research that instead emphasized descriptive studies with fans as secondary topics of interest (Tolman, 1909; Trowbridge, 1911; Lawson, 1913; Knopf, 1918; Blackwelder, 1928; Chawner, 1935). These researchers made few efforts to relate what they learned about alluvial fans to broader concepts of landscape evolution.

The Paradigm of Fan Dynamics and Hypotheses of Fan Development

The early 1960s marked a transition in alluvial fan research. Following the pre-paradigm period of description and classification in which there was no generally accepted view or body of knowledge upon which to build, one paradigm became dominant over the other competing views. The paradigm of fan dynamics was similar in many ways to the process paradigm in the parent field of geomorphology. Introduction of the equilibrium concept and systems theory encouraged quantitative studies that placed primary emphasis on fan processes and morphology. The major research question for the paradigm of fan dynamics was one of determining the processes involved in fan development, i.e. the alluvial fan problem. Interpretations of how fans developed varied considerably. To support their claims, many researchers applied allometric models to describe the rates of change between fan and drainage basin characteristics (Bull, 1964b; Melton, 1965; Hooke, 1968a; Hooke and Rohrer, 1977; Denny, 1967; Beaumont, 1972) (Figure 1.2). Fan–basin relationships were used to suggest factors that control fan development. In addition, research investigating the causes of fan entrenchment produced useful evidence to support fan development hypotheses.

The two primary hypotheses proposed to explain fan development were the evolutionary hypothesis and the equilibrium hypothesis. Climatic and tectonic effects are considered as factors influencing fan development in an equilibrium hypothesis. The evolutionary hypothesis received much less attention than the equilibrium hypothesis due to widespread dissatisfaction with historical approaches bearing any resemblance to

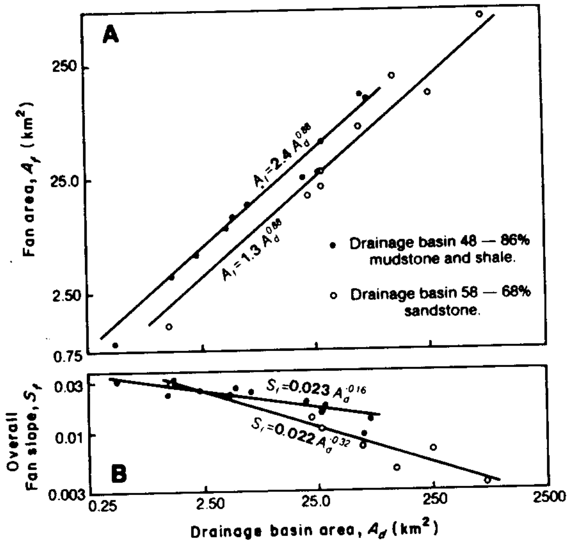

Figure 1.2. Relation between drainage basin area and (A) fan area and (B) fan slope. (A) Fans with basins containing mostly erodible mudstone and shale (solid dots) are proportionately larger than their counterparts built of material from basins composed predominantly of more resistant sandstone; (B) Fan slope decreases as basin area increases. (From Bull, 1964b)

Davis's cycle of erosion. However, it is important to recognize the evolutionary hypothesis early in the discussion of the fan dynamics paradigm because later it will play a significant role in the restructuring of the paradigm when difficulties arise in successfully applying equilibrium concepts to the alluvial fan problem.

THE EVOLUTIONARY HYPOTHESIS

The evolutionary hypothesis was first expressed in the work of Eckis (1928) during the pre-paradigm period in alluvial fan research. The influence of process and its variation with time was virtually ignored while emphasis was placed on qualitative assessments of 'stage' in Davis's (1905) arid cycle. Conditions of youth were indicated by small, actively growing fans fed by streams flowing from V-shaped canyons in uplifted mountain ranges (Lustig, 1965). As fans evolved they were thought to grow until they filled the depositional basin with sediment, burying remnants of the mountain range in alluvium.

Beaty (1970:71) rejected the possibility that the fans on the west side of the White Mountains in California are in a steady-state condition or in a state of active dissection and volume reduction. Instead, he concluded that conditions of 'active growth' and a 'Davisian stage of youth' are applicable to the west-side fans, while the older fans on the east side of the range are physiographically mature. However, Beaty also suggested that these fans would eventually reach some sort of equilibrium condition if given enough time. The evolutionary hypothesis in a strictly Davisian (cyclic, stage-oriented) sense was not likely to provide the answers sought by geomorphologists regarding fan development. A different conceptual approach was needed.

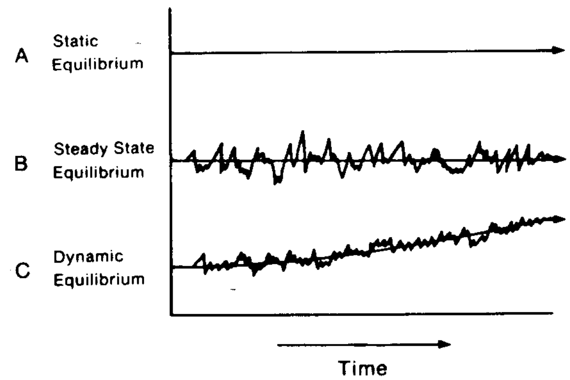

Figure 1.3. Types of equilibrium. (A) A system in static equilibrium has no change in the system variables over time; (B) Systems in steady-state equilibrium show variations about a mean condition that remains constant over time; (C) Dynamic equilibrium means that system variables fluctuate around a mean condition that changes through time. (Reproduced by permission from Schumm, 1977, after Chorley and Kennedy, 1971)

THE EQUILIBRIUM HYPOTHESIS

The concept of equilibrium soon became the guiding principle in the effort to resolve the alluvial fan problem. Initially, researchers chose to view fans in steady state equilibrium—as time-independent landforms (Figure 1.3) (see Schumm, 1977, pp. 4–13 for a review of equilibrium terminology). Denny (1965, 1967) contended that a state of dynamic equilibrium exists between alluvial fans and their source areas, an idea first proposed for alluvial fans by Hack (1960). The rate of deposition on the fan was considered equal to the rate of erosion from the fan to the floodplain. To maintain such a steady state Denny envisioned a fan divided into areas of erosion and deposition, where areas of deposition are converted to areas of erosion by repeated stream piracies (Figure 1.4).

In a different view of equilibrium, Hooke (1968a) noted that in Denny's system erosional material must be removed entirely from the basin, otherwise the playa would encroach onto the fan. In such a scenario fan area would decrease, causing an increase in the rate of deposition per unit area on the fan. The rate of erosion from the fan would decrease because erosional processes would have less area in which to operate (Hooke, 1968a). Hooke suggested that a steady-state condition exists (in a closed system) between the amounts of deposition on the fan and on the playa. These equilibrium adjustments result in equal rates of fan and playa aggradation. Thus, according to Hooke, the main flaw in Denny's analysis is that it will work only in open systems where sediment from the playa can be removed, whereas most basins of interior drainage are more easily viewed as closed systems.

Consideration of alluvial fans as time-independent landforms may seem to suggest that the equilibrium approach was not useful for resolving the alluvial fan problem. However, Schumm and Lichty (1965) showed that a system in steady-state equilibrium (during a graded time span) does not necessarily preclude evolutionary change (over a cyclic time span) (Figure 1.5). They reconciled the apparent contradiction of considering steady-state equilibrium in a model of progressive change by specifying the temporal scale involved. The graded time span therefore refers to a short period of cyclic time when dynamic equilibrium exists. Because evolutionary change takes place over long time spans (cyclic time) but is observed over shorter time spans (graded time or steady time), the system appears

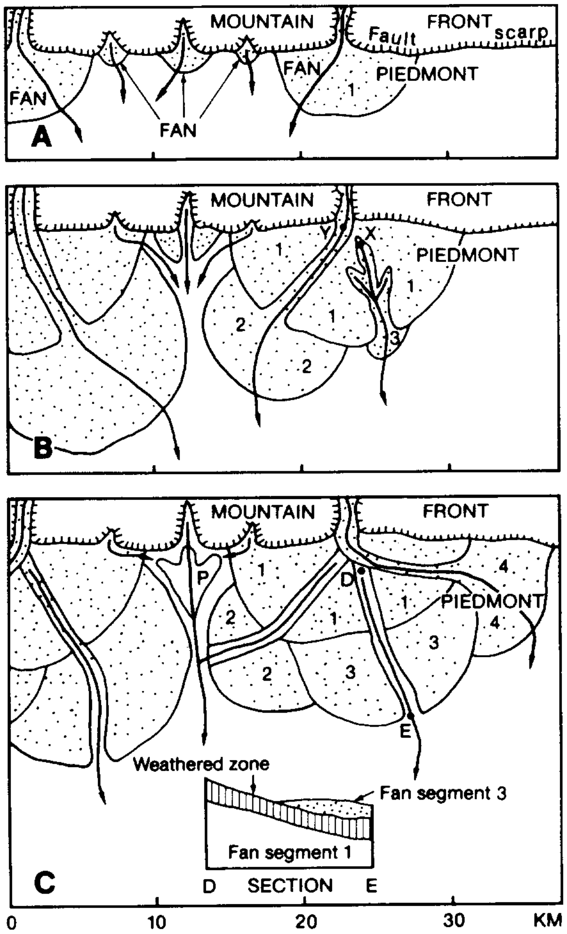

Figure 1.4. Diagram showing development of alluvial fans and shifts in the location of erosion and deposition. (A) Small fans at base of recently elevated mountain front; (B) Wash has dissected original fan segment (1) and is constructing a new fan segment (2); (C) Stream piracy has caused the abandonment of segments (2) and (3) and construction of another new fan segment (4). Stratigraphic relations between segments (1) and (3) in gully D–E. (Reproduced by permission of the American Journal of Science from Denny, 1967)

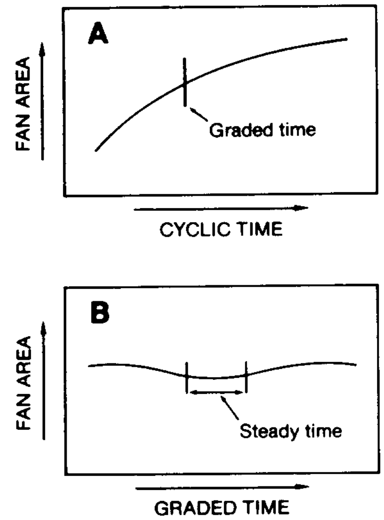

Figure 1.5. The concepts of cyclic, graded, and steady time as reflected in changes of fan area through time. (A) Progressive increase of fan area during cyclic time. Graded time is a small fraction of cyclic time, so fan area remains relatively constant during the graded time interval; (B) Fluctuations of fan area around a mean value during graded time. Fan area is constant when observed during the brief period of steady time. (Modified by permission of the American Journal of Science from Schumm and Lichty, 1965)

to be in steady-state equilibrium when, in fact, it is not. The variables in the system fluctuate about a changing mean condition (dynamic equilibrium). So, the equilibrium approach remains viable so long as the role of time is taken into account. In essence, this represents the integration of the evolutionary and the equilibrium concepts. The implications of this new approach in the fan dynamics paradigm will be considered below, but first it is necessary to comment in some detail on climatic and tectonic complications.

CLIMATIC AND TECTONIC COMPLICATIONS OF THE EQUILIBRIUM HYPOTHESIS

Schumm and Lichty (1965) argued that it may be impossible to exclude time from the analysis of landforms. Although Hack (1960) suggested that a steady-state balance exists between form and process that is independent of time, he qualified his argument by stating that if erosional energy changes through time, then form must also change. The two most important factors causing this change in erosional energy through time are climatic change and tectonics. Thus, the consideration of climatic and tectonic complications of the equilibrium hypothesis served to reintroduce the dimension of time to alluvial fan research, thereby refocusing attention on the alluvial fan problem.

The Climatic Factor

Climatic change influences the development of alluvial fans by inducing variability in the magnitude and frequency of fluvial processes that alter alluvial fan features. Lustig (1965) concluded that fans tend toward equilibrium in adjustment to different climatic conditions. Lustig's evidence included: (1) a shift in the locus of deposition downfan; (2) deep fanhead trenching at the fan apex; (3) presence of desert varnish on abandoned fan surfaces above the intersection point; and (4) greater estimated tractive force in active channels than on the fan surface.

Lustig believed that fan aggradation occurs regardless of climatic regime. During wet periods aggradation takes place within the drainage basin and below the mountain front (Figure 1.6A). During dry conditions trenching occurs in the upper portion of the fan as debris-flows become the dominant erosional process. This causes fanhead entrenchment and the shift of deposition downfan, but the fan still builds out from the mountain front (Figure 1.6B). Because fan entrenchment was so widespread in the American Southwest, Lustig cited the need for a regional explanation. He favoured a regional change in climate rather than a local explanation such as tectonic uplift. The type of climatic change required to accomplish entrenchment might be an increase in either storm frequency or intensity, in total precipitation, or a decrease in total precipitation that coincides with an increase in storm intensity (Cooke and Warren, 1973). Denny (1967:104) criticized Lustig's 'overreliance on climatic change as an explanation for features whose mode of origin may be in doubt,' noting that many of the features indicating climatic change could be explained by stream piracy.

Another problem with Lustig's model is that, in an arid phase, it requires debris-flows to be the dominant erosional agents due to their greater tractive force. Hooke (1967) and Wasson (1977b) doubted that debris-flows have the erosive ability to accomplish this. Based on observations of fans

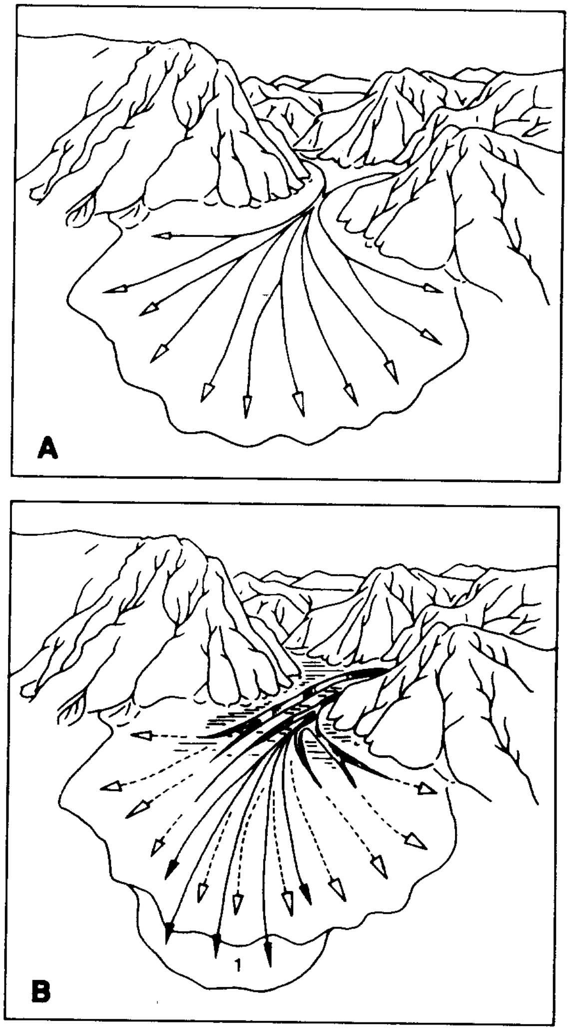

Figure 1.6. The formation of alluvial fans under the control of climate in an equilibrium hypothesis. (A) Aggradation during more humid or pluvial periods; (B) Trenching during a subsequent drier climate period. Intersection point moves downfan and mudflows and other infrequent density flows transport sediment to the lower reaches of the fan, building it outward into the valley (A). (From Lustig, 1965)

in the White Mountains of California, Beaty (1963, 1970) suggested that fans are built, not eroded by debris-flows. Others saw the present regime as a destructive phase in which no new material is being deposited (Hunt and Mabey, 1966:A97). Fans may also be relict features from different climatic conditions during the Pleistocene, therefore modern processes may not be indicative of events that influenced fan construction (Nilsen and Moore, 1984). Fan aggradation may be caused by climatically controlled increases in sediment production followed by fan trenching initiated when the temporarily abundant sediment supply is depleted. Bull (1964a, 1964b) cited variation in rainfall intensity as the principal cause of temporary fanhead trenching in Fresno County, California. As an alternative to climatic or tectonic explanations for stream entrenchment, Schumm (1973) suggested that the complex response of drainage systems may not be related to external influences. Instead a fan may grow until it exceeds some threshold slope that causes trenching to occur. Trenching was observed on an experimental fan where oversteepening of the fanhead was the result of exceeding an intrinsic geomorphic threshold (Weaver and Schumm, 1974; Schumm, 1980).

The Tectonic Factor

Although alluvial fans may form in areas where tectonic uplift is not an important factor (Drew, 1873; Carryer, 1966; Ryder, 1971a, 1971b; Church and Ryder, 1972; McPherson and Hirst, 1972; Roed and Wasylyk, 1973), they are especially prominent where uplift of mountainous regions provides a continual supply of fresh debris from steep drainage basins (Beaty, 1970). Regional analysis of landforms in the American West has revealed that the tectonically active Basin and Range Province has an abundance of alluvial fans, while in the tectonically stable areas of south–central Arizona the pediment is the dominant landform (Bull, 1977). In areas where tectonic activity is decreasing, alluvial fans may be replaced by pediments as the typical landform. The tectonic influence on the development of alluvial fans is considered in terms of fan entrenchment, fan segmentation, and the sedimentology, shape, and thickness of both modern and ancient alluvial fan deposits.

The rate of tectonic uplift in mountain areas relative to the rate of stream channel downcutting largely determines the locus of deposition and the thickness of the alluvial fan deposit (Bull, 1972, 1977). Bull proposed two phases of development for alluvial fans by considering differential uplift of the mountain block with respect to the valley block (Figure 1.1). The first type of fan develops where the rate of uplift is greater than the rate of stream channel downcutting, resulting in deposition adjacent to the mountain front (Figure 1.1A). Continued tectonic uplift results in the accumulation of thick alluvial fan deposits.

The second type occurs where the rate of channel downcutting at the mountain front exceeds the rate of uplift of the mountain mass; the fanhead becomes entrenched and the locus of deposition moves downslope from the fan apex (Figure 1.1B). This situation may be associated with a decrease in the rate of uplift. If the rate of tectonic uplift does not increase so that it exceeds the rate of stream channel downcutting, the fanhead area will be removed from active deposition and soil development will take place on that portion of the fan surface.

Although the overall radial profile of an alluvial fan is concave (Blissenbach, 1954), it is not always a smooth exponential curve. Instead, the connection of a series of distinct straight or, less commonly, concave segments that have progressively lower gradients downslope form what Bull (1961, 1964b) termed 'segmented fans' (Figure 1.7). Two types of segmented fans have been identified (Figure 1.8) and are related to changes in stream channel slope upstream from the fan apex due to tectonic uplift, climatic change, or base-level change (Bull, 1961).

The first type occurs in areas characterized by rapid, intermittent uplift. Mountain stream gradients will steepen and, as a result, a new and steeper fan segment will be constructed upslope of the previous segment. The opposite situation occurs where either a reduced rate of tectonic uplift or a climatic change induces accelerated stream incision and rapid downfan movement of the locus of deposition, resulting in a new fan segment with a lesser gradient. Therefore, in the first situation fan segments are steeper and younger in the upfan direction (Figure 1.8C), whereas in the second situation, fan segments are younger and gentler in the downfan direction (Figure 1.8D). Recognition of fan segmentation of the

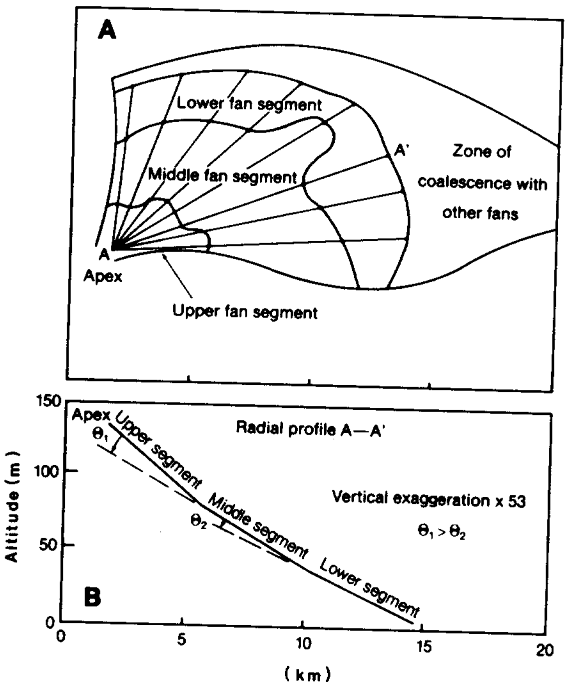

Figure 1.7. Segmentation of the Tumey Gulch fan, western Fresno County, California. (A) The segment boundaries are more strongly concentric than the contours, showing that fan segments are depositional forms rather than purely tectonic features. Each of the eight radial profiles has three straight line segments (B). (From Bull, 1964b)

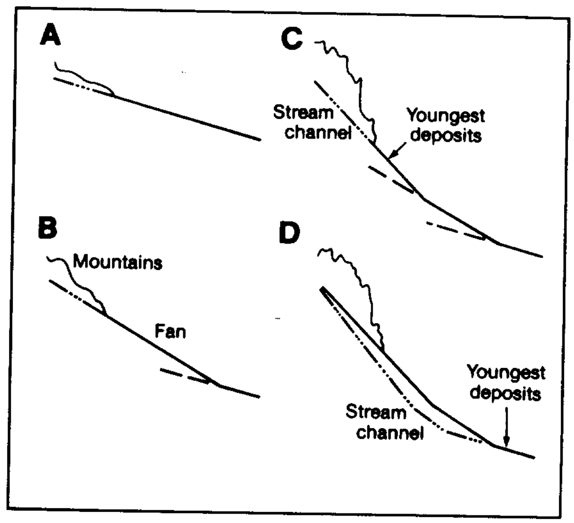

Figure 1.8. Segmented alluvial fan development in western Fresno County, California. (A) Fan and channel have developed a common gradient; (B) Fan gradient adjusts to steeper stream gradient due to uplift in mountains; (C) New phase of uplift causes younger segment, above older segment; (D) Increase in amount and intensity of precipitation causes stream channel entrenchment, moving the locus of deposition downfan. (From Bull, 1961)

first type is useful for reconstruction of the tectonic history of a mountain range (Bull, 1961).

From research conducted in Death Valley, California, Beaty (1961) provided an interpretation which conflicts with that proposed by Bull for the response of alluvial fans to differential uplift across a mountain front. Beaty suggested that uplift of the Grapevine Mountains had caused rejuvenation of the stream above the fan apex. This led to the incision of the fanhead and the construction of a new fan segment with a more gentle slope below the old fan surface. Further evidence of the influence of tectonic effects on fan entrenchment was provided by Denny (1967), who described how relative sinking of the valley floor due to normal faulting may cause fanhead trenching. Hooke (1968a, 1972) and Denny (1965, 1967) noted that deep trenching of the fans on the west side of Death Valley has been produced by the eastward tilting of the valley.

The tectonic history of a mountain range may be deciphered over longer time periods if one considers the geometry of the alluvial fan deposit. The accumulation of thick alluvial deposits in the geologic past has been noted frequently in the geologic literature (Nilsen, 1969; Miall, 1970; Steel, 1974). Bull (1972) identified three basic types of fan deposits using cross-sections along radial profiles. The first is wedge shaped with the thickest part near the mountain front and the thinnest part away from it (Figure 1.9A). The tectonic interpretation is one of major uplift in the mountains prior to fan deposition. The second type consists of lens-shaped sedimentary bodies that are thin both near the mountain front and far away from it, reflecting uplift that has continued during fan deposition (Figure 1.9B). The third type is represented by wedge-shaped deposits that are thin next to the mountain front and thick away from it. These indicate the cessation of

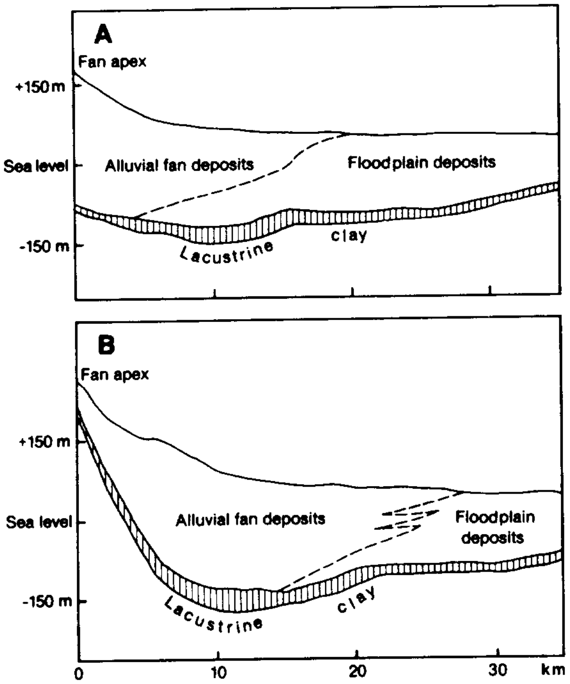

Figure 1.9. Longitudinal cross-sections of fan deposits. (A) Fan deposits that are thickest adjacent to the mountain front; (B) Fan deposits that are lenticular in shape. (Reproduced by permission from Bull, 1972 after Magleby and Klein, 1965, Plates 4 and 5)

tectonic activity and the erosion and redistribution of fan material away from the mountain front, which may eventually result in pediment formation.

Tectonic uplift affects the thickness of fan deposits and cycles of progradation, thus influencing sedimentary sequences. Two types of vertical fan sequence have generally been recognized. The first is a coarsening and thickening upward sequence that has been interpreted as indicative of fan progradation (outbuilding) at tectonically active basin margins (Heward, 1978). A fining and thinning upward sequence has been considered to be the result of fan retrogradation (retreat) and/or a reduction of source area relief associated with less tectonic activity at basin margins (Galloway and Hobday, 1983). Rust (1978) believed that the ideal sedimentary response to tectonic activity would be a coarsening upward sequence followed by a fining upward sequence as the fan system attempted to return to an equilibrium state.

CRISIS IN THE PARADIGM OF FAN DYNAMICS

Schumm and Lichty's effort to demonstrate that the equilibrium concept can be incorporated in an evolutionary approach took time to diffuse through geomorphology and be recognized explicitly by alluvial fan researchers (Wells, 1977). The investigation of climatic and tectonic complications to the equilibrium hypothesis, however, had a more direct influence on the approach taken in alluvial fan research.

The success of the equilibrium approach to the paradigm of fan dynamics was limited because geomorphologists had difficulty providing answers to the fundamental questions posed by the paradigm. After a decade of intensive study in the 1960s, researchers were unable to resolve the alluvial fan problem: to explain the evolutionary development of alluvial fans. Lustig (1967:96) concluded that 'the basic problem of fan formation is not yet resolved'. Furthermore, he suggested that future progress on this problem would require more data on rates of sedimentation and erosion on fans, and rates of bedrock weathering. The preceding discussion of fan development hypotheses illustrates the anomalies associated with each hypothesis and the overall diversity of opinions that prevailed. Although much progress was made towards understanding depositional processes, fan–basin relationships, and fan sedimentology, dissatisfaction with progress in resolving the alluvial fan problem signalled a shift in scientific efforts away from normal science and into a crisis stage.

According to Kuhn (1970), a crisis stage in the intellectual development of a scientific discipline is followed by a scientific revolution, unless the paradigm is able to adjust to accommodate the causes of the crisis. Further progress in the fan dynamics paradigm was largely dependent upon a more complete reconciliation of the evolutionary and equilibrium approaches. It was necessary to recognize that fans may tend toward some equilibrium state, but that it is difficult to evaluate what this state is or when it is reached without taking a historical perspective. This reconciliation was first suggested by Beaty (1970), but explicitly stated by Wasson (1977a). They have advocated construction of a general theory capable of accommodating the variety of conflicting conclusions reached thus far regarding the contemporary condition of alluvial fans, thereby integrating the time-independent and the time-bound aspects of alluvial fans into one comprehensive theory of alluvial fan development. Wasson (1977a) proposed a strategy for development of such a theory that would integrate investigation of modern processes on fans in different environments, with the historical analysis of alluvial fan evolution on active or relict fans. While some have doubted whether a general theory is achieveable (Rachocki, 1981), it does appear that recent fan research has adhered closely to this mandate. The fan dynamics paradigm has continued to remain viable by combining the successful parts of the evolutionary and equilibrium concepts into an approach that deals explicitly with the historical development of fans and with sedimentary processes in various environments.

An Integrated Approach to the Paradigm of Fan Dynamics

Several recent trends in the fan literature show promise to advance the field closer towards the goal of constructing a general model to explain fan development. The predominant trends observed throughout this period have been: (1) The detailed investigation of depositional processes and the relative importance of various proceses in different environments; (2) Consideration of the effects of catastrophic events on alluvial fan processes and morphology; and (3) The use of sedimentology and numerical dating techniques to analyse the historical development of alluvial fans.

DEPOSITIONAL PROCESSES

Although the basic depositional processes operating on alluvial fans were recognized early during investigation of the fan dynamics paradigm (Bull, 1963, 1972; Beaty, 1963; Hooke, 1967), substantial progress has been made recently in examining the relative roles played by these processes in various environments. Because alluvial fans are commonly inactive (in some environments) during historical time periods, sedimentological analysis is usually the method used to interpret depositional processes.

Blair (1987) pointed out that previous studies have failed to provide detailed documentation of vertical stratification sequences and the sedimentary processes that produced them. He found that the Roaring River alluvial fan (created by a catastrophic flood in Rocky Mountain National Park, Colorado) was formed by the processes of sheetflooding and noncohesive sediment–gravity flow (NCSGF) deposition. An NCSGF is similar to but differentiated from a debris-flow (cohesive sediment–gravity flow) by the near absence of silt and clay in the matrix. The dominant sedimentary process responsible for building the fan was sheetflooding, an unconfined water flow moving down a slope (Hogg, 1982). Blair's study demonstrated the importance of source area sediment characteristics in the production of an NCSGF and water flows instead of debris-flows. Fanhead incision was attributed to the progressive downslope movement of the intersection point as fan progradation occurred. In addition, because he was able to obtain aerial photographs of the fan during deposition and because postflood modifications of the fan were carefully monitored, Blair suggested that the sedimentary processes inferred from examination of surficial fan deposits are not necessarily the same processes that build alluvial fans. Postflood modifications (i.e. development of braided distributary channels on top of the sheetflood deposits) on the Roaring River fan have eliminated almost all evidence that sheetflooding was the dominant depositional process responsible for fan aggradation.

The relative importance of different depositional processes on fans has become a major topic of interest (Harvey, 1984b; Kostaschuk *et al.*, 1986; Wells and Harvey, 1987). A more traditional methodological approach using fan–basin morphometric relationships was applied to a group of alluvial fans in a recently glaciated, subhumid, mountainous region in the Bow River Valley of Alberta, Canada (Kostaschuk *et al.*, 1986). The fans were classified as fluvially dominated or debris-flow dominated. Allometric analysis of fan–basin morphometric relationships for these two distinct types of fans showed that large low gradient fans dominated by fluvial processes were associated with large, less rugged drainage basins. On the other hand, small, steep fans dominated by debris-flow processes were found to be associated with small rugged basins.

In a field study of small alluvial fans in northwestern England, Wells and Harvey (1987) showed that the spatial variation of the type of depositional process was controlled by variables other than tectonism or climatic change. They attributed the dominance of a particular depositional process to drainage basin size, channel gradient, the percentage of the drainage basin eroded, the type of sediment available from the drainage basin, and the location of the storm cell. Debris-flow processes were associated with small steep basins peripheral to the centre of the storm cell with a large percentage of the basin area yielding sediment. Intrinsic geomorphic thresholds were recognized as influencing depositional process types and the resulting spatial distribution of facies. Harvey (1984b) obtained similar results from a study of Spanish Quaternary deposits, but he also showed the importance of source area geology. Debris-flow fans were associated with small steep basins on sedimentary and low-grade metamorphic rocks, while fluvial fans were associated with high-grade metamorphic rocks.

Wasson (1977a,b) pointed out the importance of studying the differences in process in various environments. The primary factor responsible for the differences in fan morphology and sedimentology that exist between fans that form in different climates is the nature of the dominant depositional process on the fan (Kochel and Johnson, 1984). Detailed analysis of fan sediments in the Lower Derwent Valley, Tasmania, indicated that the processes operating on the Derwent fans were similar in most respects to those on the arid fans of the American Southwest (Wasson, 1977b). However, comparison with Hooke's (1967) maps showed that the Death Valley fans demonstrated little surface evidence of sheet-like flows, while the Derwent fans showed few indications of leveed debris-flows. Wasson (1977b) concluded that these kinds of comparisons could be improved only if processes of fan accumulation were catalogued for fans with different geologic, climatic, and topographic environments.

As a result, previously neglected alluvial fans found in humid-temperate and wet–tropical regions have received recent attention. While many humid-temperate fans have been considered as relict landforms, Kochel and Johnson (1984) demonstrated that a group of fans in central Virginia are still active today and were formed primarily by mass-wasting processes (debris-flows and debris-avalanches) generated by catastrophic precipitation events. Alluvial fans in Costa Rica provide further insight into the processes associated with a wet-tropical environment where an episodic sediment supply and highly variable stream discharge controls fan morphology and sedimentology (Kesel, 1985). These fans are dominated by relatively brief periods of active streamflow deposition in braided channels separated by long periods when deposition is minor and the growth of tropical vegetation gradually alters the braided, active channel to a more sinuous, inactive channel pattern.

CATASTROPHIC EVENTS

Previous study of the magnitude and frequency of fluvial processes (Wolman and Miller, 1960) has suggested that relatively frequent events of moderate intensity accomplish the greatest amount of geomorphic work—a defence of the principle of uniformitarianism. In contrast, based on evidence from the White Mountains of California and Nevada, Beaty (1974) reported that 'normal' stream processes contribute little in the way of sediment to the fans—no more than 10–15% by volume. He argued that catastrophic events (producing debris-flows) of low frequency and high magnitude are the usual geomorphic process in the western Great Basin. Although uniformitarianism may prevail over long time-scales, catastrophism is more applicable over short time spans at the small scale of the individual drainage system (Beaty, 1974:50).

Determination of a dominant discharge has the potential to answer some of the questions posed by the catastrophism–uniformitarianism debate, but 'identification of the dominant event in controlling landforms has been an elusive problem' (Graf *et al.*, 1980:282). Fan research has presented ideas on both sides of the argument: control by extreme events, or control by moderate events. The concept of dominant discharge as adapted to alluvial fan studies is defined as 'that discharge which, if it alone occurred, would produce a fan having the same slope as a fan built with a distribution of discharges' (Hooke and Rohrer, 1979:151). In the absence of a way to determine the magnitude and frequency of the dominant discharge on alluvial fans, Hooke and Rohrer used data from laboratory fans. They concluded that these fans were adjusted to forces of moderate magnitude and not to catastrophic events. The dominant discharge was also found to increase with increasing debris size, reaffirming Wolman and Miller's (1960) observation that catastrophic events become increasingly important as the threshold stress required to move material increases.

Although the geomorphic role of infrequent, large magnitude events is controversial, much recent research in the integrated approach to the fan dynamics paradigm has focused on catastrophic events. Radiocarbon dating of fan stratigraphy in central Virginia provided a preliminary estimate of a recurrence interval of 3000 to 6000 years for events with a magnitude similar to Hurricane Camille (which initiated the most recent activity on these fans in 1969) (Kochel and Johnson, 1984). In another humid–temperate region (England), Wells and Harvey (1987) concluded, on the effects of a storm with a return interval greater than 100 years, that high magnitude events of low frequency may be equally important in accomplishing geomorphic work as relatively frequent events of moderate magnitude.

In an attempt to describe the spatial variation of erosion and deposition during flood events, Harvey (1984c) looked at stream channel adjustment produced by a flood with a return interval of 25–100 years on an alluvial fan in a semiarid region in southern Spain. Even with continuous flow from this extreme event, erosion predominated in the proximal areas of the fan (fanhead trench) and deposition took place downfan. It was concluded that the spatial distribution of flow frequency influenced channel differences between the proximal and distal parts of the fan. The fanhead is modified by frequent events while downfan locations are affected only by extreme events. The creation of the Roaring River alluvial fan, formed during a catastrophic flood caused by the failure of a dam in Colorado, further demonstrates the importance of extreme events. However, Blair (1987) also pointed out that postflood, noncatastrophic events significantly modified the fan surface, obscuring evidence of the depositional process primarily responsible for fan formation (sheetflooding).

HISTORICAL ANALYSIS

Research dealing with the historical development of alluvial fans clearly demonstrates continued interest in the alluvial fan problem. The concurrent development and maturity of several dating techniques and sedimentological analyses has been the most important means for attacking this question. Studies of fan evolution fit well with research dealing with dominant depositional processes because progressive change in fan morphology also involves progressive change in the dominant process (Harvey, 1984a).

Wasson (1977a) provided a historical account of the evolution of a group of relict fans in Tasmania by using stratigraphic methods to determine the age of the fans. He suggested controls on their accumulation and dissection by examining changing sedimentary conditions in the drainage basin. Fan construction was associated with debris-flows caused by increased sediment production from periglacial and nivational processes of the last glacial period. Fan dissection occurred as drainage basins were revegetated following deglaciation, causing a decrease in the ratio of sediment yield to discharge.

In a series of papers from research conducted on Spanish alluvial fans, Harvey (1978, 1984a,b) first described their sedimentary and geomorphic characteristics and then identified two main phases of development. These were, first, a fan aggradation phase during a period of net excess sediment supply, and second, a fan dissection phase of net sediment deficiency. He then proposed that fan development reflected long-term progressive change (dynamic equilibrium over cyclic time) complicated by short-term response to climatic fluctuations and spatially variable trenching thresholds (Harvey, 1984b). Harvey (1984a) concluded that the Spanish fans were not equilibrium forms as proposed by Hooke (1968a).

The development of alluvial fans in or near glaciated regions is often strongly controlled by the cyclic alternation of glacial and nonglacial conditions, presenting geomorphologists with a potentially useful method for reconstructing Quaternary history. 'Fan formation continues until the system reaches a quasi-equilibrium condition or the supply of fan sediment is arrested' (Ritter and Ten Brink, 1986:621). In this perspective fans are seen as time-dependent landforms. Similarly, the development of wet-tropical fans is closely related to an episodic sediment supply, in this case, caused by volcanic activity or earthquakes in the source basin (Kesel, 1985).

Rachocki (1981) suggested a model of fan evolution in which fans develop through time until the source area can no longer provide sediment to the fan. The model (his figure 132) is similar to Figure 1.5A showing fan area (a surrogate measure of fan volume) increasing with time at a decreasing rate until fan growth levels off and the depositional landform (Bull, 1977) becomes an erosional surface which decreases in volume.

The establishment of depositional chronologies for fan deposits would be an important step towards construction of an acceptable model of fan development, but dated fan surfaces and knowledge of their associated environmental conditions are rarely available (Cooke and Warren, 1973; Lustig, 1967), particularly in arid regions where organic material for radiocarbon dating is lacking. The stable carbon isotopic analysis of organic matter in rock varnish provides information on the relative aridity of the environment in which varnish is formed, and when used with cation–ratio dating, it can provide a chronology of fan development related to climatic fluctuations (Dorn *et al.*, 1987). Reconstruction of the history of two alluvial fans in Death Valley has led Dorn *et al.* (1987) to identify three aggradation–entrenchment cycles. They concluded that these fans were deposited during humid periods with greater basin vegetation cover and soil development. Climatic change to more arid conditions was thought to have promoted fanhead trenching which was made permanent by the eastward tilting of the Panamint Range. The use of rock varnish has the potential to resolve some of the conflicting interpretations of fan development arrived at by early researchers in the Death Valley region.

The integrated approach to the fan dynamics paradigm has been relatively successful in providing a focus for alluvial fan research. Researchers interested in studying alluvial fans are not yet ready to reject the basic precepts of the fan dynamics paradigm. Instead, the reconciliation of equilibrium and evolutionary approaches has led to the detailed investigation of process with significant attention paid to long-term development.

Alluvial Fans and Fluvial Theory

In reviewing the intellectual history of alluvial fan research it is useful to consider how research on alluvial fans has contributed to theory development in the broader field of geomorphology. Following dissatisfaction with concepts of long-term landform evolution associated with Davis's cycle of erosion, geomorphologists shifted to the smaller temporal and spatial scales of process investigation. In order to describe the direction of research in contemporary fluvial geomorphology, Knighton (1984) emphasized the distinction between empirical and theoretical approaches. The empirical approach is largely inductive and involves establishing relationships between form and process variables obtained from the analysis of field data. Its goals are prediction using a 'black-box' approach rather than explanation of causal process links (Chorley, 1978). Statistical relationships and use of power functions are typical of this mode of inquiry. This approach treats external artifacts that result from the operation of geomorphic systems rather than the systems themselves (Chorley, 1978). The deductive nature of the theoretical approach involves the construction of deterministic and stochastic models. It places more emphasis on explanation than the identification of functional relationships. A 'white-box' approach is used in the detailed investigation of transfers of mass and energy. Deductive reasoning leads to statements that constitute theories (Church and Mark, 1980). Due to the lack of established fluvial theory in geomorphology, ideas have been borrowed from related fields such as hydraulic engineering and then modified for use in geomorphic problem-solving. These theories have their foundation in the laws of chemistry and physics.

Most research on alluvial fans has followed the empirical approach (Beaty, 1963; Bull, 1964b; Denny, 1965; Hooke, 1968a). Bull (1964b) proposed

$$A_f = cA_d^{\,b} \qquad (1.1)$$

to relate characteristics of alluvial fans to characteristics of their drainage basins, by the use of the power function where A_f is fan area, A_d is drainage basin area, and b and c are empirically derived coefficients. The exponent b has been found to be approximately equal to 0.9, while c varies geographically (Denny, 1967; Hooke, 1968a) (Figure 1.2). This relationship represents the correlation between fan and basin geometry. Church and Mark (1980) stated that these relationships are of scientific interest only if they can provide a better understanding of causal mechanisms. Even though such techniques are not deductively rigorous, they may serve as important preliminary steps in the development of geomorphic theories.

Thus, the contribution made by alluvial fan research to the development of fluvial theory has been to provide a preliminary step in theory formulation. This is not surprising in view of the general lack of theory in geomorphology (Knighton, 1984). Fan research has focused on the collection and analysis of empirical data and on the establishment of relationships between variables expressing geomorphic phenomena. The empirical approach is considered a necessary precursor to successful theory formulation since the testing of theoretical models with 'real world' data is required to verify their validity as accurate representations of natural phenomena. Herein lies the value of field research in theory development. Fan research is therefore an ideal example of the field approach in geomorphology.

Although field work has been an essential element in alluvial fan studies, generalizations arrived at empirically are influenced by the selection of one geographic region over another. Graf (1984) concluded that the size of the geomorphic research community has been a major factor influencing spatial bias in geomorphic theory development. By analogy, the smaller size of the alluvial fan research community would be expected to have promoted an even greater spatial bias in the selection of fan field sites. Indeed, this has been the case. Most field sites have been located in the arid and semiarid regions of the American Southwest, namely portions of California, Arizona, and Nevada that lie within the Basin and Range Province. If one identifies the number of publications that emanate from selected field locations, spatial bias in the selection of field sites becomes even more pronounced. For example, W. B. Bull (western Fresno County, California), R. L. Hooke (Death Valley, California), and C. B. Beaty (White Mountains, California and Nevada) have produced a disproportionately large number of publications from research conducted largely in just these three field locations (about 25% of the literature dealing with modern alluvial fans). More importantly, those publications considered as the seminal works in fan research come almost exclusively from the American Southwest.

In spite of recent attempts to study fans in different environments, striking gaps remain in site selection for alluvial fan field research. Review of Nilsen and Moore's (1984) *Bibliography of Alluvial Fan Deposits* (containing over 700 entries) revealed only two references each from the continents of Africa and South America and none from China or Southeast Asia. Language barriers undoubtedly explain part of the apparent spatial bias in field site selection. All too often research in languages other than English goes unnoticed. Efforts are needed to expose English-speaking fan researchers to work done in these other regions. Future investigators might consider selecting field sites in different environments in order to test hypotheses based on previous research in spatially biased localities.

Even though field research has played a predominant role in fan research, the construction of artificial alluvial fans in the laboratory has been attempted by several researchers (Hooke, 1965, 1967, 1968a, 1968b; Weaver and Schumm, 1974; Hooke and Rohrer, 1979; Rachocki, 1981; Schumm *et al.*, 1987) partly because the conditions required for their construction are easily simulated (Schumm, 1977). Processes of erosion, transportation, and deposition on natural alluvial fans can be observed only infrequently; therefore, experimental fans are useful for investigating temporal changes in process operation. Hooke (1968b) recognized the difficulty involved with scaling problems and chose to treat laboratory fans as small fans in their own right instead of as scale models of larger natural fans. His 'similarity of process' approach involved using fans constructed in the laboratory to answer questions of process and morphology posed by the investigation of fans in the field. Data obtained from laboratory fans were qualitative because scaling relationships for sediment transport by streams and debris-flows were not understood sufficiently to permit exact modelling. Hooke and Rohrer (1979) later used laboratory fans to show the effect of discharge and sediment size on fan slope, the effect of sediment size on the magnitude of dominant discharge, and the variation of slope with azimuth. Hooke's 'similarity of process' approach served to enhance the position of geomorphology as a field science because it made laboratory modelling dependent upon information obtained by field observation.

Conclusion

Review of the alluvial fan literature shows that research paradigms provide a useful means for evaluating trends in fan research and the progress made towards resolving the alluvial fan problem. Most research has been accomplished under the paradigm of fan dynamics. The fundamental research question posed by this paradigm addressed the determination of the long-term development of alluvial fans (i.e. the alluvial fan problem). The equilibrium hypothesis soon became the main approach that dealt with the question of fan development. The early assumption of the time-independence of alluvial fans was followed by the recognition that fan variables may fluctuate around a mean condition that changes with time. Investigation of the climatic and tectonic complications of the equilibrium hypothesis also demonstrated the need to incorporate the equilibrium concept in an evolutionary hypothesis. Dissatisfaction with the progress made towards resolution of the alluvial fan problem resulted in an intellectual crisis which was resolved by combining the equilbrium and evolutionary approaches. This integrated approach to the fan dynamics paradigm has attempted to combine the investigation of sedimentary processes on fans in different environments with the historical analysis of fan evolution for the purpose of formulating a general model of fan development.

The contribution made by fan research to the development of fluvial theory has been to establish empirical relationships between fan and basin variables that may be used to verify theoretical models. Field work has been an essential component of fan research; however, generalizations based on evidence gathered from past alluvial fan field sites are likely to be spatially biased. Future research efforts should consider the selection of field sites in different environmental settings. Laboratory fan models have also been used to answer questions of process and morphology derived from the study of fans in the field, and are heavily dependent upon empirical field data.

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