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# Tectonic control of fan size: the importance of spatially variable subsidence rates

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## ABSTRACT

We study the geophysical controls on the size of alluvial fans. Simple relationships between catchment characteristics, sediment yield, subsidence patterns and fan size are developed. As predicting fan size is essentially a conservation of mass problem, our analysis is general, applying to all types of fan landform. The importance of spatially variable subsidence rates has gone largely unrecognized in previous studies of modern fans. Here we stress that the distribution of subsidence rates in the depositional basin is a primary control on relative fan size. Both free coefficients in the oft-cited power-law correlation of fan area and catchment area can be shown to be set primarily by the tectonic setting, taken to include source area uplift rate and the subsidence distribution in the depositional basin. In the case of a steady-state landscape, relative fan size is shown to be independent of both climate and source lithology; only during times of significant departure from steady state can relative fan size be expected to vary with either climate or source lithology. Transients associated with (1) a sudden increase in rock uplift rate, (2) a sudden change in climate and (3) the unroofing of strata with greatly differing erodibilities may produce variation of relative fan areas with both climate and source lithology. Variation of relative fan size with climate or lithology, however, requires that catchment–fan system response to perturbations away from steady state is sensitive to climate and lithology. Neither the strength of transient system responses nor their sensitivity to climate or lithology are known at present. Furthermore, internal feedbacks can significantly dampen any climatic or lithological effect. Thus theoretical considerations of the importance of climatic and lithological variables are inconclusive, but suggest that climatic and lithological effects are probably of secondary importance to tectonic effects. Field data from an unsteady landscape in Owens Valley, California, support and illustrate theoretical predictions regarding tectonic control of fan size. Field data from Owens Valley allow, but do not prove, a secondary dependence on source lithology. In addition, the Owens Valley field data indicate no relationship between relative fan size and climate. Headward catchment growth and enhanced sediment bypassing of fans during times of increased sediment yield (glacial) are put forward as plausible explanations.

## INTRODUCTION

### The problem

Fans have been heralded as sensitive indicators of climatic fluctuations and neotectonic activity and their deposits as indicators of movement on basin-bounding faults, palaeogeography and even palaeoclimate. For these reasons, there has been great interest in exploring the relationships between the size of modern fans and such environmental variables as climate, source lithology and tectonic setting (Bull, 1964; Denny, 1965; Lustig, 1965; Hooke, 1968, 1972; Hooke & Rohrer, 1977; Harvey, 1984; Lecce, 1991; Jansson *et al.*, 1993; Ritter *et al.*, 1995). Studies of controls on the relative size of modern fans have direct relevance to the problem of progradation of clastic wedges often approached from a stratigraphic perspective (e.g. Paola *et al.*, 1992; Gordon & Heller, 1993).

Power-law correlations between fan area ($A_f$ [m2]) and catchment area ($A_d$ [m2]),

$$A_f = cA_d^n \tag{1}$$

have been reported for modern fans in many field sites, covering diverse geological and climatic settings. Compilations of available data have been published elsewhere and are included in most textbooks covering the topic of alluvial fan geomorphology ( Hooke, 1968; Bull, 1977; Lecce, 1990). A wide range values of both the coefficient (c) and the exponent ($n$) in Eq. (1) have been reported. This variability is usually ascribed to some combination of climatic, lithological and tectonic factors (e.g. Bull, 1964; Hunt & Mabey, 1966; Hooke & Rohrer, 1977; Lecce, 1991; Ritter *et al.,* 1995). However, a general, process-based statement of the linkages between catchment characteristics (climate, lithology, rock uplift rate), sediment yield ($Q_s$ [m3 yr$^{-1}$]), volumetric rate of fan deposition ($V_f$ [m3 yr$^{-1}$]), rates and patterns of basin subsidence ($\sigma$ [m yr$^{-1}$]), and fan size ($A_f$) is lacking. In particular, the role of differential rates and patterns of subsidence has not been clearly elucidated in the literature on modern fans.

Gordon & Heller (1993) highlight the need for a quantitative assessment of how and why $c$ and $n$ values (Eq. 1) reflect the physical environment of a fan. Their study emphasizes the profound importance of the distribution and rate of subsidence in determining the extent of gravel (i.e. fan) progradation. Gordon & Heller (1993) comment that they are surprised that fan area and catchment area should have a simple power-law relationship (Eq. 1) for the simple reason that the fundamental relationship should be between catchment area and fan volume (more precisely the volumetric rate of fan deposition; Hooke, 1968), not fan area. They further suggest that differences in subsidence may explain much of the variability recorded in modern fans. Gordon & Heller's insightful comment is borne out in our analysis of the controls on fan size. It will be shown that straightforward consideration of mass conservation in fan–catchment systems, and distribution of that mass in depositional basins according to the distribution of subsidence rates, is capable of reconciling apparent disagreements in the literature regarding the relative roles of tectonic, lithological and climatic conditions (e.g. Bull, 1964, 72; Hunt & Mabey, 1966; Hooke & Rohrer, 1977; Lecce, 1991; Gordon & Heller, 1993; Ritter *et al.,* 1995).

## Approach and scope

We present a theoretical analysis of the controls on fan size. We consider fan size as the end product of a simple mass-balance involving the production of sediment, the deposition (or nondeposition) of sediment on fans and the distribution of mass in a subsiding basin. The treatment is general and applies to all types of fan landform, regardless of geological and climatic setting. We consider an idealized landscape consisting of a mountain block subjected to a spatially uniform uplift rate ($U_r$ [m yr$^{-1}$]) separated by a fault from a depositional basin experiencing steady but spatially variable subsidence ($\sigma$). Both steady-state and disequilibrium landscapes are considered. Here 'steady state' implies that two conditions hold: (1) uplift is balanced by erosion in the source area and (2) subsidence is balanced by deposition in the basin. The discussion on nonsteady-state landscapes focuses primarily on circumstances in which the former condition is not satisfied. Short-term fluctuations in sedimentation rate that may invalidate the latter condition are considered briefly.

The cornerstone of the analysis is a set of simple equations describing the relationships between catchment characteristics, sediment yield, subsidence patterns and fan size. We subdivide the analysis into two parts: (1) the relationship between catchment characteristics, sediment yield and the volumetric rate of fan deposition ($V_f$), and (2) the relationship between $V_f$ and fan area ($A_f$). The latter is governed by the distribution of subsidence and will be shown to have a profound influence on fan area – catchment area relationships. The results of this theoretical analysis are supported and illustrated by new field data from Owens Valley, California (Fig. 1). In addition, well-known data sets from the literature are discussed.

# RELATIONSHIPS FOR SEDIMENT YIELD AND FAN AREA

## Sediment yield and the volumetric rate of fan deposition

We assert that the fundamental reason for a correlation between fan area ($A_f$) and catchment area ($A_d$) is that sediment yield ($Q_s$) increases monotonically with catchment area:

$$Q_s = \bar{\varepsilon}(1-\lambda_r)A_d, \tag{2}$$

where $\bar{\varepsilon}$ denotes the spatially averaged erosion rate (m yr$^{-1}$) and $\lambda_r$ denotes rock porosity. Note that in principle $\bar{\varepsilon}$ may vary with climate, lithology, catchment area and relief. In many landscapes, specific sediment yield ($Q'_s$ [m yr$^{-1}$]) is found to be a function of catchment area,

$$Q'_s = Q_s/A_d = \bar{\varepsilon}(1-\lambda_r) = f(A_d), \tag{3}$$

with specific sediment yield diminishing with increased catchment area as hillslope gradients decline, valleys widen and sediment storage increases (Church *et al.,* 1988). However, in many mountainous areas, the steep, rugged catchments supplying debris to alluvial fans have narrow valley floors and negligible amounts of sediment storage – diminishing specific sediment yield with catchment area is unlikely to be an important factor. We restrict our discussion to fans derived from this type of steep, mountainous catchment where the assumption that $\bar{\varepsilon}$ does not vary with drainage area is valid. Channels are assumed to be bedrock controlled, with only minor alluvial reaches above the fan apex.

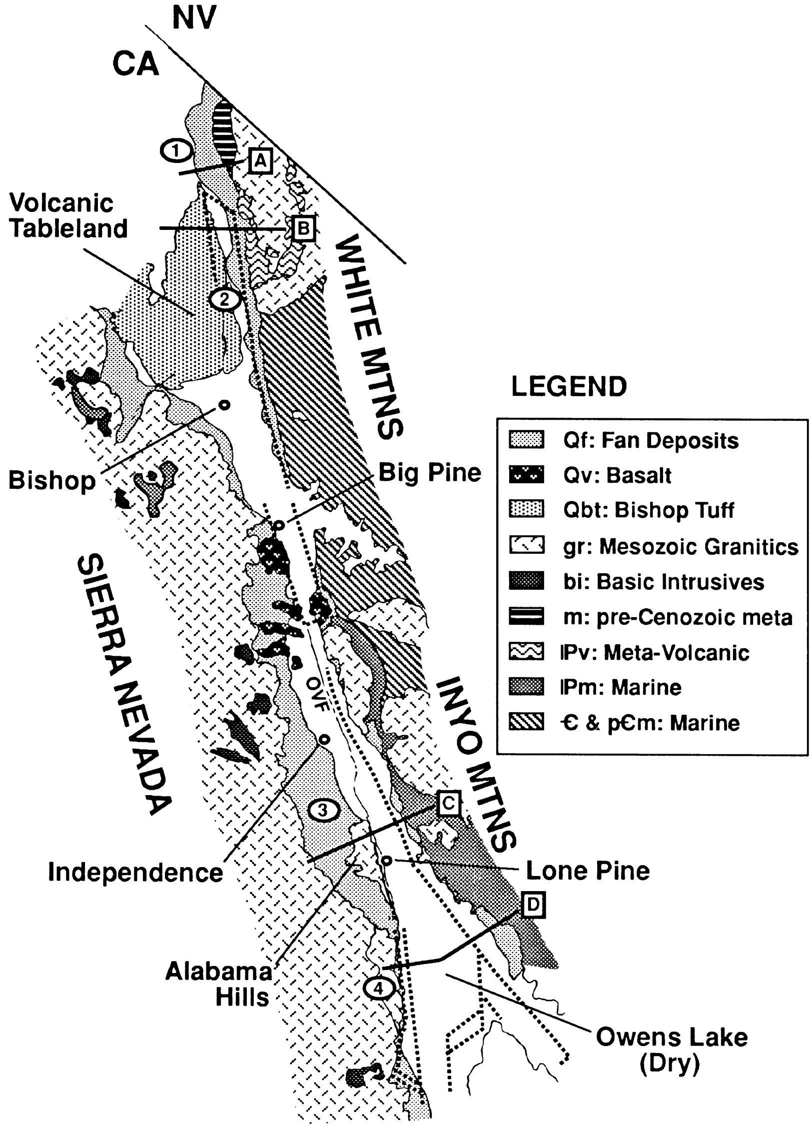


**Fig. 1.** Simplified geological map of Owens Valley, California. Major graben-bounding faults, inferred from gravity data, are shown as heavy dotted lines (Pakiser *et al.*, 1964). Surface trace of Owens Valley Fault (OVF) shown as solid, broken line. Fan groups studied indicated by number (1–4): (1) northern White Mountains (NWM); (2) southern White Mountains (SWM); (3) western bajada (WB); and (4) Owens Lake (OL). Gravity profiles (A–D) indicated.

*Steady state*

In a steady-state landscape subjected to a uniform rock uplift rate, surface erosion rate ($\varepsilon$) is everywhere equal within the uplifted source area. The linkages between the steady-state erosion rate and catchment properties are usefully illustrated in terms of the erosion of bedrock channels. Since erosion rate is uniform, it is sufficient to consider the local channel lowering rate at the catchment outlet. Moreover, in nonsteady-state landscapes (discussed below) the channel lowering rate sets the local base level for the entire catchment. The erosion rate at the catchment outlet ($\varepsilon_{dh}$) is set by the erodibility of the rock ($k_r$), the erosivity of the climate ($k_c$), the drainage area ($A_d$) and the local channel gradient ($S_d$):

$$\varepsilon_{dh} = k_c k_r A_d^p S_d^q, \tag{4}$$

where $p$ and $q$ are constants and the units of $k_r$ and $k_c$ depend on the exponent $p$ (Howard & Kerby, 1983; Seidl & Dietrich, 1992; Howard *et al.*, 1994). Note that Eq. (4) is not inconsistent with the assumption that $\bar{\varepsilon}$ does not vary with drainage area, rather it implies a mutual adjustment of drainage area ($A_d$) and slope ($S_d$). Erodibility ($k_r$) is assumed to vary with lithology and erosivity ($k_c$) with runoff, extent of glaciation or the magnitude and frequency of debris-flow scouring events, depending on climatic and physiographic conditions. Both the coefficients ($k_r$ and $k_c$) and exponents ($p$ and $q$) in this generalized erosion law are poorly constrained at present and almost certainly vary with process (e.g. fluvial incision, glacial erosion or debris-flow scour).

In the steady state, erosion rate is uniform within the catchment ($\bar{\varepsilon} = \varepsilon_{dh}$) and the volume rate of the removal of rock from the source drainage per unit time (sediment yield, $Q_s$) is equal to the product of the rate of incision of the trunk stream and the drainage area. Combining Eqs. (2) and (4) gives

$$Q_{se} = \bar{\varepsilon}(1-\lambda_r)A_d = k_r k_c (1-\lambda_r) A_d^{p+1} S_d^q, \tag{5}$$

where $Q_{se}$ denotes the sediment yield at steady state. Thus, at first glance there appears to be a simple and direct relationship between sediment yield and source lithology and climate. However, as mentioned above, channel gradient ($S_d$) is not an independent variable.

In a steady-state landscape an additional constraint can be placed on the problem: average surface erosion rate (or exhumation rate) ($\bar{\varepsilon}$) must exactly balance the rock uplift rate ($U_r$) (Molnar & England, 1990). Substituting this condition ($\varepsilon_{dh} = \bar{\varepsilon} = U_r$) into Eq. (4) gives

$$S_d = \frac{U_r}{k_r k_c} A_d^{-p}. \tag{6}$$

Substituting Eq. (6) into (5) we find that

$$Q_{se} = U_r(1-\lambda_r)A_d. \tag{7}$$

Thus for a steady-state landscape with bedrock channels we have the simple result that equilibrium sediment yield varies directly with catchment area ($A_d$) and uplift rate ($U_r$). Besides a weak lithological dependence associated with different rock porosities, specific sediment yield is set by the rock uplift rate. In a steady-state landscape climatic and lithological differences between catchments will be reflected in catchment physiography (e.g. Kooi & Beaumont, 1994), but not specific sediment yield.

### *Departures from steady state*

Only under unsteady conditions does the potential for lithological and climatic control of specific sediment yield arise. However, departures from steady state are common in the landscape, and their durations may be long compared with the response time-scale of fans (e.g. Ritter *et al.*, 1995). The potential for a lithological or climatic signal in relative fan areas lies in the system's response to large perturbations from the base steady-state condition, such as a dramatic increase in rock uplift rate, a sudden change in climate or the unroofing of strata with significantly different erodibilities. In all cases the system will move towards re-establishing equilibrium through adjustments of catchment physiography (e.g. Adams, 1980).

We postulate that the sensitivity of the catchment–fan system to perturbations away from steady state may be a function of climate and source lithology: both the response time-scale of catchment physiography and the total amount of physiographic adjustment necessary to re-establish equilibrium may depend on climate and source lithology. We parameterize system response during transients with a hypothetical nondimensional response function ($\beta(t)$) and present speculative sediment yield curves to illustrate how differences in lithology and climate might influence fan area – catchment area relationships. We stress that the form of $\beta(t)$ and its sensitivity to climate and lithology are unknown at present. It is possible that $\beta(t)$ is not a function of either climate or lithology. The salient point in the following arguments is that climate and lithology can only influence fan area – catchment area relationships through variations in $\beta(t)$ of the type we describe. Numerical simulations of landscape evolution such as those presented by Tucker & Slingerland (1996) show promise for developing quantitative insights into the nature of $\beta(t)$, the catchment response function.

Two restrictive conditions were imposed in the derivation of Eq. (7), which gives $Q_{se}$ as a function of rock uplift rate ($U_r$), rock porosity ($\lambda_r$) and drainage area ($A_d$): (1) that the erosion rate is everywhere equal to the rock uplift rate and (2) that the trunk stream had an equilibrium profile as prescribed by Eq. (6). The former assumption is the most restrictive. Channel profiles should recover first from perturbations away from the base steady-state condition, with adjustments in hillslope profiles lagging channel response significantly. Below we assume this to be the case and consider variations in sediment yield during the interval between adjustment of bedrock channels and the eventual adjustment of catchment physiography. This facilitates a simple definition of $\beta(t)$, the catchment response function.

During perturbations away from steady state the condition that erosion rate is everywhere equal is not satisfied ($\bar{\varepsilon} \neq \varepsilon_{dh}$). The resulting imbalance can be parameterized as

$$\bar{\varepsilon} = \beta(t)\varepsilon_{dh}, \tag{8}$$

where $\beta(t)$ is assumed to vary with climate and lithology. In principle, the average erosion rate could vary as a power of channel erosion rate, but since so little is known about the form of $\beta(t)$, that additional complexity is unwarranted at this time. Combining Eqs (2), (4), (6) and (8) yields a simple expression for sediment yield during excursions from steady state ($Q_{st}$):

$$Q_{st} = \beta(t)U_r(t)\,(1-\lambda_r)A_d. \tag{9}$$

Substituting Eq. (7) into (9) gives

$$Q_{st} = \beta(t)\,\frac{U_r(t)}{U_r}\,Q_{se}. \tag{10}$$

Equations (9) and (10) are strictly only valid during the post-channel-adjustment interval when Eqs (4) and (6) apply. However, $\beta(t)$ may be generalized to incorporate the early stages of channel adjustment as is done below.

Figure 2 schematically illustrates probable forms of the generalized $\beta(t)$. That is, Fig. 2 illustrates probable responses in specific sediment yield to hypothesized changes in rock uplift rate, climate and lithology (i.e. due to progressive unroofing of a stratigraphic sequence). Figure 2(A) illustrates the differential response of two catchments to the same step function increase in rock uplift rate. A catchment that is either subjected to a more 'erosive' climate, or rests on less resistant rock units (solid curve) is hypothesized to undergo a brief, intense phase of increased sediment yield, returning to equilibrium faster than a neighbouring catchment subjected to a less 'erosive' climate or cut into more resistant rock units (dashed curve). Thus, for a time, an enhanced specific sediment yield is expected from the more erodible rock units, or under the more 'erosive' climate. However, sediment yields rapidly return to equilibrium levels

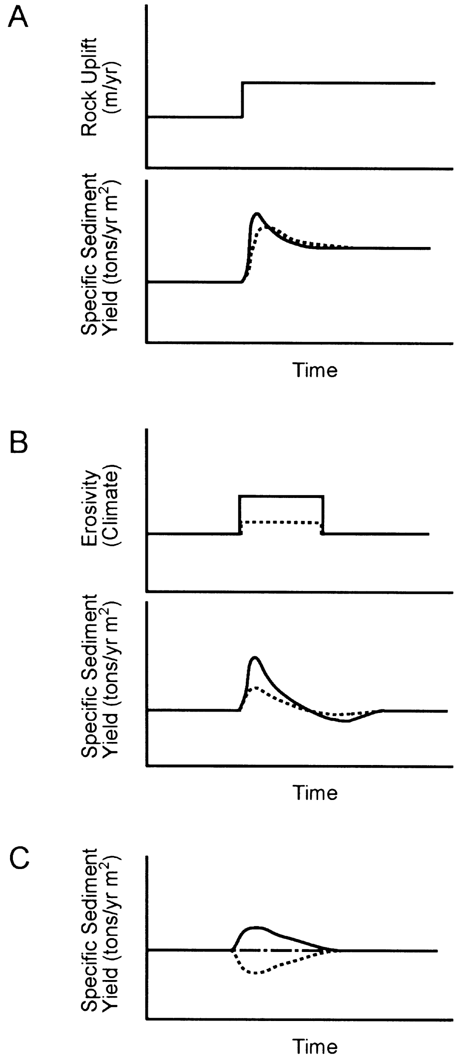


**Fig. 2.** Schematic illustration of sediment yield responses to perturbations from steady state. A. Step function increase in rock uplift rate. Solid line – erodible rock type or a more 'erosive' climate; dashed line – resistant rock type or a less 'erosive' climate. B. Pulsed increase in 'erosivity' (glaciation). Solid line – glaciated catchments; dashed line – unglaciated catchments. C. Unroofing of strata with markedly different erodibilities (uplift rate and climate assumed constant). Solid line – exposure of weaker rock; dashed line – exposure of more resistant rock.

(Fig. 2; Schumm & Rea, 1995) and it is possible that the sediment yield curves will cross, effectively reversing the 'normal' lithological or climatic signal. This reversal can occur if and only if the more responsive catchment re-establishes equilibrium in a shorter time, as illustrated in Fig. 2(A).

Figure 2(B) illustrates the response of two catchments subjected to a sudden change in climatic regime, but where the intensity of this change is greater in one catchment than the other. This scenario is presented as analogous to the response of glaciated and unglaciated catchments to a glacial cycle. The hypothetical response in specific sediment yield is similar to that illustrated in Fig. 2(A), and a similar cross-over is anticipated. Note that sediment yield is predicted to drop below equilibrium levels when the climate returns to 'normal' at the end of the glacial cycle. The hypothesized oscillation in specific sediment yield may explain the episodic aggradation of fans characteristic of glaciated areas during the Quaternary (e.g. Ritter *et al.,* 1995). Finally, Fig. 2(C) illustrates the probable pattern of specific sediment yield response to the unroofing of strata of either higher or lower erodibilities, assuming constant uplift and climate. Again, a transient increase in specific sediment yield following the exposure of weaker units is anticipated.

*Internal feedbacks and the volumetric rate of fan deposition*

Whether or not lithology- or climate-driven differences in specific sediment yield are translated into measurable differences in relative fan size depends in part on the efficacy of internal feedbacks which can act to dampen the relationship between sediment yield and the volumetric rate of fan deposition. An obvious feedback mechanism is the possible headward growth of drainages and the expansion of catchment areas. Catchments cut into more erodible lithologies, or subjected to a more erosive climate, may produce more sediment during excursions away from steady state (Eq. 10). However, this increase in sediment flux may be accompanied by an increase in catchment area, with important implications for *relative* fan areas.

A more subtle, but potentially important, internal feedback mechanism is associated with the partitioning of sediment between the fan and the valley floor. The effect of this partitioning can be quantified in a simple way as a dimensionless 'trap efficiency factor' ($E_t$). Trap efficiency ($E_t$) varies between 0 and 1, and is simply defined as the fraction of the total sediment yield that is deposited on fans:

$$V_f = E_t \left( \frac{1}{1-\lambda_s} \right) Q_s, \tag{11}$$

where $\lambda_s$ is the porosity of the fan sediments, and $V_f$ is the volumetric rate of fan deposition. The role of trap efficiency ($E_t$) is analogous to that of the proportion of sediment flux that is 'gravel' in the basin fill model of Paola *et al.* (1992). Paola *et al.* (1992), however, purposefully do not consider possible interrelationships (e.g. the feedback mechanisms) between variables in their model. In addition to possible interdependencies between $E_t$ and climate or lithology, trap efficiency may be a function of catchment area, with trap efficiency declining with catchment size (Hooke & Rohrer, 1977):

$$V_f = E_{to} A_d^{-r} \left( \frac{1}{1-\lambda_s} \right) Q_s, \tag{12}$$

where $E_{to}$ is the trap efficiency of a 1-km2 catchment, and $r$ is a constant which, in principle, may vary with process (e.g. debris-flow vs. fluviatile transport). Empirical evidence suggests that $E_t$ is only a weak function of $A_d$, with $r$ taking a narrow range of values between 0.0 and 0.2 (Hooke, 1968; Hooke & Rohrer, 1977; Jansson *et al.*, 1993).

Trap efficiency is largely determined by two factors: (1) the grain-size distribution of the source regolith and (2) fan depositional processes. As such, lithology, climate and tectonic setting all have important effects. Both $E_{to}$ and the exponent ($r$) may vary during departures from steady state. Temporal variations in trap efficiency ($E_t$) in response to climatic change have been discussed by Harvey (1984). Both positive and negative correlations between trap efficiency and other lithological and climatic factors ($k_r$ and $k_c$) are possible, resulting in either positive or negative feedback. For instance, enhanced erodibility is sometimes associated with increased regolith fines content (erodible volcanic terranes) and sometimes with decreased regolith fines content (weakly indurated coarse clastic sedimentary rock or highly fractured but well-indurated sedimentary rocks). Similarly, increased sediment yields from glaciated basins might be negated by decreased trap efficiency associated with sustained higher stream discharges. Moreover, as discussed below, reduced trap efficiencies imply enhanced rates of valley floor deposition, with important consequences for fan area – catchment area relations in closed basins (Hooke, 1968; Jansson *et al.*, 1993).

### *Summary*

The volumetric rate of fan deposition is primarily controlled by the tectonic setting, more specifically by the rock uplift rate. Tectonic control is most direct in a steady-state landscape, where specific sediment yield must balance rock uplift (Adams, 1980; Molnar & England, 1990). Secondary variations associated with source lithology and climate can arise in both steady-state and disequilibrium landscapes, but their magnitudes and possibly signs will be different. Combining Eqs (7) and (12) reveals that, in a steady-state landscape, lithological and climatic influences are only felt through the trap efficiency factor ($E_{to}$, $r$):

$$V_f = E_{to}\left(\frac{1-\lambda_r}{1-\lambda_s}\right) U_r A_d^{1-r}. \tag{13}$$

Conversely, during transients associated with sudden changes in uplift rates, climate or lithological erodibility, lithology and climate may directly influence specific sediment yield (Fig. 2). Combining Eqs (9) and (12) for unsteady conditions gives

$$V_f = \beta(t) E_{to}(t)\left(\frac{1-\lambda_r}{1-\lambda_s}\right) U_r(t) A_d^{1-r'}, \tag{14}$$

where $E_{to}(t)$ and $r'$ may be different than their steady-state values. In this case, the trap efficiency factor may act as either a positive or negative feedback.

## Basin structure, subsidence patterns and fan size

Depositional surfaces tend towards a condition of equilibrium in which the mean rate of net surface aggradation relative to a fixed horizontal datum is everywhere approximately equal (Hooke, 1968; Paola *et al.*, 1992):

$$\frac{\partial \eta(x, y)}{\partial t} = \dot{z}(x, y) - \sigma(x, y) \approx k, \tag{15}$$

where $x$ and $y$ are the cross- and down-valley coordinates, $\eta$ is surface elevation, $\dot{z}$ is the deposition rate, $\sigma$ is the subsidence rate and $k$ is a constant equal to zero in a steady-state landscape. Regardless of whether the valley floor is experiencing net deflation ($k<0$) or net aggradation ($k>0$), averaged over long time, local sedimentation rate varies with local subsidence rate (Paola *et al.*, 1992; Gordon & Heller, 1993). For the purpose of simplicity, in the following discussion we will assume that the condition $k=0$ is approximately satisfied. However, it should be noted that pulses of accelerated erosion (e.g. Fig. 2) may cause sedimentation to temporarily out-pace background subsidence rates, potentially enhancing climatic or lithological control of relative fan areas in the short term (e.g. Ritter *et al.*, 1995).

As first described by Hooke (1968) for the restricted case of uniform subsidence, the long-term tendency towards equilibrium dictates that fan size ($A_f$) be set by $V_f$, the volumetric rate of fan deposition, and $\dot{z}_p$ ($\sim\sigma_p$), the rate of playa or valley floor deposition. In the sections below we first review the condition of uniform subsidence discussed by Hooke (1968), and then generalize the arguments to idealized but common nonuniform subsidence patterns. The form of the relationship between $A_f$ and $V_f$ will be shown to be governed by the distribution and rate of subsidence in the depositional basin.

### *Uniform subsidence: simple graben*

Consider a complex of coalescing fans building into a simple graben experiencing uniform subsidence (Fig. 3A). Fan area ($A_f$) is set by the net volume of sediment deposited on the fan per unit time ($V_f$) and the mean deposition rate on the valley floor ($\dot{z}_p$):

$$A_f = \frac{1}{\dot{z}_p} V_f, \tag{16}$$

where sedimentation rate just balances subsidence in a steady-state landscape (Fig. 4A; Hooke, 1968, 1972; Jansson *et al.*, 1993). Note that in a closed basin, the valley floor sedimentation rate is set by the area of the valley floor and the total contribution of sediment to the valley floor from surrounding catchments (Jansson *et al.*, 1993). In other words, $\dot{z}_p$ is not independent of $V_f$ in closed basins. This relationship constitutes another internal feedback mechanism. However, in open basins, or in closed basins with complex internal structure, the local $\dot{z}_p$ may be largely independent of the local $V_f$. For

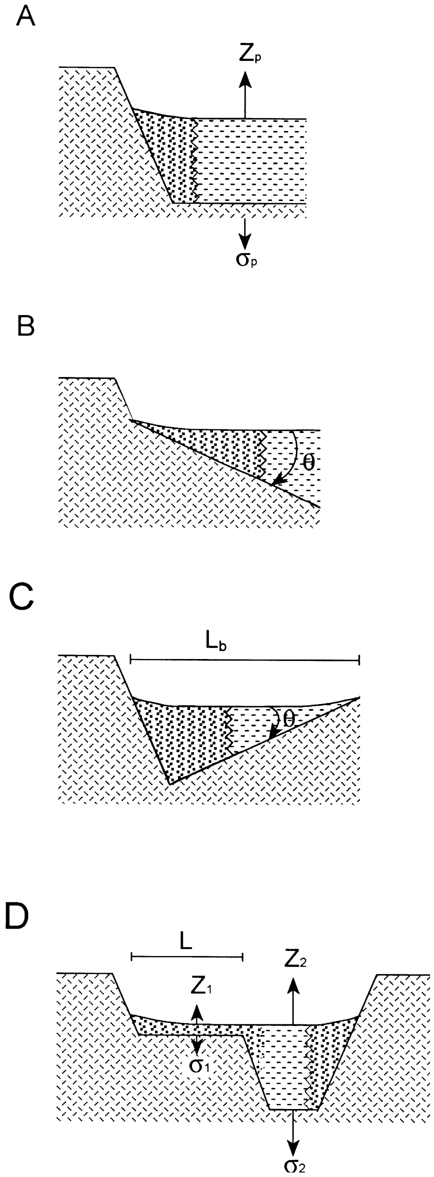


**Fig. 3.** Idealized basin structures. A. Simple graben – uniform subsidence ($\sigma_p \sim \dot{z}_p$). B. Half-graben tilt block (deposition from left). Angular rate of tilting (θ) shown. C. Simplified foredeep basin: linear decrease in subsidence away from range front. Angular rate of tilting (θ) and basin length ($L_b$) are shown. D. Complex graben – nonuniform subsidence. Z and σ are sedimentation and subsidence rates, respectively. Subscripts 1 and 2 refer to the fault block on the left and right, respectively. Width of the fault block on the left (L) is indicated.

simplicity we will assume independence of $V_f$ and the background rate of deposition ($\dot{z}_p$), which is the general case.

Substituting Eqs (13) and (16) into Eq. (1) ($A_f = cA_d^n$) yields explicit expressions for $c$ and $n$ values for steady-state landscapes:

$$c = \frac{E_{to}}{\dot{z}_p}\left(\frac{1-\lambda_r}{1-\lambda_s}\right) U_r, \tag{17a}$$

$$n = 1 - r. \tag{17b}$$

Similarly, substituting Eqs (14) and (16) into Eq. (1) gives, for nonsteady-state landscapes,

$$c = \frac{\beta(t) E_{to}(t)}{\dot{z}_p}\left(\frac{1-\lambda_r}{1-\lambda_s}\right) U_r(t), \tag{18a}$$

$$n = 1 - r'. \tag{18b}$$

Thus in the special case of uniform subsidence, tectonic, lithological and climatic influences on the volumetric rate of fan deposition (Eqs 13 and 14) directly affect the relationship between fan area and catchment area. Note that exponents close to unity ($0.0 < r < 0.2$) are expected in this environment for both steady and unsteady landscapes (Hooke, 1968; Jansson *et al.*, 1993).

### *Nonuniform subsidence 1: half graben*

Consider a complex of coalescing fans building into a laterally uniform half-graben. Subsidence varies only in the $x$-direction (perpendicular to the range front), with the subsidence rate increasing linearly away from the range front (Fig. 3B). In this case, fan area ($A_f$) increases nonlinearly with the volumetric rate of fan deposition ($V_f$):

$$A_f = \left[\frac{W_f}{\tan\theta}\right]^{1/2} V_f^{1/2}, \tag{19}$$

where $W_f$ is fan width (set by valley spacing and lateral competition between fans) and θ is the angular rate of fault-block rotation (Figs 3B and 4A). Clearly, the simple half graben structure has a marked influence on expected $c$ and $n$ values (compare Eqs 19 and 16; Fig. 4A). For example, substituting Eqs (13) and (19) into (1) gives, for steady-state,

$$c = \left[\frac{E_{to} W_f}{\tan\theta}\left(\frac{1-\lambda_r}{1-\lambda_s}\right) U_r\right]^{1/2}, \tag{20a}$$

$$n = 1/2(1-r). \tag{20b}$$

### *Nonuniform subsidence 2: foredeep basin*

In the case of an idealized foredeep basin in which subsidence is uniform in the down-valley direction, but decreases linearly with distance from the range front (Fig. 3C), fan area ($A_f$) again increases nonlinearly with the volumetric rate of fan deposition ($V_f$):

$$A_f = \frac{-L_b \tan\theta \pm \sqrt{L_b^2 \tan^2\theta - (4\tan\theta / W_f) V_f}}{-2\tan\theta / W_f}, \tag{21}$$

where $L_b$ is the distance from the range front to the hinge point (Fig. 3C). Again $c$ and $n$ values in Eq. (1) fitted by regression through field data obtained in a 'foredeep basin' setting will be strongly influenced by the subsidence pattern, with, in this case, $n$ values greater than unity expected (Fig. 4A). The strength of the tectonic control in both half graben and foredeep basins

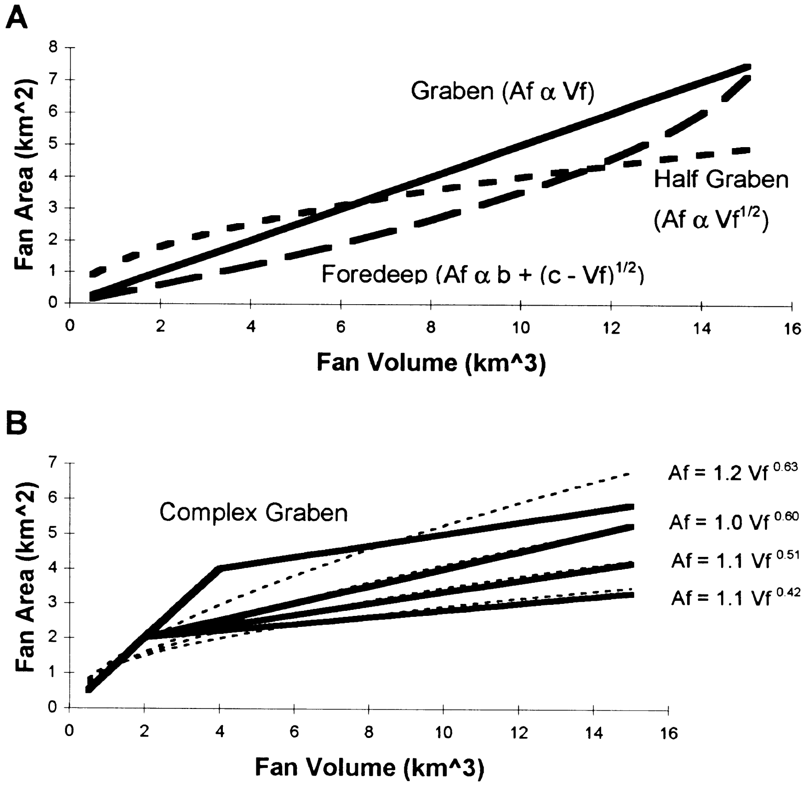


**Fig. 4.** Schematic illustration of fan area – volume (per unit time) relationships. A. Relationships derived in text for the simple graben, half-graben and foredeep structures illustrated in Fig. 3. B. Fan area relationships for the complex graben structure (heavy lines) (Fig. 3D). Power-law fits (thin dashed lines) are shown to highlight the relationship between c and n values and various combinations of L and the ratio $Z_1/Z_2$

is such that any lithological or climatic influences (through β(*t*), the catchment response function) are likely to be overwhelmed.

*Nonuniform subsidence 3: complex graben*

The dependence of relative fan sizes on tectonic setting is particularly profound in settings where fans build across major geophysical structures – across sudden changes in subsidence rate. Complex grabens are one such setting, and are common in extensional basins. Consider the simple hypothetical basin illustrated in Fig. 3(D). Where the rate of sediment delivery to the fans is small, such that the condition

$$V_f < \dot{z}_1 L W_f, \qquad (22)$$

(where $L$ is the length of the bedrock bench and the subscript 1 refers to values for the left-hand side, and 2 to values for the right-hand side, of the basin in Fig. 3D) holds, then the exponent in Eq. (1) is independent of subsidence rate ($n_1 = n_2$) and $c$ is directly dependent on sedimentation rate (Eq. 16; $c_1 = V_f/\dot{z}_1 > c_2 = V_f/\dot{z}_2$). However, where sediment delivery to some fans is large, such that

$$V_f > \dot{z}_1 L W_f, \qquad (23)$$

then both $c_1$ and $n_1$ (assuming an equation of the form of (1) is fit to field data) are dependent on $L$, $\dot{z}_1$ and $\dot{z}_2$ (Fig. 4B). To date, analytical expressions for the parameters $c$ and $n$ have not been found for this structural configuration. However, it can be seen that for smaller ratios of fan to valley floor sedimentation rate ($\dot{z}_1/\dot{z}_2$), $n$ decreases and $c$ increases (Fig. 4B).

## Summary

The fundamental implication of the preceding analysis is that in any tectonic setting where subsidence is nonuniform, relative fan sizes are largely controlled by the spatial distribution of subsidence rates and bear little direct relation to the physical characteristics of the source area. Fan area – drainage area relationships of the form ($A_f = cA_d^n$) must be considered in the context of local tectonic setting. Moreover, in all cases relative fan sizes are primarily controlled by the combination of rock uplift rate and basin subsidence. Lithological and climatic influences are second-order effects, are strongest during transients associated with sudden changes in rock uplift rate, climate (e.g. Ritter *et al.,* 1995) or source lithology, and may be damped by internal feedback mechanisms. Lithological and climatic effects can be expected to be most important in basins experiencing spatially uniform subsidence.

# FIELD EVIDENCE

## Motivation and approach

We have shown that climate and lithology could have opposite effects on fan area – catchment area relationships, depending on (1) whether the system is in steady state, (2) the time elapsed since the system was last perturbed away from steady state and (3) the operation of internal feedback mechanisms associated with either catchment growth or the trap efficiency factor ($E_t$). Unfortunately neither the magnitudes of the hypothesized transients in specific sediment yield associated with departures from steady state (Fig. 2) nor the strength of the internal feedback mechanisms are quantitatively understood at present. Field data are required for evaluation of the relative roles of climate and lithology in setting relative fan sizes.

Extensive bajadas (piedmonts of coalescing fans) of coalescing debris-flow fans occur in places on both sides of Owens Valley and along the full length of the valley (Fig. 1). Great variability in fan size with geographical position is obvious on Fig. 1. Associated with the range of debris-flow fan properties in Owens Valley is a wide range of lithological, climatic and tectonic conditions including: (1) granitic, metasedimentary, and metavolcanic rock types (Fig. 1), (2) a strong west–east precipitation gradient in the Sierra Nevada rain shadow (Bierman *et al.*, 1991), (3) both glaciated (Late Pleistocene) and unglaciated drainages (Gillespie, 1982; Bierman *et al.*, 1991) and (4) spatially variable subsidence rates (Pakiser *et al.*, 1964; Hollett *et al.*, 1989). We capitalize on this diversity of field conditions to isolate and evaluate the effects of lithological, climatic and tectonic differences on the size of fans. Late Quaternary climatic fluctuations and variable tectonic rates in the rapidly evolving Owens Valley argue against a steady-state condition in this field area (Gillespie, 1982; Chase & Wallace, 1988; Bierman *et al.*, 1991).

## Methodology

Four fan groups in Owens Valley were chosen for quantitative analysis. These include, from north to south, the northern White Mountains (NWM), southern White Mountains (SWM), western bajada (WB) and Owens Lake (OL) fan groups (Fig. 1). Data used in the analysis were obtained from topographic, geological and gravity maps of each study site. Fan and catchment sizes were measured on 1 : 24 000-scale US Geological Survey topographic maps with aid of a digitizer. Aerial photographs were used to help in delimiting boundaries between coalescing fans. Delimited fan areas include in all cases both the modern, active fan and any abandoned fan segments, in keeping with our interest in the long-term interplay of sediment supply rate and tectonic setting.

An additional suite of measurements were made to characterize source basin lithology, climatic setting and long-term sedimentation rates. Source lithology was classified on the basis of information on 1 : 24 000-scale and 1 : 250 000-scale geological maps (Matthews & Burnett, 1965; Nelson, 1966a,b; Strand, 1967; Crowder *et al.*, 1972; Crowder & Sheridan, 1972; Streitz & Stinson, 1977) ( Table 1). Differences in climatic setting were assessed on the basis of: (1) modern precipitation records (Rantz, 1969) and (2) morphological indicators of the degree of source area glaciation.

Spatial variation in relative long-term sedimentation rate (and therefore subsidence rate) was assessed from local differences in the total depth of low-density alluvial fill, as inferred from published gravity data (Pakiser *et al.*, 1964; Hunt & Mabey, 1966; Chapman *et al.*, 1973; Oliver & Robbins, 1978; Oliver & Robbins, 1982). Precise determination of fill depths is not warranted because it is not possible at present to determine accurately the timing of opening and deepening of the various structures comprising the Owens Valley graben. We assume that the evolution of these structures has been relatively continuous and contemporaneous such that relative long-term sedimentation rates are faithfully reflected in the relative magnitudes of total fill depth. Previous studies have demonstrated that interpretations based on the regional gravity data sets cited above are consistent with both newer, more densely sampled gravity data and shallow seismic data (Pakiser *et al.*, 1964; Serpa *et al.*, 1988; Keener *et al.*, 1993).

Gravity models for representative cross-sections through the various structural blocks which comprise the Owens Valley graben were fit with aid of a two-dimensional computer algorithm (Fig. 5). Following Pakiser *et al.* (1964) and Keener *et al.* (1993) an estimated density contrast of 0.4 g $cm^{-3}$ was assumed in all cases, except in the deep graben beneath Owens Lake, where particularly fine-grained sediments are deposited. Here a density contrast of 0.5 g $cm^{-3}$ was assumed (Pakiser *et al.*, 1964).

For analysis, fans in the four fan groups studied were classified according to their geological, climatic and tectonic setting. Lithological assemblages in each basin were classified on the basis of broadly defined lithotypes only (granitics, metavolcanics and metasedimentary rocks). Fans derived from basins with more than 70% outcrop in a given rock type were considered monolithological; others were simply considered 'mixed'. The 'mixed' classification in all cases represents a combination of granitic, metasedimentary, and metavolcanic rock types. Tectonic setting was simply classified as one of either 'low' ($<1$ km fill) or 'high' ($>2$ km fill) subsidence rate, and either a 'simple' or 'complex' graben structure. Climatic setting was characterized by modern mean annual precipitation data and the size of late Pleistocene glaciers supported by the source basin.

Divisions between the four fan groups studied (NWM, SWM, WB and OL) were chosen purposefully on tectonic boundaries. The fans were then subdivided according to lithological (NWM and SWM groups) and climatic setting (WB and OL groups) and plotted on scatter diagrams. Power-law regression models (Eq. 1) were computed for each fan group. The single outliers in both the WB group (Sawmill Creek) and the SWM group (Millner Creek) were excluded from regression analysis.

## Study site descriptions

Lithological, climatic and tectonic classifications are summarized in Table 1 and are outlined briefly here. The

**Table 1.** Fan morphology data.

| Fan Group: | Subsidence rate | Lithology | Catchment area (km2) | Fan area (km2) |
|---|---|---|---|---|
| White Mountains Fan data | | | | |
| (1) Northern (NWM) | simple graben | | | |
| Montgomery | v. low | granite | 13.14 | 24.74 |
| Marble | v. low | granite | 15.31 | 20.85 |
| Queen Dicks | low | granite | 8.64 | 6.24 |
| Rock | low | granite | 8.87 | 9.29 |
| Falls Canyon | low | granite | 6.89 | 2.38 |
| Pellisier | low | granite | 13.48 | 7.32 |
| Middle Canyon | low | granite | 6.64 | 1.18 |
| (2) Southern (SWM) | complex graben | | | |
| Birch | high | mixed | 21.84 | 4.16 |
| Willow | high | mixed | 13.37 | 5.11 |
| Cottonwood | high | mixed | 12.25 | 4.68 |
| Lone Tree | high | mixed | 17.96 | 5.54 |
| Jeffrey Mines | high | mixed | 7.64 | 3.35 |
| Millner | high | mixed | 33.62 | 17.50 |
| Sabies | high | granite | 11.81 | 3.36 |
| Straight | high | granite | 9.95 | 3.19 |
| Sacramento | high | granite | 23.57 | 3.10 |
| Piute | high | metased | 22.96 | 5.00 |
| Coldwater | high | metased | 31.00 | 6.69 |
| Silver | high | metased | 55.89 | 6.76 |
| Sierra Nevada Fan data | | | | |
| (3) Western Bajada (WB) | simple graben | | | |
| Sawmill | low | glacial | 19.05 | 7.08 |
| Black Canyon | low | glacial | 6.89 | 4.73 |
| Thibaut | low | glacial | 4.49 | 8.04 |
| North Oak | low | glacial | 20.95 | 16.95 |
| South Oak | low | glacial | 19.30 | 18.50 |
| Independence | low | glacial | 24.74 | 16.47 |
| Pinyon | low | glacial | 12.25 | 13.30 |
| Symmes | low | glacial | 11.58 | 18.33 |
| Shephard | low | glacial | 32.58 | 32.98 |
| North Bairs | low | glacial | 10.07 | 9.79 |
| Bairs | low | glacial | 7.74 | 12.13 |
| George | low | glacial | 24.54 | 23.77 |
| Hogback | low | glacial | 12.60 | 15.45 |
| Lone Pine | low | glacial | 30.57 | 28.67 |
| Tuttle | low | glacial | 21.32 | 19.60 |
| Diaz | low | glacial | 12.22 | 8.26 |
| North Lubken | low | glacial | 9.41 | 6.51 |
| South Lubken | low | non-glacial | 3.28 | 9.31 |
| Carroll | low | non-glacial | 9.90 | 13.57 |
| Olancha | low | non-glacial | 12.55 | 9.08 |
| Falls/Walker | low | non-glacial | 12.80 | 11.11 |
| (4) Owens Lake (OL) | complex graben | | | |
| Slide Canyon | high | non-glacial | 7.74 | 2.73 |
| Timosea Peak | high | non-glacial | 3.87 | 1.36 |
| Cottonwood | high | non-glacial | 35.17 | 4.09 |
| Ash | high | non-glacial | 38.55 | 2.95 |
| Peak 8728 | high | non-glacial | 4.83 | 0.93 |
| Braley | high | non-glacial | 13.91 | 1.61 |
| Cartago | high | non-glacial | 24.30 | 3.18 |
| Olancha-Cartago 3 | high | non-glacial | 2.27 | 1.17 |
| Olancha-Cartago 2 | high | non-glacial | 1.43 | 0.69 |
| Olancha-Cartago 1 | high | non-glacial | 3.33 | 1.00 |

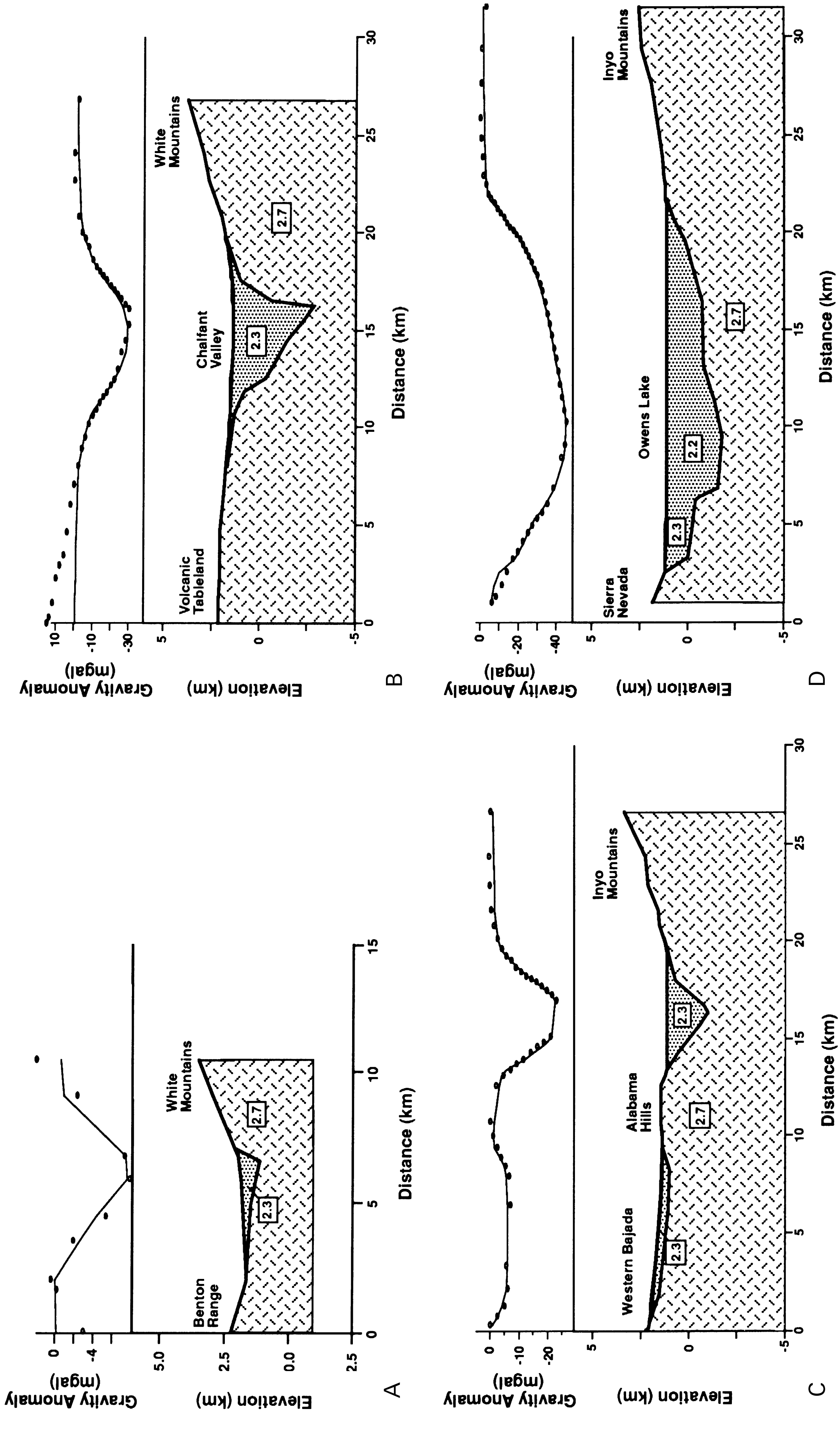


Fig. 5. Subsurface geometry of low-density, late Cenozoic alluvial fill in Owens Valley, California. Assumed fill and background densities are indicated. Upper plot shows both the observed (solid dots) and estimated (solid line) local Bouguer gravity anomaly (a linear regional trend has been extracted in all cases). Lower plot shows the reconstructed fill geometry shown without vertical exaggeration. Location of lines A–D indicated on Fig. 1. A. Structure beneath the NWM fan group. B. SWM fan group. C. WB fan group. D. OL fan group.

fans of the northern White Mountains (NWM) group are derived from predominantly granitic rocks and are building out onto a shallow bedrock bench north of the termination of the narrow graben that separates the White Mountains from the Volcanic Tableland (Fig. 1; Pakiser *et al.*, 1964). Here the depositional setting is that of a slowly subsiding, simple graben (Fig. 5A). The southern White Mountains (SWM) group includes fans derived from dominantly granitic, metasedimentary and metavolcanic lithologies. These fans are being deposited directly into the narrow graben north of Bishop (Figs 1 and 5B). The depositional setting is that of a rapidly subsiding, complex graben with the fans building across a shallow bedrock bench and into the deep graben (Fig. 5B). The catchments above both the White Mountains fan groups remained unglaciated during the late Pleistocene and stand within the rain shadow of the Sierra Nevada.

The western bajada (WB) group includes all fans between the southern tip of the Alabama Hills and the Big Pine volcanic complex (Fig. 1). These fans are derived from predominantly granitic rocks and include source basins which were variously unglaciated, slightly glaciated and extensively glaciated. The impressive fans of the WB group are building out onto a shallow bedrock bench (Figs 1 and 5C). This is a low-subsidence-rate environment and is classified as a simple graben because the fans do not extend beyond the shallow bedrock bench. Finally, the fans of the Owens Lake (OL) group are derived from the granitic rocks of the Sierra Nevada and are being deposited into the deep Owens Lake graben after bypassing a narrow bedrock bench (Figs 1 and 5D). This is a rapidly subsiding, complex graben depositional setting. Catchments above the OL fan group did not support valley glaciers during the late Pleistocene.

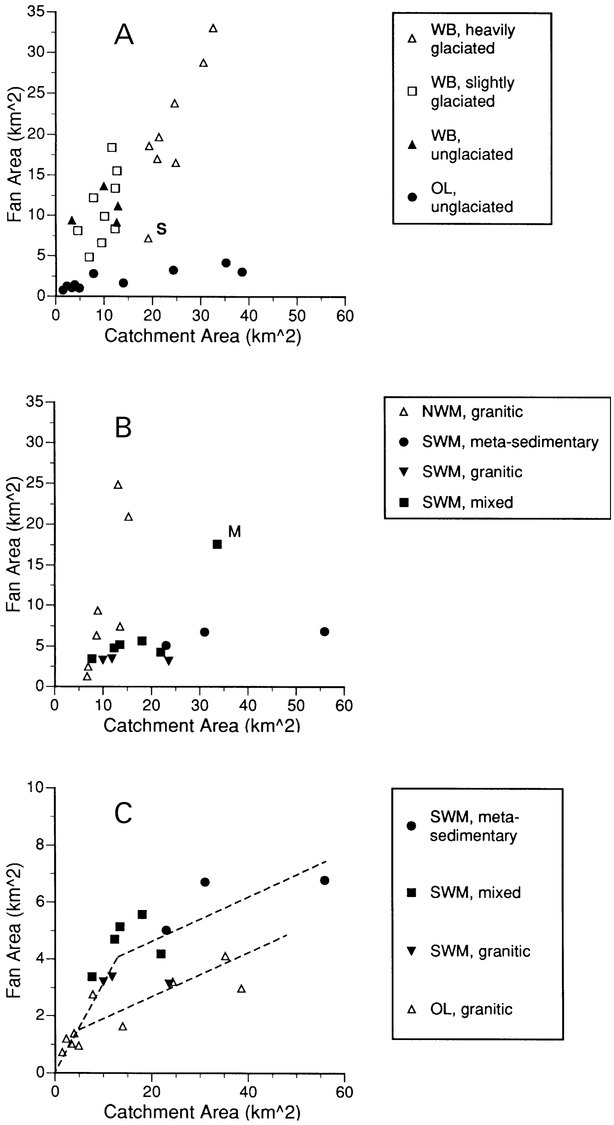


**Fig. 6.** Fan area vs. drainage area. A. Fans of the western bajada (WB) and Owens Lake (OL) groups. Outlier (S) is Sawmill Creek fan (excluded from regression analysis). B. Fans of the southern (SWM) and northern White Mountains (NWM) groups. Single outlier (M) is Millner Creek fan (excluded from regression analysis). C. Comparison of OL fans with SWM fans.

## Results and analysis

### *Catchment area and subsidence rate*

Fan size is strongly correlated with catchment area and depth of low-density fill (inferred subsidence rate). The correlation with catchment area is obvious, with fan area ($A_f$) increasing monotonically with drainage area ($A_d$) within each fan group, as anticipated in Eq. (13) and (14) (Fig. 6A,B). The dependence on tectonic setting is clearly displayed in between-group differences in relative fan size and is particularly well illustrated in the difference between the western bajada (WB) and Owens Lake (OL) fan groups (Fig. 6A; Table 2). Here fans building into the high-sedimentation-rate environment of the southern graben are approximately one-tenth the size of fans on the western bajada. This difference in relative fan size is commensurate with the difference in estimated fill depths (*c.* 2.5 and 0.25 km, respectively; Fig. 5) and therefore average long-term sedimentation rates, consistent with the direct tectonic control anticipated in Eqs (16), (19) and (21).

### *Source lithology*

Direct evaluation of the lithological influence on fan area – catchment area relationships is made possible by the range of source lithologies present in the SWM fan group: lithological variability is isolated in a setting with uniform climate and uniform basin structure, fill depth, and inferred long-term subsidence rate (Fig. 1; Table 1). Lithological differences also exist between the tectonically similar OL and SWM fan groups. However, although both the OL and SWM fan groups classify as high-subsidence-rate, complex grabens, the gravity data indicate that the distribution of subsidence below the fans is different (Fig. 5B,D). Comparisons of relative fan sizes

  

**Table 2.** Regression analysis.

| Fan Group | Sample size | | | 95% confidence band | $t$ statistic (c) | $P$-value (c) | r2 |
|---|---|---|---|---|---|---|---|
| (1) Northern Whites (NWM) | 7 | c | 0.01 | 0.00–0.07 | −2.76 | 0.033 | 0.757 |
| | | n | 2.82 | 0.98–4.65 | 3.94 | 0.008 | |
| (2) Southern Whites (SWM) | 11 | c | 1.66 | 0.73–3.78 | 1.40 | 0.191 | 0.325 |
| | | n | 0.34 | 0.06–0.62 | 2.76 | 0.02 | |
| (3) Western Bajada* (WB) | 20 | c | 2.59 | 1.33–5.02 | 3.00 | 0.007 | 0.609 |
| | | n | 0.64 | 0.39–0.90 | 5.29 | 4.2 E-5 | |
| (linear: $n=1$ forced)† | | c | 0.94 | 0.84–1.04 | 19.68 | 1.5 E-15 | 0.754 |
| | | n | 1.00 | – | – | – | |
| (4) Owens Lake (OL) | 10 | c | 0.64 | 0.42–0.99 | −2.36 | 0.043 | 0.808 |
| | | n | 0.47 | 0.28–0.66 | 5.81 | 2.6 E-4 | |

* Data for fans derived from glaciated, slightly and unglaciated catchments fall on a single trend and were lumped together for regression analysis. † The low $n$-value in the power-law regression fit ($n=0.64$) is not statistically significant.

between these two field sites as a function of either precipitation (nonglacial) or lithology must be made with caution.

Comparison of data on fans derived from different source lithologies within the SWM group does not convincingly support even a second-order dependence of relative fan size on source lithology (Fig. 6B). The granitic-source fans are among the smallest in this group, but they are not statistically separable. At first glance, comparison of data from the OL group appears to strengthen the argument that resistant granitic lithologies produce smaller fans (Fig. 6C). However, the comparison is not quantitatively valid because: (1) differences in graben structure (i.e. subsidence distribution), although not precisely known, are apparent in Fig. 5(B,D) and (2) source climates are different owing to the east–west precipitation gradient in the rain shadow of the Sierra Nevada (Rantz, 1969 ; Bierman *et al.,* 1991). Differences in average subsidence rates and/or the geometry of the graben structures are the most likely explanations. The dashed lines on Fig. 6(C) illustrate how differences in graben structure alone (inferred from gravity sections in Fig. 5B,D) could explain the observed differences in relative fan size (see Fig. 4B). At best the evidence for a significant lithological effect is inconclusive.

### *Climatic setting*

The approximate quantitative correspondence between relative fan size and sedimentation rate seen in comparison of the WB and OL groups (Fig. 6A) suggests that fan areas are insensitive to the climatic differences between these two fan groups (glaciated vs. nonglaciated). This inference can be tested by looking closely at the fans of the WB group. The extent of Late Pleistocene glaciation is the only significant difference between adjacent fans within the WB group and relative fan sizes can be expected to record the climatic signal (Eq. 14; Fig. 2B), if any exists. Remarkably, within the WB group, fans derived from variously unglaciated, slightly glaciated and heavily glaciated drainages all plot on the same trend, with no discernible differences in relative fan size (Fig. 6A).

## DISCUSSION

Theoretical relationships developed earlier predict that, to first order, tectonic setting controls relative fan areas regardless of whether the fan system is in steady state or not. This follows because tectonic setting strongly influences both (1) the relationship between catchment area ($A_d$) and the volumetric rate of fan deposition ($V_f$) and (2) the relationship between $V_f$ and fan area ($A_f$). Moreover, where subsidence rates are nonuniform both the $c$ and $n$ values in familiar power-law correlations of fan area and catchment area (Eq. 1) are found to be largely determined by the distribution of subsidence (i.e. basin structure) and bear little relation to catchment characteristics. Additionally, the theory suggests that the relative importance of lithological and climatic influences depends on (1) deviations from steady state, (2) differences in response time-scale between fans and their catchments and (3) the efficacy of internal feedback mechanisms associated with catchment growth and the fractionation of sediment between fans and the valley floor. However, neither the catchment response functions ($\beta(t)$) nor the internal feedback mechanisms are well enough understood to make general, quantitative statements about the roles of climatic and lithological variables. The Owens Valley field data shed some light on the relative importance of lithological and climatic effects and the significance of internal feedback mechanisms.

Field data from Owens Valley strongly support the theoretical predictions outlined above. Unfortunately the combination of (1) nonsteady-state conditions associated with climatic fluctuation during the Quaternary and (2) the limited range of rock uplift rates in Owens Valley (Gillespie, 1982; Chase & Wallace, 1988; Bierman *et al.,* 1991) precludes the possibility of testing theoretical predictions of the importance of rock uplift rate. However, the overriding importance of spatially variable subsidence rates is particularly well illustrated by the

Owens Valley field data. For instance, the low exponent values (in Eq. 1) found in regression analysis of some of the Owens Valley data (Table 2) are most likely due to spatially variable subsidence rates.

Exponents (in Eq. 1) slightly less than unity have been explained previously in terms of either declining specific sediment yield or declining trap efficiency with increasing catchment area (e.g. Hooke, 1968; Hooke & Rohrer, 1977). However, as discussed earlier, this explanation is untenable for $n$ values much less than unity, particularly in the rugged terrain of the Basin and Range Province. Subsidence rates that increase with distance from the range front probably explain the low exponents obtained for the southern White Mountains ($n = 0.34$; Table 2) and the Owens Lake ($n = 0.47$; Table 2) fan groups (Figs 4B and 6C). In both cases, the $n$ value is significantly less than unity at the 95% confidence level (Table 2). Furthermore, differences in relative fan size between the WB and OL fan groups and the NWM and SWM fan groups are primarily due to between-group differences in long-term subsidence rates (Figs 5 and 6).

The Owens Valley field data also demonstrate that, at least in this field setting, marked differences in lithological and climatic conditions have no demonstrable influence on relative fan sizes. This lack of correspondence is particularly well illustrated in the case of climatic variation (between glaciated and unglaciated catchments) and is significant for two reasons: it demonstrates (1) that so long as short-term sedimentation rates do not greatly outpace tectonic subsidence rates, climatic influences are of second-order importance and (2) that the feedback mechanisms discussed in earlier can be of considerable importance. The finding that variations in bedrock lithology do not markedly influence relative fan sizes within the SWM group can be interpreted in three ways: (1) the fan–catchment system is at or near steady state (unlikely); (2) the catchment response function ($\beta(t)$) is not particularly sensitive to source lithology; or (3) internal feedback mechanisms effectively counteract the lithological influence. These competing hypotheses cannot be tested rigorously with current data.

### *Relation to previous work*

Several authors have argued that source lithology has an important influence on relative fan size (e.g. Bull, 1964; Hooke & Rohrer, 1977; Lecce, 1991). However, the only convincing field data are those of Hooke & Rohrer (1977). Hooke & Rohrer (1977) clearly establish, based on field data from Death Valley, that (1) differential subsidence rate is the overriding first-order control on relative fan areas and (2) second-order differences in relative fan areas are systematically correlated with source lithology. Other published data sets are inconclusive. Bull (1964) was the first to show an apparent lithological dependence in relative fan sizes. However, this well-known data set is unconvincing because: (1) lithological differences amongst the various basins studied are subtle and (2) catchments classified as 'mudstone' tend to be significantly steeper than those classified as 'sandstone'. The less-steep, 'sandstone' catchments are associated with smaller relative fan sizes. It is unclear whether basin slope or source lithology is more important: reclassifying the catchments as either 'steep' or 'less steep' separates the data into a pair of distinct trends as effectively as the original lithological classification. Steeper catchments supported by ostensibly weaker (more erodible) lithologies suggest the possibility that differential uplift rates may be responsible for the observed differences in relative fan size in this field area.

Lecce (1991) presents an interesting argument to explain what he perceives as a paradox in fan area – catchment area data from the White Mountains in Owens Valley (Lecce lumps our 'southern' and 'northern' fan groups together): larger fans are associated with the more resistant granitic units in the northern part of the range (Fig. 1). Lecce argues that downwearing of hillslope gradients and subsequent increases in sediment storage in catchments underlain by weaker lithological assemblages ought to reduce sediment yield and lead to the development of smaller fans. The argument has merit. Such a condition could develop in a nonsteady-state landscape, and is anticipated by the cross-over of the two sediment yield curves in Fig. 2. However, we believe that in the specific case of the White Mountains in Owens Valley, Lecce's (1991) data are best explained as a difference in subsidence rates. An unfortunate geographical coincidence is apparently responsible for the confusion: the termination of the deep, narrow graben that runs along the flank of the White Mountains approximately coincides with the transition to more resistant granitic rocks in the northern White Mountains (Fig. 1).

## CONCLUSIONS

Predicting fan areas is essentially a conservation of mass problem: mass is produced by surface erosion (sediment yield), transported and deposited, with some fraction contributing to fan deposition, and distributed in the depositional basin according to the spatial pattern of tectonic subsidence rates. By coupling conservation of mass with a simple erosion law, the physical relationships that govern fan size can be expressed quantitatively, explicitly accounting for the varied roles of climatic, lithological and tectonic variables (Eqs 13, 14, 16, 19 and 21). The theoretical expressions developed here unequivocally demonstrate that in a steady-state landscape, fan area – catchment area relationships are determined almost entirely by the tectonic setting (Eqs 17 and 20; Fig. 4). Lithology and climate play a subsidiary role, influencing only porosity changes and the proportion of sediment sequestered in fans (Eq. 17; Harvey, 1984). However, fluctuations in climate and tectonic uplift rates are prevalent in Earth history and landscapes are frequently perturbed away from the steady state. Nonsteady-state conditions are particularly important because the response time-scale of fans is typically much shorter than the response time-scale of catchment physiography, implying that, in the wake of major perturbations, climate and lithology could significantly influence fan area – catchment area relationships where conditions are appropriate.

A qualitative discussion of catchment and fan responses to a suite of tectonic, climatic and lithological perturbations, including hypothetical sediment yield curves, has been presented. Evaluation of catchment response functions ($\beta(t)$), and their sensitivity to climate and lithology, through either theoretical modelling exercises (e.g. Tucker & Slingerland, 1996) or careful field observation is identified as an important area for future research. We argue that climatic and lithological variables may become important during transient responses to large perturbations away from steady state, such as the onset of glaciation or a dramatic increase in rock uplift rates. However, even during transients, internal feedback mechanisms can, in some circumstances, significantly dampen the response. In general, tectonic setting is the dominant control, particularly over the long term. Short-term exceptions are possible when the response is particularly strong and background tectonic subsidence rates (and/or valley floor deposition rates) are relatively low. Ritter *et al.* (1995) document a field example of such short-term fluctuations.

New field data from Owens Valley generally support theoretical predictions, and demonstrate the potential importance of internal feedback mechanisms. Differences in tectonic setting account for the full range of variability in relative fan sizes in Owens Valley and there is no conclusive evidence in our data that either source lithology or climate importantly influence either relative fan sizes or the coefficients in the familiar power-law relationship (Eq. 1) used to describe them. Finally, the theory appears to be sufficiently general to reconcile apparent disagreements in the literature regarding the relative roles of tectonic, lithological and climatic conditions (e.g. Bull, 1964; Lustig, 1965; Hunt & Mabey, 1966; Hooke & Rohrer, 1977; Lecce, 1991; Ritter *et al.,* 1995).

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