The influence of debris-flow rheology on fan morphology, Owens Valley, California

KELIN X. WHIPPLE
THOMAS DUNNE
Department of Geological Sciences, University of Washington, Seattle, Washington 98195

ABSTRACT

We have investigated factors controlling the surface morphology of debris-flow fans comprising the bajada along the western slope of Owens Valley, California. These fans have average slopes of 4°; an extensive network of abandoned, boulder-lined channels; rough, undulatory surfaces near the range front; and smooth distal surfaces. Field relationships and mechanical considerations indicate that the channels of the bajada are products of fluvial incision and not debris-flow scour. This is significant because detailed geomorphic maps indicate that the channels strongly influence the pattern of debris-flow deposition. The locus of debris-flow deposition on a channelized fan surface is set by the interaction of debris flows with the channel system and is controlled by channel size, channel gradient, flow volume, flow hydrograph, and flow rheology. Debris-flow behavior is most directly controlled by variations in bulk-sediment concentration and its influence on flow rheology. Whereas low-sediment-concentration debris flows tend to smooth the surface of the lower fan, spreading into thin sheets and filling channels and surface undulations, repeated deposition of high-sediment–concentration debris flows produces the rugged topography of the upper fan. The texture of the fan surface, rough or smooth, is determined by the relative volumetric importance of these two types of debris flow. In addition, channel avulsions and the associated long-term shifting of depositional loci are driven by in-channel deposition of debris flows with the highest sediment concentrations. These debris flows, therefore, play a critical role in determining both the structure of the channel network and the long-term pattern of deposition on the fan surface as a whole. We infer that the frequency distribution of debris-flow rheologies, set by source-terrain geology and hydrology, is an important control on fan morphology.

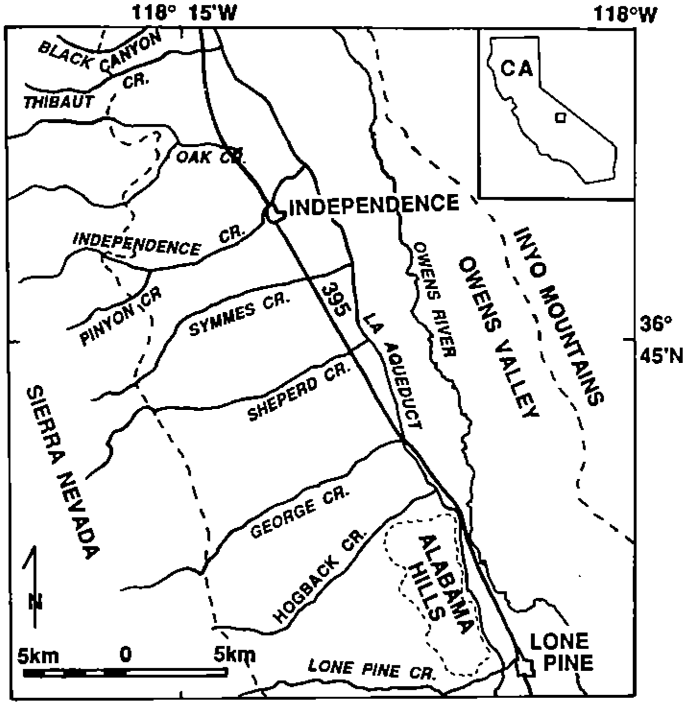

Figure 1. Index map of the study site in Owens Valley, California. The bajada, consisting of coalescing fans, is delineated approximately by the trace of the Sierran range front (dashed line) to the west and the Los Angeles Aqueduct to the east.

INTRODUCTION

Debris-flow fans occur in a range of environments and show great variability in size, slope, and surface morphology (Blissenbach, 1954; Beaty, 1963; Ryder, 1971; Suwa and Okuda, 1983; Harvey, 1984; Johnson, 1984). The present study analyzes the process of debris-flow fan construction on a bajada along the western slope of Owens Valley, California (Fig. 1) to explain the physical controls on fan morphology. We discuss controls on the original depositional morphology exclusively. We avoid a discussion of tectonic or climatic factors, in order to study the operation of the fan depositional system in isolation. In addition, controls on the overall properties of fan size and slope are discussed only qualitatively; we focus on fan-surface morphology, that is, the combination of surface texture, textural patterns, and the morphology and spatial distribution of channels crossing the fan. Field mapping indicates that the Owens Valley bajada consists almost entirely of debris-flow deposits (see below), and our interpretations in their strictest form should be extended only to similar depositional systems, although certain generalizations may be made from our results.

The surface morphology of debris-flow fans is set by the nature of the channel system, the spatial distribution of debris-flow deposits on the fan surface, and the interaction between the debris flows and the channels. Johnson (1970, 1984) and Hooke (1967, 1987) have established that the locus of debris-flow deposition is controlled by debris-flow volume and yield strength and the degree of flow confinement within channels. The present study builds on their work by (1) documenting the interplay between channels and debris flows in the formation of the Owens Valley

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bajada; (2) evaluating the "degree of flow confinement" through an analysis of the factors controlling channel conveyance capacity (defined as the discharge of the bankfull flow); and (3) considering the long-term morphological consequences of deposition by debris flows with variable volumes, peak discharges, and rheologies. Our approach is first to define the interplay of debris-flow and fluvial processes in fan formation on the basis of field observations in Owens Valley and then to draw upon current understanding of debris-flow rheology (for example, Johnson, 1970; Major and Pierson, 1990; Whipple, 1992) to explore the interaction of debris flows with the fan surface and the sensitivity of this interaction to rheological variability.

This paper presents (1) a description of the Owens Valley field site, (2) a description of fan morphology, (3) a discussion of the relative roles of fluvial and debris-flow processes in fan aggradation and in the channelization of the bajada surface, (4) an analysis of debris-flow processes and their role in setting the surface morphology of the fans, and (5) a general discussion of the physical controls on the depositional morphology of debris-flow fans.

OWENS VALLEY FIELD SITE

Owens Valley is a graben bounded on the west by the Sierra Nevada and on the east by the White-Inyo Range (Fig. 1). Sediment shed from the rugged highlands, mostly as debris flows, has contributed to broad piedmonts of coalescing fans (bajadas) at the foot of both the White Mountains (Beaty, 1963) and the Sierra Nevada (Trowbridge, 1911; Blackwelder, 1928), and to a deep valley fill (Knopf, 1918; Pakiser and others, 1964). The eastern escarpment of the Sierra Nevada is flanked by an extensive, uninterrupted bajada between the towns of Independence and Lone Pine (Fig. 1). Drainage basins supplying debris to the bajada extend 5–8 km from the fan heads to the range crest, cover 12–32 km^2, have total relief of 2–2.5 km, and stream gradients that increase from about 6° at the mountain front to >30° in the headwaters. The bajada itself extends 10–12 km from the range-front and has a slightly concave-upward, longitudinal profile: surface gradients decrease linearly with distance from the range front but average about 4°. Transverse profiles are convex upward near the range front but are nearly flat farther downslope where adjacent fans have coalesced.

The bajada surface between Independence and Lone Pine (Fig. 1) was chosen for study because (1) this stretch of the piedmont is particularly well developed, and fan morphology is not complicated by bedrock constrictions, volcanic activity, or complex foothill tectonics; and (2) the Quaternary history of fan aggradation on this part of the bajada is known (Gillespie, 1982; Bierman and others, 1991). Our field mapping was restricted to late Wisconsinan (Tioga, 15–18 ka) age surfaces (Gillespie, 1982) on two adjacent fans (Fig. 2). The Tioga surface is the youngest extensive surface on the bajada and offers the best preservation of the original depositional morphology.

FAN MORPHOLOGY

The spatial distributions of channels, bouldery levees, boulder fields, and boulder-laced snouts or terraces were mapped in the field using aerial photographs, enlarged to 1:3,000 scale, as base maps. The bajada surface has been smoothed on a centimeter-to-decimeter scale by the processes of soil creep, biogenic transport, slope wash, and rainsplash, and thus some of the finer details of the original surface morphology have been degraded.

The bajada, which from a distance appears to have a smooth, unbroken surface, is found upon closer inspection to have an intricate, undulating surface marked by boulder-laced, lobate snouts or terraces and by channels lined with paired, narrow boulder levees formed by trains of boulders along the channel edge. The distribution, pattern, and spatial density of boulders, snout-nosed terraces, channels, and boulder levees all vary with distance from the range front. The upper reaches of the bajada (0–3 km from the range front), where surface gradients average about 5°, have a rough, boulder-strewn surface with overlapping bouldery terraces and many boulder-lined channels (Fig. 3). Local relief is typically 2–3 m. The mid-fan reaches (3–7 km from the range front) have gradients of about 3°, smoother surfaces, fewer overbank debris-flow lobes, and a lower density of boulders; here, broad, smooth interfluves are cut by 1.5- to 2.5-m-deep channels with patchy boulder levees. Farther from the range front, distinct debris-flow lobes are less common, and boulders are sparse on a very smooth, low-relief surface, interrupted only by subdued channels, often less than 1 m deep.

Individual debris-flow deposits on the upper- and mid-fan portions of the bajada occur both on the open fan surface and in channels. Diffusive degradation of the fan surface may have obliterated the margins of thin, boulder-free, overbank debris-flow deposits. Few of these could be mapped (Fig. 3). Mappable overbank deposits are preserved as flat-topped terraces or lobes which are commonly 20–30 m wide, 50–100 m long, and 1–2 m thick (Fig. 3) and are usually found immediately upslope of discontinuous channel segments. Boulder-rich deposits without distinct margins were mapped simply as "boulder fields" (Fig. 3) and may represent either partially buried or morphologically degraded overbank debris-flow lobes or boulders stranded in zones of decreasing flow depth (that is, unconfined flow of mobile debris flows). Debris flows that came to rest in channels are preserved as elongate plugs (Fig. 4) which block channels (Figs. 2 and 3).

Channels that cross the bajada are relatively straight, have broadly U-shaped cross sections, smooth floors, width-to-depth ratios ranging from 7 to 12, and gradually decrease in cross-sectional area down the fan (Figs. 5 and 6). Since their abandonment in late Wisconsinan time, channel walls have been slightly degraded by slope processes, and channel floors have been smoothed by the accumulation of a thin layer of colluvium, but, in essence, the channels preserve their original morphology (see below). The drainage system as a whole consists of a subparallel-to-dendritic network of discontinuous channels (Fig. 2) rather than the branching distributary network usually associated with alluvial fans (Denny, 1965; Bull, 1977). Although few channels at present can be traced to the fan apex, they do not head as gullies on the fan surface; the discontinuous channels have been buried from up-fan and abandoned (see Fig. 7). The distinctive network of discontinuous channels on the bajada reflects a suite of channel-shifting and fan-building processes which are different from those operating on alluvial fans, as recognized by Beaty (1970).

RELATIVE ROLES OF FLUVIAL AND DEBRIS-FLOW PROCESSES

The relative importance of fluvial and debris-flow deposition was determined on the basis of examination of surficial deposits and exposures of the fanglomerate over much of the bajada surface between Thibaut Creek and George Creek, and along Lone Pine Creek (Fig. 1), where channel incision has exposed extensive sections. Criteria used to distinguish debris-flow from fluvial deposits included the presence of boulder-laced snouts and levees on the surface; matrix-supported structure

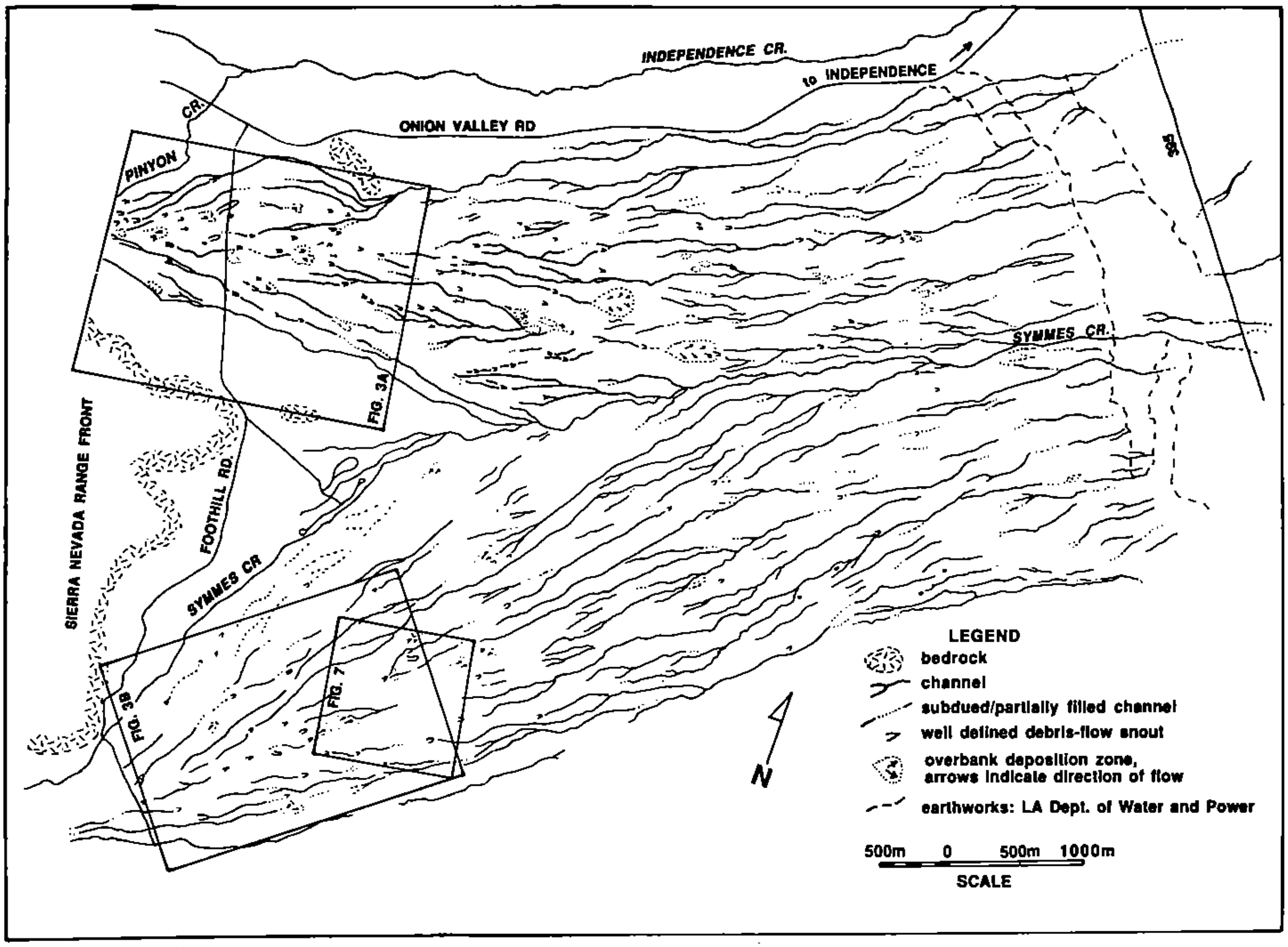

Figure 2. Channel network on Pinyon and Symmes Creek fans. Channel patterns were traced from 1:24,000-scale aerial photographs and the distribution of major debris-flow snouts transferred from geomorphic maps prepared at a 1:3,000 scale. Insets show the locations of Figures 3A, 3B, and 7.

of exposed sediments; poorly sorted textures, including a minimum of 5%–10% silt and clay by weight; and the absence of stratification, rounding, or sorting of clasts (Sharp and Nobles, 1953; Bull, 1977). The fanglomerate is predominantly a matrix-supported diamicton with a gravelly, silty-sand matrix (Fig. 8), and we found no distinctively fluviatile sediments except along the eastern margin of the bajada (Fig. 8C) and in exposures along Lone Pine Creek where it crosses the Alabama Hills (see Trowbridge, 1911). Boulders with median diameters >1 m are common within the diamicton; those >5 m across are rare. Although fluvial sedimentation has contributed little to the aggradation of most of the bajada, fluvial processes have played a critical role in the construction of the fans by eroding channels through the debris-flow deposits (see below).

Channels on a debris-flow fan can be built by either (1) self-confinement of debris flows between their own levees or (2) channel scour by floodwaters or debris flows. The degree to which pronounced levee aggradation occurs varies between debris-flow fans (see Beaty, 1963; Whipple, 1991) and is controlled at least in part by the physical properties of the debris flows (see below; Whipple, 1992). The relative importance of self-confinement of debris flows and channel scour, however, is easily discerned on the basis of cross-sectional morphology; self-confinement of debris flows between steep-sided levees produces channels that have beds which lie above the general elevation of the fan surface (Sharp, 1942, Fig. 2, p. 224).

The abandoned channels on the Owens Valley bajada (in contrast to those described by Sharp) are inset into the fan surface (Figs. 5 and 6), and only short reaches of a few channels exhibit sharply defined levees. In some cases, as seen in Figure 7, channels on the upper slopes of the bajada run down the axes of broad topographic highs, indicating that overbank deposition has aggraded the adjacent fan surface and contributed to apparent channel entrenchment, in the manner described by Hooke (1967, p. 457–458). Most of the channels, however, have been produced predominantly by erosional processes and not by levee aggradation; chan-

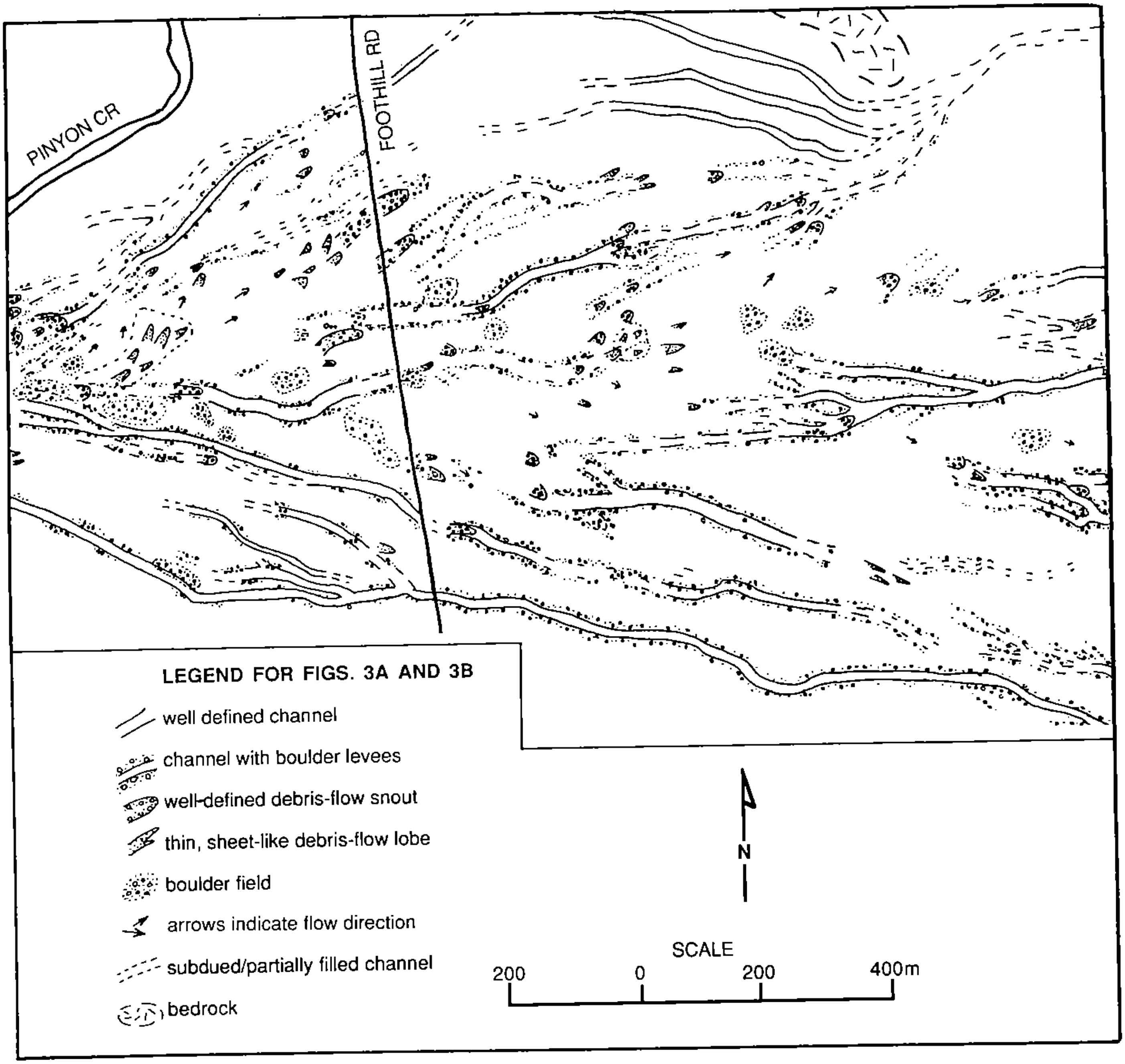

Figure 3A. Geomorphic map of part of upper Pinyon Creek fan, showing the distribution of debris-flow snouts and levees, boulders, and channels on the fan surface.

nel morphology is everywhere consistent with partial infilling of originally steep-sided, V-shaped or flat-floored channels (Figs. 6 and 9). In addition, the general structure of the channel network is diagnostic of an erosional, rather than depositional, system: the network forms a subparallel to dendritic pattern (Fig. 2). Whether channels were excavated by debris-flow or fluvial scour, however, cannot be determined on the basis of cross-sectional morphology. Observations of the erosional potential of modern debris flows must be used to address this important issue.

Field observations in Owens Valley and elsewhere indicate that debris flows cannot have contributed significantly to channel scour on the moderate slopes of the bajada. Channels exploited by debris flows within the past decade (three on the western and two on the eastern slopes of Owens Valley) show no sign of scour by the debris flows. Vegetation is flattened and stripped of bark, but channel-bed elevation is unchanged except where incised by subsequent stream flows. Similar conclusions about the geomorphic role of debris flows on fans have been reached by

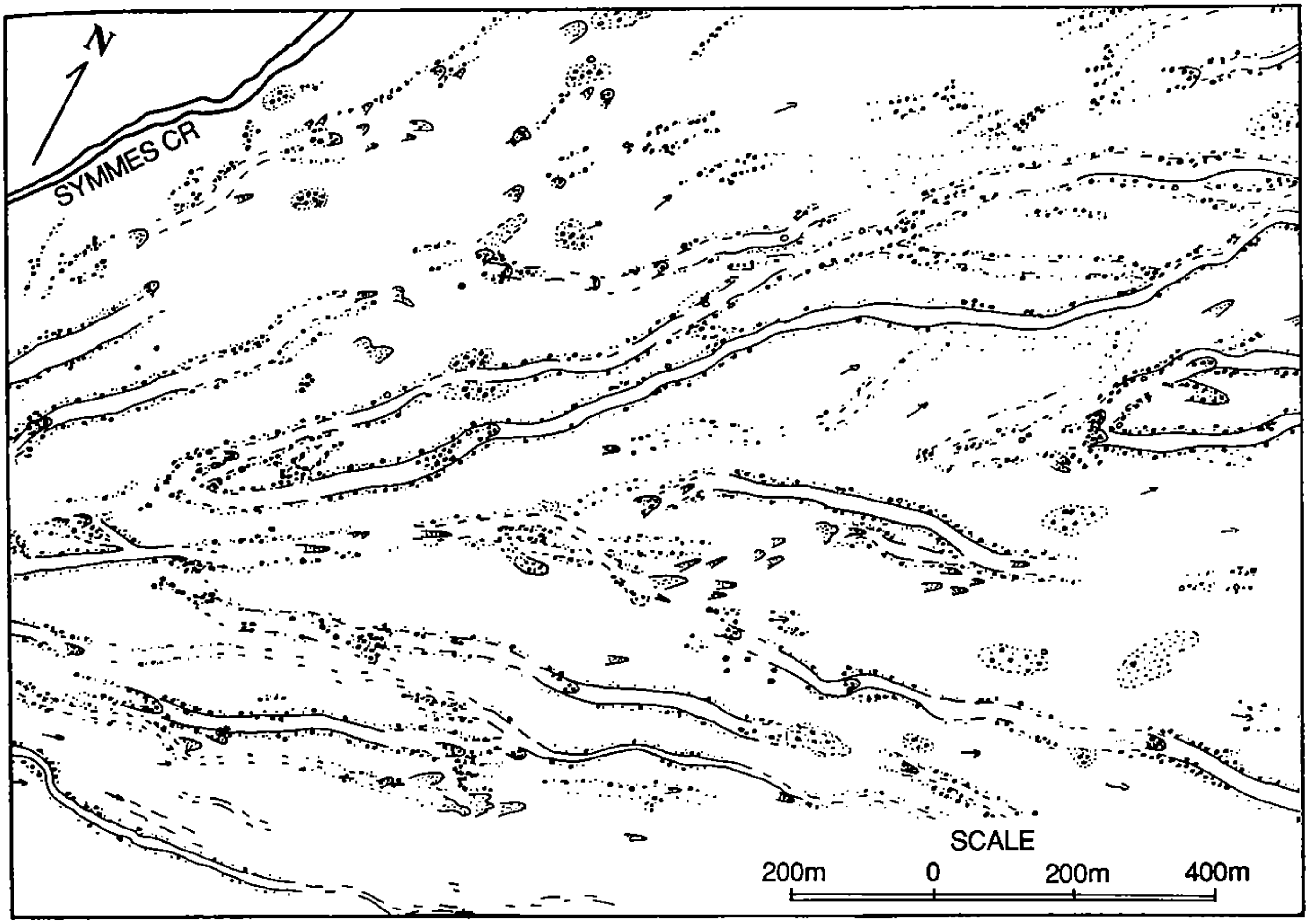

Figure 3B. Geomorphic map of part of upper Symmes Creek fan. The repeated pattern of channel blockage, up-fan aggradation and channel in-filling, followed by channel diversion is seen on both maps and is characteristic of the upper two thirds of the bajada. The lower left portion of this map is covered by the stereo-pair of aerial photographs in Figure 7.

many investigators (for example, Blackwelder, 1928; Beaty, 1963; Hooke, 1987). Moreover, Pierson (1980), Okuda and others (1980), and Suwa and Okuda (1980) have documented that scour gives way to deposition on slopes of 6°–8° for debris flows with flow depths, and thus basal shear stresses, comparable to those in Owens Valley. We conclude, therefore, that the channels of the Owens Valley bajada were cut by streams and not by the debris flows themselves.

DEBRIS-FLOW PROCESSES AND FAN-SURFACE MORPHOLOGY

Some debris flows come to rest after only a short transport distance, freezing on the relatively steep slopes (4°–6°) of the fan head as sharply defined lobes and channel plugs. Other debris flows traverse the entire length of the fan, eventually spreading as thin, tabular deposits on the gentle slopes (1°–2°) of the bajada margin. Similar observations have been made on many debris-flow fans (for example, Blackwelder, 1928; Sharp and Nobles, 1953; Beaty, 1963; Johnson, 1984). Because the spatial pattern of debris-flow deposition in part controls the morphology of the fan surface, it is useful to explain the down-fan segregation of these two types of debris flows.

Textural Analysis of Debris-Flow Deposits

Textural analyses were conducted to determine whether sedimentological variability is an important factor in the mobility of the Owens Valley debris flows. Clasts in exposures were point-counted to characterize the coarse fraction (clasts coarser than 32 mm) of the deposits. Samples (2–3 kg each) of the matrix (defined as material finer than 32 mm) were sieved to characterize the finer fraction.

The results of point counting, augmented by visual estimates of the percentage of cobbles and boulders in many additional exposures, indicate that the Owens Valley debris-flow deposits are matrix rich, with clasts >32 mm in diameter composing 30%–40% of the volume of the proximal and mid-fan deposits (Fig. 8A), and 10%–20% of the finer-grained distal deposits (Fig. 8C). Concentrations of as much as 60%–80% coarse clastic

Figure 4. Debris-flow plug in a channel; photograph taken from the left bank of the channel, just downstream of the plug (figure to left of debris snout for scale).

material occur locally in levees and on the margins of debris-flow snouts (see Fig. 4).

Sieve analyses show that there is little variability in the matrix portion of different debris-flow deposits (Table 1). The matrices of all debris-flow deposits sampled are very poorly sorted ($\sigma_\phi = 2.1–3.3$) and by weight are composed of 30%–55% angular gravel, 40%–60% sand, and 7%–12% silt-and-clay. The consistent composition of the matrix fraction of debris-flow deposits from all parts of the fan, particularly in terms of their silt-clay content (Table 1) implies that textural variability has not strongly influenced depositional patterns on the Owens Valley bajada.

Rheological Analysis of Debris-Flow Deposits

Motivation. The rheology of debris flows has received much attention (see reviews by Takahashi, 1981; Costa, 1984; and Iverson and Denlinger, 1987), and a wealth of estimates of rheological parameters has been published (for example, Pierson, 1980, Table 2, p. 244; Fink and others, 1981; Costa, 1984, Table 1, p. 272; Johnson, 1984, Table 8.1, p. 294; Major and Voight, 1986). With the exception of work by Suwa and Okuda (1983) in Japan, however, previous studies have not attempted to use the study of debris-flow rheology to address the formation of debris-flow landforms. In this study, we draw upon current understanding of debris-flow rheology (for example, Johnson, 1970; Fairchild, 1985; Major and Pierson, 1990, 1992; Phillips and Davies, 1991; Whipple, 1992) to elucidate quantitatively the controls on (a) debris-flow deposition and (b) the confinement of debris flows within channels. Both aspects of the debris-flow runout problem (controls on deposition and confinement) are important because a debris flow entering a channel from the mountain front will remain mobile until the combination of its depth and the channel gradient require the cessation of flow (see below). The depth of a given flow is maintained by flow confinement between channel banks, and therefore important controls on runout distance are the degree to which a

Figure 5. Channel on upper Pinyon Creek fan, typical of the bajada's abandoned channels and illustrating their broadly U-shaped cross-sectional morphology, the well-developed, paired boulder levees, and the smooth convergence of the levees with the adjacent fan surface. Channel is 20 m wide and 2 m deep. See Figure 6B for a surveyed cross section.

TABLE 1. SUMMARY OF SIEVING ANALYSES

	Runout distance (km)	Mean grain size (mm)	Sorting (phi)	Silt-and-clay (%)
Debris flows	0.94	1.1	3.0	8.8
	1.00	1.0	3.0	11.1
	1.25	0.9	2.9	7.5
	1.30	0.8	2.9	10.3
	1.70	0.5	2.8	12.2
	2.06	0.5	3.3	18.8
	2.11	0.7	2.7	11.5
	2.40	1.3	2.7	5.3
	2.50	0.8	2.8	10.7
	2.70	1.1	2.7	7.9
	2.93	1.0	2.8	9.1
	4.37	1.4	2.1	4.2
	8.50	1.0	2.7	7.9
	8.50	1.0	2.6	8.7
	8.50	0.8	2.5	9.2
	8.52	0.7	2.9	14.0
	8.60	0.9	2.5	7.2
	8.90	1.2	2.7	8.3
Fluvial samples	. .	1.1	1.3	1.5
	. .	1.1	1.7	1.4

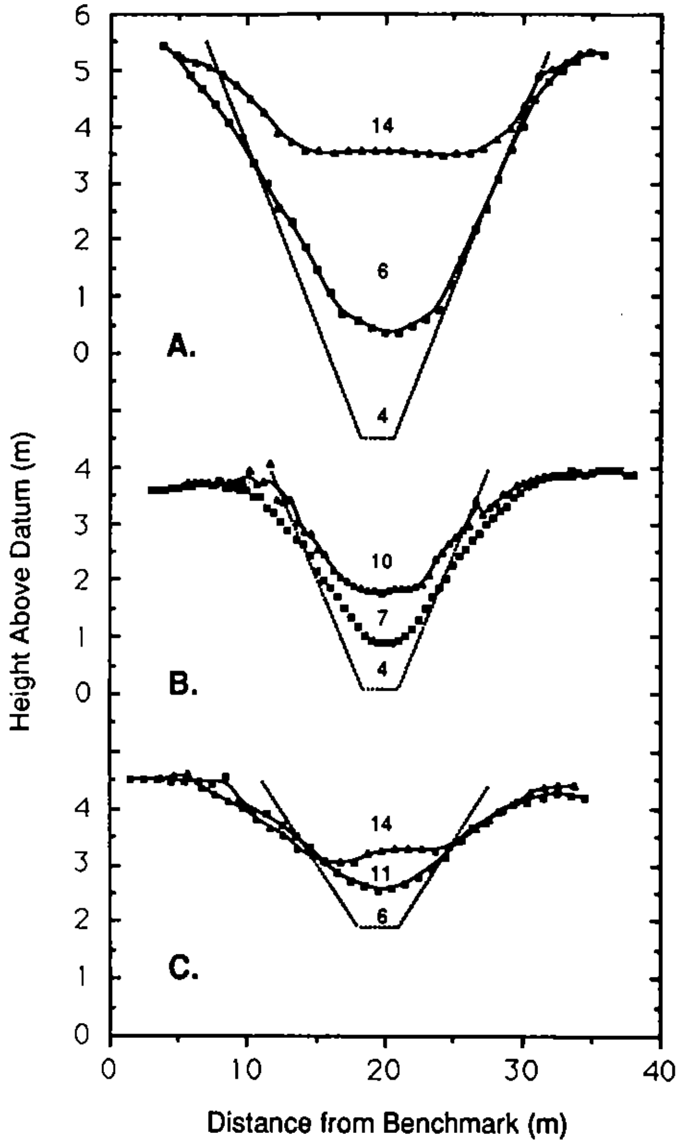

Figure 6. Surveys of representative channel cross sections, plotted at a 4× vertical exaggeration. For each channel, a survey immediately upstream of a debris-flow plug (triangles) is compared with a survey immediately downstream of that plug (squares). Width-to-depth ratios are indicated for each channel section. The steep-sided, flat-floored channel cross sections shown for comparison (dotted lines) are referred to in the discussion of channel formation (see also Fig. 9). (A) Deeply incised channel on upper Pinyon Creek fan. (B) Typical channel on upper Pinyon Creek fan. (C) Channel typical of the lower bajada (located 6 km from the range front).

debris flow is confined within the channel and the degree to which it is allowed to spread overbank, thin, and deposit (Johnson, 1984; Hooke, 1987).

Theory. Debris flows involve the rapid downslope translation of poorly sorted debris admixed with a small amount of water, typically 10%–25% by weight (Pierson, 1986). Debris flows such as those in Owens Valley are matrix rich, with a predominantly granular matrix containing about 10% silt-and-clay by weight. The silt-clay fraction is critical to retention of water within the slurry and, hence, is the most important textural control on flow mobility.

Deformation of debris slurries under shear involves a complex suite of grain-grain and grain-fluid interactions and is governed by both frictional and viscous forces (Savage and Sayed, 1984; Iverson and Denlinger, 1987; Iverson and LaHusen, 1989). On a macroscopic scale, however, the dynamic response of debris slurries to an applied shear stress can be modeled as that of a non-Newtonian continuum with the properties of yield strength and viscosity. Although both the yield strength and viscosity may vary with sediment concentration (C_s), grain-size distribution (GSD), clast angularity and roughness, clay mineralogy, effective normal stress, strain rate, and strain history, to a first order approximation C_s and GSD are the dominant variables (see below). Consequently, many hydrodynamic attributes of debris slurries and some important characteristics of their deposits can be accounted for with relatively simple constitutive equations.

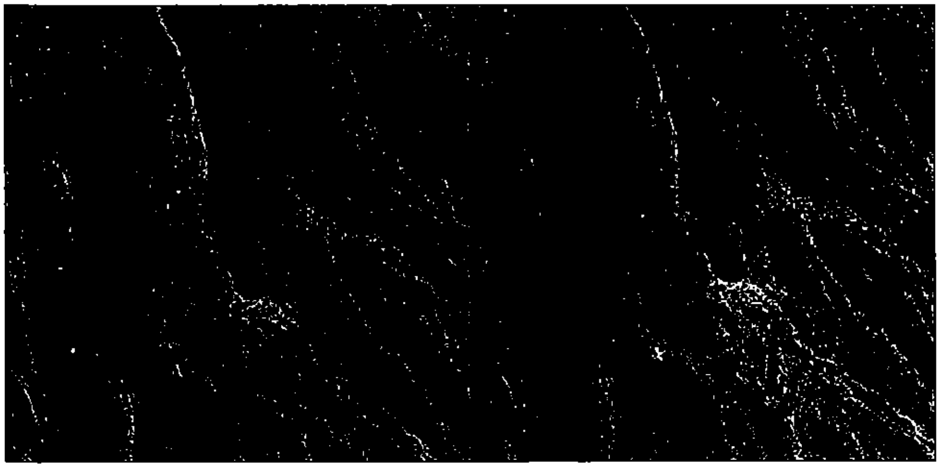

Figure 7. Stereo-pair of aerial photographs of part of Symmes Creek fan (BLM Project CA01-77, Frames 1-35-7 and -8), illustrating the relationship between channels and the adjacent fan surface. Field of view is 1 km^2. North is to the right; and flow, from top to bottom. Orientation relative to field maps is shown in Figure 2. Several well-defined debris-flow plugs are visible and can be seen to have blocked the channels. The topographic high upstream of the right-most channel is a direct result of channel blockage; local aggradation in the interim between channel blockage and the excavation of a new channel obliterates channel courses and adds to the topographic complexity of the upper slopes of the bajada.

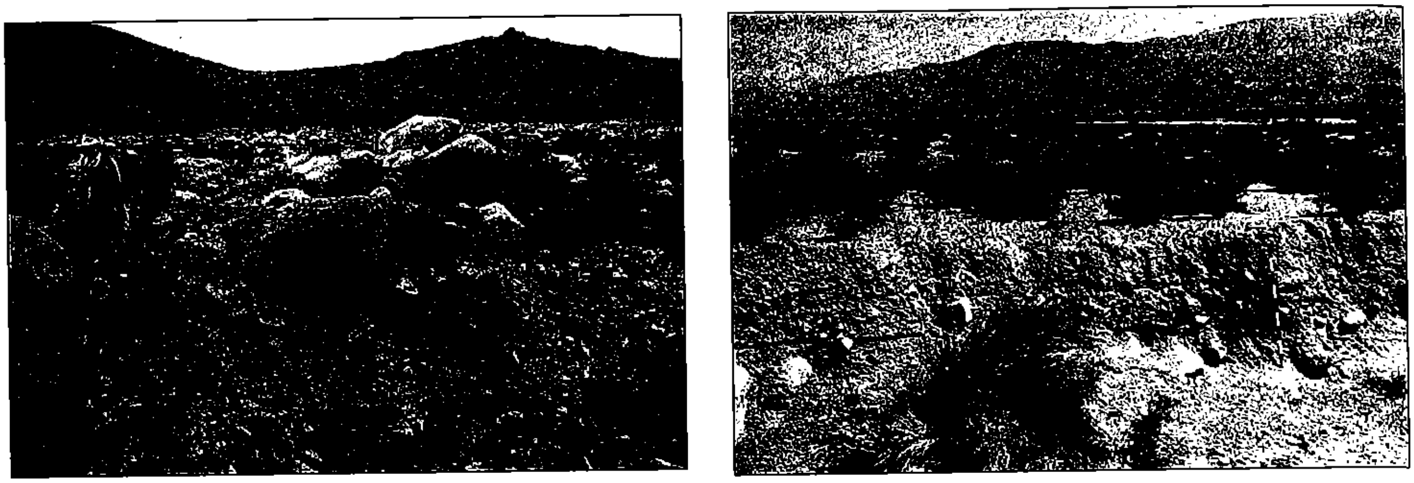

Figure 8. (A) Debris-flow deposit along the upper reaches of Symmes Creek, person for scale. Note the lack of sorting and stratification and the matrix-supported structure. (B) Debris-flow sediments exposed in a gully wall (1.5 m high for scale) on the lower portion of Symmes Creek fan. (C) Debris-flow overlying stratified fluvial sand and fine gravel in a gully immediately east of Highway 395 on Pinyon Creek fan (scale marked in decimeters).

For the purpose of this study, the visco-plastic, or Bingham, flow law proposed by Johnson (1970) is taken as an adequate description of debris-flow dynamics. In one-dimensional form, the visco-plastic flow law is

$$\tau_{zx} - \tau_o = \mu_B \frac{du}{dz}; \quad \tau_{zx} > \tau_o \qquad (1a)$$

$$\frac{du}{dz} = 0; \quad \tau_{zx} \leqslant \tau_o, \qquad (1b)$$

where τ_{zx} is the driving stress, τ_o is the yield strength, μ_B is the viscosity, and du/dz is the velocity gradient. In the discussion below, we constrain yield strength and viscosity to be constant in any given debris flow, but to vary with the physical composition of the debris flow, as observed in laboratory and field studies.

Laboratory studies have documented a dependence of yield strength and viscosity on debris-flow texture and sediment concentration (Fairchild, 1985; O'Brien and Julien, 1988; Phillips and Davies, 1991; Major and Pierson, 1990, 1992). In general, these studies have shown that (1) for a given grain-size distribution, yield strength and viscosity are correlated with one another and with sediment concentration; (2) both yield strength and viscosity increase by over an order of magnitude over a narrow range of sediment concentration; and (3) for a given water content, flows with a larger proportion of fines have higher yield strengths and apparent viscosities. The last statement is a little misleading, however, because slurries of finer-grained material typically hold more water than do more granular slurries. As a consequence, slurries with the greatest proportions of silt and clay usually have the lowest yield strengths and viscosities and are generally more mobile.

Methods. Prediction of debris-flow runout patterns requires that the yield strengths and viscosities of the debris flows be known. The late Wisconsinan age of the fan surfaces studied precludes detailed rheological analyses of the debris-flow deposits; the degree of deposit preservation on these surfaces permits estimation of flow yield strengths but not viscosities. As this is not sufficient to fully develop the rheological controls on fan surface morphology, Whipple (1992) conducted a companion study of well-preserved, modern debris-flow deposits on the Black Canyon fan just north of Independence (Fig. 1) and documented a correlation between yield strength and viscosity. The reported correlation is used here to complement field estimates of yield strength in a quantitative description of the rheological variability recorded in the fan deposits.

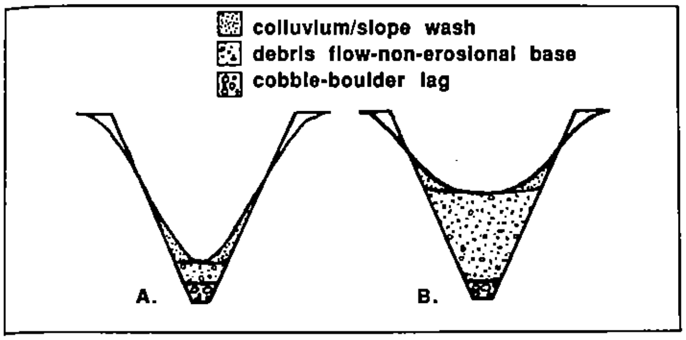

Figure 9. Schematic illustration of channel modification by debris flows. Vertical exaggeration is 4×. (A) This sketch depicts a fluvial channel (w/d = 4) with an armored floor which has been exploited by one or more debris flows, resulting in minor axial deposition (as explained by Johnson, 1970) but no significant in-channel deposition. Since abandonment, colluvium derived from the adjacent sidewalls has accumulated on the channel floor. Modified width-to-depth ratio is 6. (B) This sketch depicts the same channel, but this time partially filled by a debris-flow plug before adandonment. Modified width-to-depth ratio is 12.

Johnson (1970, 1984) outlined field methods for estimating the yield strength of debris flows from their deposits. At the instant of deposition, the yield strength of a visco-plastic material must be equal to the basal shear stress ($\tau_o = \tau_b$). Assuming conditions of steady, uniform, gravity-driven flow, the basal shear stress is given by

$$\tau_b = \rho_b g h \sin \theta = \tau_o, \tag{2}$$

where ρ_b is the bulk density, h is flow depth, θ is the surface slope of the flow, and the equivalence on the right-hand side indicates the condition for deposition. Equation 2 is best applied to debris deposits on planar surfaces and Johnson (1984) has derived another relationship for channelized flows:

$$\tau_o = \frac{\rho_b g d_c \sin \theta}{(2d_c/w_c)^2 + 1}, \tag{3}$$

where w_c and d_c are the critical width and depth at which channelized flow ceases, and where the magnitude of the denominator scales with the relative importance of sidewall to channel-floor drag. An estimate of yield strength thus can be derived from field surveys of deposit geometry and an estimate of bulk density.

Thickness and surface slope were measured for all well-preserved, overbank debris flow lobes, as were depth, width, and surface slope for all well-preserved channel plugs. Bulk density was estimated following a procedure outlined by Johnson (1984) in which debris is reconstituted in the laboratory to its approximate original water content. The bulk density estimate depends partly on estimates of the volumetric concentration of coarse debris (V_C) (≥32 mm) obtained by point counting. The density of the reconstituted matrix (~2.1 g/cm^3), however, is close enough to that of granitic boulders (~2.7 g/cm^3) that the total bulk density is not sensitive to errors in V_C; it was taken as 2.1 g/cm^3 for boulder-poor deposits and 2.3 g/cm^3 for boulder-rich deposits.

Results. Equations 2 and 3 were used to estimate yield strength for 38 well-defined debris-flow lobes on Pinyon Creek and Symmes Creek fans. The results of the analysis are compiled in Table 2. Sources of error include estimation of bulk density (±10%), measurement of deposit thickness (±5%), measurement of surface slope (±10%), and deviations from the ideal conditions assumed in equations 2 and 3. Measurement uncertainties alone are responsible for a possible ±15% error in yield-strength estimates.

TABLE 2. DEBRIS-FLOW RHEOLOGY

Runout (km)	Deposit geometry			Silt-and-clay (% by weight)	Yield strength* (Pa)
	Slope (%)	Thickness (m)†	Width/depth (m)§		
0.36	7.9	1.5–2.0	· ·	· ·	3,120
0.67	9.4	· ·	32/3.0	· ·	6,000
1.00	10.5	1.2–1.3	· ·	11.1	2,900
0.94	7.0–7.7	· ·	13/1.5–2.3	8.8	2,770
1.25	7.9	0.8–1.0	· ·	7.5	1,530
1.30	9.0	· ·	30/2.0–2.2	10.3	4,000
1.46	9.5	· ·	14/2.8	· ·	4,940
1.70	8.0	· ·	30/3.0–3.6	12.2	5,450
1.78	7.3–8.7	1.2	· ·	· ·	1,980
2.06	7.0–8.7	0.9	· ·	18.8	1,450
2.11	8.0	0.5–1.0	· ·	11.5	1,240
2.28	11.4	1	· ·	· ·	2,350
2.40	9.6	2.2	· ·	5.3	4,450
2.88	8.0	2.0–2.2	· ·	· ·	3,180
2.93	7.0	· ·	13/1.5–1.8	9.1	2,230
3.05	8.0	0.8–1.2	· ·	· ·	1,400
3.15	8.0	· ·	10/1.9	· ·	2,850
3.40	6.0–12.0	1.0–1.3	· ·	· ·	2,260
3.48	7.0	0.3	· ·	· ·	450
2.70	4.5	0.5	· ·	7.9	460
4.37	6.6	0.7–1.0	· ·	4.2	1,090
4.97	6.5	· ·	9/1.2	· ·	1,500
5.66	5.2	· ·	9/1.5	· ·	1,440
8.50	1.9	0.45	· ·	8.7	180
8.50	1.8	0.6	· ·	9.2	220
8.50	1.8–2.6	0.2–1.0	· ·	· ·	350
8.50	4.9–5.2	0.6	· ·	7.9	625
8.52	1.8–2.1	0.35	· ·	14.0	140
8.60	3.5	0.75–1.2	· ·	7.2	700
8.90	2.1–2.6	0.6	· ·	8.3	300

*Yield strength estimated using equation 2 or 3, depending on deposit geometry.
†Thickness of debris-flow deposit on a planar surface (equation 2).
§Critical width and depth of a channelized debris-flow plug (equation 3).

Runout distances of debris flows on the bajada are correlated with estimated yield strength (Fig. 10). Debris flows with the highest yield strengths are limited to the upper reaches of the bajada, and only the low-yield-strength debris flows are capable of reaching the bajada margin, as anticipated by Johnson (1984) and Hooke (1987). A low-yield-strength debris flow, however, which encounters a channel blocked by previous in-channel deposition is forced overbank where it spreads laterally, thins, and halts, regardless of position on the fan. Overbank flow and deposition also occur wherever peak discharge exceeds the conveyance capacity of unblocked channels. Depending on the peak flow rate and the geometry of the fan surface, a low-yield-strength debris flow thus may deposit on any part of the fan; the greater scatter among the short-run debris flows in Figure 10 is a result of these factors. On the other hand, the upper envelope defined by the data in Figure 10 represents the maximum potential run-out distance of a flow with a given yield strength, as constrained by the gradual down-fan decrease in fan slope and channel depths.

Interpretation. The rheological variability documented in Table 2 is interpreted as resulting predominantly from variations in sediment concen-

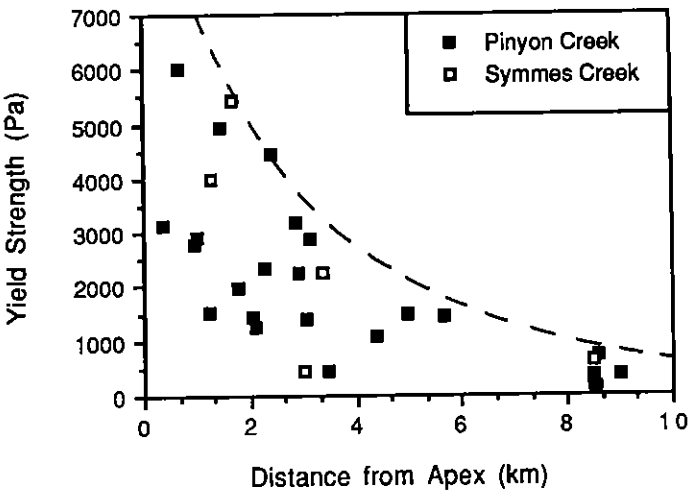

Figure 10. Yield strength estimates from debris-flow deposits on Pinyon and Symmes Creek fans plotted as a function of runout distance, measured in km radially from the apex. The upper envelope of yield strength estimates represents the rheological limitation on flow runout distance.

tration. The observed variability in silt and clay content is of sufficient magnitude to influence flow mobility (Fairchild, 1985; O'Brien and Julien, 1988; Phillips and Davies, 1991; Major and Pierson, 1990, 1992), but there is no systematic or fan-wide correlation between percentage of fines and either flow runout distance or estimated yield strength (Table 2, Fig. 11). Data on a suite of debris-flow deposits at the bajada margin (triangles in Fig. 11) suggest a second-order dependence of flow mobility on matrix GSD. This second-order effect, however, apparently has had little influence on the general pattern of debris-flow deposition. Thus, insofar as the mobility of a debris flow is governed by the properties of its matrix, it may be inferred that variable sediment concentration and therefore water content, rather than grain-size composition, has been the most important (first-order) control on flow mobility.

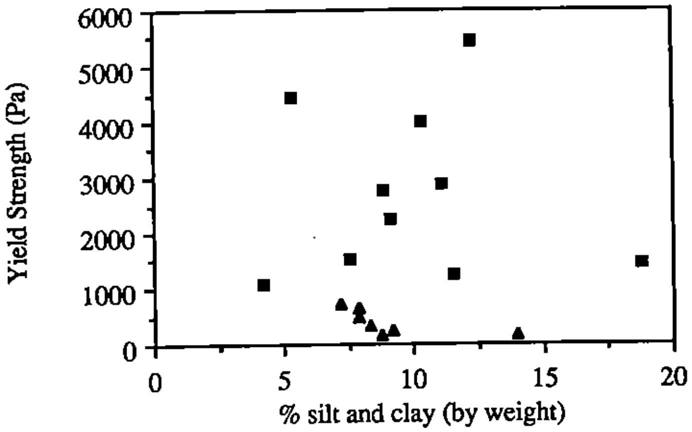

Figure 11. Estimated yield strength plotted against percentage of silt-and-clay in the matrix for all debris-flow deposits for which sieve analyses are available. No overall correlation is evident. Triangles represent debris-flow deposits at the distal margin of the bajada and suggest a second-order correlation with silt-clay content.

The mobility of matrix-supported debris flows is controlled predominantly by matrix properties and differences in the percentage of coarse material are almost certainly less important than variations in sediment concentration. Although a greater percentage of large clasts (⩾32 mm) was observed in deposits on the upper fan, those deposits are matrix supported (Fig. 8), and interlocking of the larger clasts is unlikely to have greatly influenced flow mobility, except perhaps at bouldery fronts and margins (Pierson, 1986). Even so, frictional resistance at the flow front is unlikely to influence the mobility of the main body of a debris flow unless it is already moving slowly and decelerating (see footage in Costa and Williams, 1984). Only in the final stages of debris-flow deposition, therefore, is a concentration of boulders at the flow front likely to enhance the effective yield strength and viscosity of the flow. In this paper, we ignore this late-stage effect and concentrate only on the dominating influence of the sediment concentration in the main body of the debris flow. In general, our arguments about the controls on debris-flow deposition are not significantly affected by this simplification, only the specific details of the frequency distribution of debris-flow rheologies delivered to any fan (see below) will be altered by considering the secondary influence of the presence or absence of a bouldery frontal bore.

Rheological Constraints on Channel Conveyance Capacity

Motivation. Where debris-flow runout is significantly influenced by the channel system, as documented earlier for the Owens Valley bajada (Fig. 3), it is useful to quantify the influence of the channels on debris-flow runout patterns in terms of the physical properties of the debris flows, such as their rheology and peak discharge. These are the most relevant properties because the degree to which debris flows are confined within channels and conveyed farther down-fan depends on the relative magnitudes of the peak discharge and the conveyance capacity of the channel, which is a function of flow rheology as well as channel size and gradient. We therefore have analyzed the relationship between flow rheology and channel conveyance capacity.

Methods. We use the visco-plastic model (equation 1) to calculate channel conveyance capacity as a function of flow rheology and distance down-fan. The analytical approach is simple but results in a reasonable approximation of the relationship between channel conveyance capacity and debris-flow rheology (see below). The size and geometry of the channels as a function of distance down-fan is constrained by field surveys of representative channel cross sections. The rheology of the debris flows, as a function of sediment concentration, is constrained by data on modern debris flows in Owens Valley (Table 3; Whipple, 1992) which document a correlation between yield strength and viscosity for a series of flows with similar grain-size distributions. Coupled with the range of yield strengths estimated on the basis of field measurements (Table 2), this correlation is taken to describe, to first order, the rheological variation characteristic of the debris flows of the Owens Valley bajada.

Bankfull discharges of debris flows with a range of yield strengths and viscosities were calculated for channel cross sections and gradients characteristic of the upper, middle, and lower reaches of the bajada (see Fig. 6). Steady, uniform flow through straight channels was assumed. The channel cross section was divided into a series of 1-m-wide vertical sections, and independent one-dimensional solutions were obtained for each section. The discharge through each meter-wide increment of the channel cross section (q_i) is obtained by solving the visco-plastic constitutive equation 1

TABLE 3. RHEOLOGIC PARAMETERS: BLACK CANYON, CALIFORNIA

Debris-flow surge	Yield strength (Pa)	Bingham viscosity (Pa-s)
83-II*	2150 ± 150	430 ± 50
83-IIIa†	540 ± 30	380 ± 70
83-IIIb†	540 ± 30	180 ± 45
83-IV	300 ± 45	30 ± 15
90-I	340 ± 80	225 ± 75
90-II	80 ± 35	18 ± 3

Best fit correlation: $\mu_B = 310 \log(\tau_0) - 600$.
*No estimates for pulse 83-I available.
†Estimates for pulse 83-III from two isolated locations.
Source: Whipple, 1992.

for the velocity gradient (du/dz) and twice integrating over the flow depth (h) (see Johnson, 1970, p. 503):

$$q_i = \frac{1}{2}\left\{\frac{1}{\eta}\rho_b g \sin\theta\left[0.67\, h_d^3 + h_d^2\,(h - h_d)\right]\right\}, \qquad (4)$$

where h_d is the thickness of the deforming region, which is a function of the yield strength and is determined by application of equation 2 ($h_d = h - \tau_0/\rho_b g \sin\theta$). Discharges determined with equation 4 were summed across the channel to estimate the total bankfull discharge, which is taken as an estimate of the channel-conveyance capacity.

This method of calculation ignores the lateral stresses between adjacent sections and therefore creates an artificial condition in which the nondeforming "plug" deforms in the cross-stream direction (only), greatly simplifying the calculations but suppressing the importance of sidewall drag. As a result, the estimates of bankfull discharge presented below are somewhat overestimated. Debris flows, however, have some capacity for self-confinement (Sharp, 1942) and bankfull discharge is in fact a minimum estimate of the true conveyance capacity of a channel. Furthermore, from a more sophisticated analysis presented by Whipple (1992), it is known that for the broad channels of the bajada the one-dimensional analysis only overestimates the discharge by 15%–50%, with the greater errors occurring for higher values of the yield strength. The weak dependence on flow-yield strength implies that channel conveyance capacity will be slightly more sensitive to changes in flow rheology than indicated in the calculations presented below. This effect, however, is minimal, and the predicted sensitivity of channel conveyance capacity to variations in flow rheology or to changes in channel size and slope is not significantly affected by the above simplification of the open-channel flow problem.

Results. Channel conveyance capacity varies non-linearly with flow rheology (Fig. 12A), and declines steadily down-fan as channel gradient and size diminish (Fig. 12B). Low-sediment-concentration debris flows travel farther down-fan than high-sediment-concentration flows because (a) they have lower yield strengths, and (b) their lower yield strengths and viscosities allow them to remain confined within channels for a greater distance down-fan. This interaction causes a greater down-fan segregation of debris flows according to rheology than anticipated on the basis of yield strength alone. Because channel size and gradient decline with distance down-fan, however, unless flow volume is consumed by deposition on channel floors, even the most mobile debris flows eventually spill overbank and spread on the fan surface.

According to Figure 12, flows with peak discharges less than or equal to the conveyance capacity of a channel remain fully confined and are translated farther down-fan without significant flood-peak attenuation. Flows with peak discharges in excess of channel conveyance capacity lose part of their volume overbank with consequent flood-peak attenuation. That portion of a debris flow which is forced overbank spreads laterally, thins, and deposits. Near-zero values (<25 m^3/s on Fig. 12) of the calculated bankfull discharge, therefore, indicate imminent deposition of all debris flows, regardless of peak discharge. This follows because flows with peak discharges up to the bankfull value are approaching the critical flow depth and will soon freeze as channel plugs, and flows with greater peak discharges will be forced overbank where deposition will likewise occur. The very low conveyance capacities of channels for high-sediment-concentration debris flows therefore anticipates their propensity for blocking channel courses.

DISCUSSION

Patterns of deposition by debris flows with variable rheologies, volumes, and hydrographs produce the surface morphology of debris-flow fans. Variations in the physical properties of the debris flows delivered to any given fan arise from a combination of (1) differing initiation mechanisms (Fairchild, 1987), (2) differences in water content at time of failure, (3) differences in the GSD of the source regolith, and (4) varying degrees of dilution of the debris flows by incorporation of floodwaters while in transit to the fan head (see Pierson and Scott, 1985). These variations can be described statistically as a frequency distribution of debris-flow rheologies, volumes, and hydrographs at the fan head. The rheological analysis presented above allows us to describe, albeit qualitatively, the dependence of depositional morphology on the frequency distribution of debris-flow properties. In order to facilitate this discussion, we consider the morphological consequences of deposition by the two end members of the possible suite of debris-flow rheologies: "high-sediment-concentration" debris flows (high-C_s flows) and "low-sediment-concentration" debris flows (low-C_s flows). Although many debris flows exhibit surging behavior characterized by spatially variable sediment concentrations (highest at the flow front and progressively lower toward the tail) (Pierson, 1984, 1986), in the discussion that follows we treat the high-C_s and low-C_s surges conceptually as separate events.

High-Sediment-Concentration Debris Flows

High-C_s debris flows are only mobile on relatively steep slopes. They overtax the conveyance capacity of even steep channels on the upper part of the fan (Fig. 12) and either freeze as lobate snouts a short distance after overtopping channels or freeze within channels as elongate plugs, depending on whether their peak discharge exceeds the conveyance capacity of the channel or not. Their deposits are generally limited to the upper reaches of the bajada where slopes exceed 4.5°. The rough, undulating surface of the upper reaches of the bajada results from repeated and overlapping deposition of such flows. High-yield-strength flows have great boulder-transporting competences (Rodine and Johnson, 1976), and the boulder-laced character of their deposits augments the rough appearance of the upper reaches of the bajada. Many of the "boulder fields" mapped on the upper reaches of the fans represent degraded or partially buried accumulations of high-C_s–debris-flow deposits within which individual flow boundaries could not be reliably demarcated in the field.

Mappable overbank lobes of high-C_s flows are rare except near the fan head and debris-flow deposition is largely directed by the channels (Fig. 3). The channels themselves, however, are often blocked by deposition of high-C_s debris flows, which plays an important role in the long-term evolution of the channel system and in the dispersal of debris-flow sediments across the fan. In many cases the upstream ends of discontinuous channel segments are marked by well-defined debris-flow lobes (Figs. 2, 3, and 7). In other cases, abandoned channels have been buried from

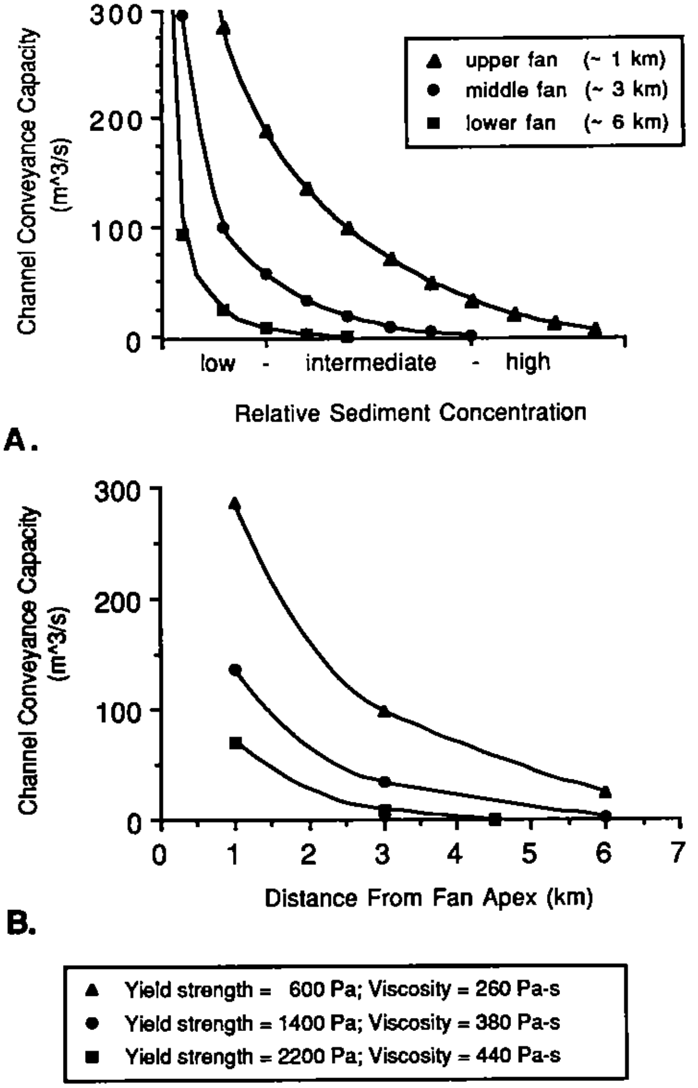

Figure 12. Conveyance capacities calculated for channels representative of the uppermost (~1 km down-fan), middle (~3 km), and lower fan (~ 6 km) are shown in (A) as functions of rheology (sediment concentration). Yield strength and viscosity are correlated as constrained by data in Table 3 (Whipple, 1992), and are related to "relative sediment concentration" as follows: "low" = $\tau_0 < 1{,}000$ Pa $\mu_B < 300$ Pa-s; "high" = $\tau_0 > 3{,}000$ Pa, $\mu_B > 500$ Pa-s. Channels used in the calculations have cross-sectional areas of 31, 24, and 20 m^2, and gradients of 0.087, 0.070, and 0.052, for the upper, middle, and lower fan respectively. (B) Results of calculations from (A) rescaled to emphasize the gradual down-fan decrease in channel capacity for debris flows with "low" and "intermediate" sediment concentrations.

up-fan, but no distinct debris-flow snout could be identified in the field and thus does not appear on the geomorphic maps. We infer that new channels are cut in response to channel blockage by high-C_s debris flows; floodwaters are diverted around recently deposited debris-flow plugs, and avulsion of the channel results. The network of sub-parallel, abandoned channels thus arises from repeated avulsions of a single channel, driven by deposition of high-C_s debris flows. Typically, however, final diversion of flow to a new channel course is not accomplished instantaneously and the upper portion of the plugged channel is usually obliterated by deposition of debris flows during the interval between channel blockage and the excavation of a new channel. Localized deposition during this interval builds up a local topographic high which adds to the relief or roughness of the fan surface. As a result, new channel courses rarely diverge immediately behind the channel plugging debris flow, but rather some distance up-fan (Fig. 3).

Low-Sediment-Concentration Debris Flows

Debris flows with relatively low sediment concentrations have low yield strengths and viscosities (Fairchild, 1985; O'Brien and Julien, 1988; Phillips and Davies, 1991; Major and Pierson, 1990; Whipple, 1992). They can traverse slopes as gentle as 1°–2°, are capable of spreading laterally into thin sheets, have limited boulder-transporting capabilities, and can attain high velocities, particularly where confined in channels. On the upper reaches of the bajada, large discharges of such flows remain within the channel (Fig. 12). As a result, the fate of a low-C_s flow is dictated largely by the condition of the channel system it encounters. When an unblocked channel presents an open transport corridor, one of these flows typically (1) moves rapidly down-fan through the channel, leaving behind thin sheets of mud and rocks on interfluves wherever peak discharge exceeds channel-conveyance capacity; (2) deposits boulders on channel margins during overbank flow; and (3) spreads laterally into a wide, smooth lobe, usually devoid of boulders, at the point down-fan where flow discharge greatly exceeds channel-conveyance capacity. Selective deposition of boulders occurs not only along channel margins but also in zones of expanding or unconfined flow, such as where channels are partially infilled but not blocked. This selective deposition process has been recognized elsewhere (Suwa and Okuda, 1983; Fairchild, 1985; Suwa, 1988) and contributes to the formation of "boulder fields" and to the relative depletion of boulders in the distal fan deposits. If the channel has actually been blocked, rather than just partially infilled, by a preceding high-C_s debris flow, wholesale deposition of even the most mobile debris flows may occur on the upper slopes of the bajada. In this case, the low-C_s flows are trapped behind the intervening channel plug and contribute to the rapid in-filling and obliteration of the up-fan reach of the recently plugged channel. Thus, low-C_s debris flows are responsible for (in part) the rapid in-filling of the upper reaches of blocked channels, the aggradation of the interfluves of the middle and upper fan, and the aggradation of the lower fan. As a result, the distal portion of the fan develops a smooth, low-relief surface, and the interfluves on the middle fan are likewise smooth.

Controls on Depositional Morphology

Rheological controls on depositional patterns in combination with fluvial controls on the erosion of channels determine the morphology of an aggrading fan surface. The depositional morphology of debris-flow fan surfaces is most directly affected by the efficiency or vigor of the fluvial system and the frequency distribution of debris-flow rheologies, volumes, and hydrographs (here represented by the peak discharge). Fluvial processes control (1) channel size and down-fan extent; (2) the likelihood that a recently deposited channel plug will be scoured away; and (3) the duration of the interval between channel blockage and the establishment of a new, continuous channel course. For a given fluvial system, the frequency distribution of debris-flow rheologies, volumes, and hydrographs sets (1) the slope of the fan surface (depending on the volumes of overbank flows and their yield strengths); (2) the proportion of the surface which is rough (characteristic of high-C_S flows) and smooth (characteristic of low-C_S flows); (3) whether debris-flow deposition characteristically produces wide overbank lobes or is restricted to narrow strips along channels (the former circumstance leads to steeper fan slopes and is favored by debris flows with high-peak discharges and volumes); and (4) the temporal frequency and spatial pattern of channel blockages. The last is particularly important because it controls the frequency of channel-shifting events. This determines both the extent and structure of the network of abandoned channels and the longevity of any given channel course, which importantly constrains the height that can be attained by aggrading levees and, therefore, limits the convexity of cross-fan profiles.

With the controls on the depositional morphology of debris-flow fans thus delimited, the morphological expression of different frequency distributions of debris-flow properties can be predicted in a qualitative manner. For instance, if built exclusively by high-C_S debris flows, the entire fan would resemble the steeper proximal reaches of the Owens Valley bajada. Slopes would be steep. The surface would have a rough texture, lacking the broad interfluves of the lower portions of the bajada. If the fluvial system were strong, the surface would exhibit many well-defined abandoned channels. A fan built exclusively by low-C_S debris flows would, on the other hand, have a gentler slope and smoother surface with few well-preserved channels. The latter follows because channel avulsion would be less frequent and shifting would more likely be driven by gradual up-fan migration of depositional centers. Any abandoned channels, furthermore, would tend to be filled in by subsequent overbank spreading of the low-C_S debris flows. Finally, a fan built by a strongly bimodal population of high- and low-C_S debris flows would likely exhibit a steep, proximal portion with surface features characteristic of high-C_S flows separated by a distinct break in slope from a smoother, more gently sloping lower fan.

In a less hypothetical application, the characteristics of the late Pleistocene depositional system preserved on the Owens Valley bajada can be constrained qualitatively. Channel longevity and channel-shifting intervals were apparently short; surface convexity is minimal, little levee aggradation has occurred (Figs. 5, 6, and 7), and an extensive network of abandoned channels is preserved on much of the bajada (see Fig. 2). High-C_S, channel-plugging debris flows must have occurred frequently. The general paucity of overbank lobes of high-yield-strength debris flows (Fig. 3), however, implies that (1) the high-C_S debris flows generally did not involve great volumes and peak discharges of material, and (2) the fluvial system was vigorous and managed to maintain relatively deep, continuous channels despite the frequent channel-blockage events. Further, the predominance of low-relief surfaces on the bajada (for example, the lower fan and the broad, smooth interfluves of the midfan) suggests that the greatest proportion of sediment was delivered to the fans as low-C_S debris flows.

CONCLUSIONS

A model has been presented which relates the morphology of an aggrading debris-flow fan to the physical properties of the debris flows (temporal frequency, rheology, volume, peak discharge) and the "strength" of the fluvial system. The conceptual framework for the model was based on field mapping on a bajada in Owens Valley, California, and the model is strictly applicable only to similar depositional systems. On the Owens Valley bajada, fluvial processes are dominantly erosional and the active channel system has at all times consisted of a single, or few, active channel(s). Debris-flow depositional patterns are controlled by the channels and the physical properties of the debris flows; channel avulsion, and hence the shifting of depositional loci, is driven by in-channel deposition of relatively immobile debris flows. Fans of the type described in our model are common in mountainous regions in both semi-arid (for example, Basin and Range province, United States) and humid-temperate (for example, Japanese Alps) climatic zones, and our model is applicable in a wide range of environments. Fans frequently inundated by huge debris flows that massively overwhelm their channels, however, such as those situated below active stratovolcanoes, are not well described by our model.

In our model, the morphology of an aggrading debris-flow fan is related to debris flow properties via a rheological analysis of debris-flow confinement (in channels) and runout. The rheological analysis assumes that (1) the visco-plastic rheological model adequately describes debris-flow behavior, (2) debris-flow mobility is sensitive to the water content of the slurry (sediment concentration), and (3) variations in matrix–grain-size distribution and the concentration of large boulders in the flow are less important to flow mobility than differences in the bulk sediment concentration. The last assertion is valid for the Owens Valley field setting but may break down in field areas where textural variability is greater. In such cases, the model must be augmented to consider variations in both texture and sediment concentration. With these assumptions, we show that channel capacity, and hence the degree of flow confinement, is very sensitive to changes in debris-flow sediment concentration, with important consequences for fan morphology. The model predicts that fan slope, roughness patterns, channel network structure, levee heights, and the convexity of cross-fan profiles are strongly influenced by the frequency distribution of debris-flow rheologies, volumes, and hydrographs delivered to the fan. The model provides a framework for the study of how and why morphological differences arise between debris-flow fans derived from different source areas or under different climates.

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