Depositional Processes in Large-Scale Debris-Flow Experiments[1]

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ABSTRACT

This study examines the depositional process and characteristics of deposits of large-scale experimental debris flows (to 15 m^3) composed of mixtures of gravel (to 32 mm), sand, and mud. The experiments were performed using a 95-m-long, 2-m-wide debris-flow flume that slopes 31°. Following release, experimental debris flows invariably developed numerous shallow (~10 cm deep) surges. Sediment transported by surges accumulated abruptly on a 3° runout slope at the mouth of the flume. Deposits developed in a complex manner through a combination of shoving forward and shouldering aside previously deposited debris and through progressive vertical accretion. Progressive accretion by the experimental flows is contrary to commonly assumed *en masse* sedimentation by debris flows. Despite progressive sediment emplacement, deposits were composed of unstratified accumulations of generally unsorted debris; hence massively textured, poorly sorted debris-flow deposits are not emplaced uniquely *en masse.* The depositional process was recorded mainly by deposit morphology and surface texture and was not faithfully registered by interior sedimentary texture; homogeneous internal textures could be misinterpreted as the result of *en masse* emplacement by a single surge. Deposition of sediment by similar, yet separate, debris flows produced a homogenous, massively textured composite deposit having little stratigraphic distinction. Similar deposit characteristics and textures are observed in natural debris-flow deposits in China. Experimental production of massively textured deposits by progressive sediment accretion limits interpretations that can be drawn from deposit characteristics and casts doubt on methods of estimating flow properties from deposit thickness or from relations between particle size and bed thickness.

Introduction

Debris flows are gravity-driven, highly concentrated mixtures of sediment and water commonly composed of poorly sorted rock, soil, organic matter, and sundry debris. Debris flow deposits typically are massively textured, poorly sorted, matrix-supported mixtures of sediment ranging in size from clay to cobbles and boulders meters in diameter (Jahns 1949; Johnson 1965, 1970; Fisher 1971; Pierson 1980; Suwa and Okuda 1983; Costa 1984). Deposits commonly are ungraded, although some exhibit normal or inverse grading of their coarsest fragments (e.g., Costa and Jarrett 1981; Janda et al. 1981; Koster and Steel 1984; Major and Voight 1986; Scott 1988; Blair and McPherson 1994; Vallance and Scott 1996). Where deposit termini are preserved they typically are lobate, have blunt margins that commonly are studded with coarse debris, and may form channel-bounding levees (e.g., Sharp and Nobles 1953; Johnson 1965, 1970; Costa 1984; Hooke 1987; Whipple and Dunne 1992; DeGraff 1994).

Most analyses of debris-flow, and kindred mass-flow, deposits assume that massive, poorly sorted textures result from simple *en masse* emplacement (e.g., Johnson 1965, 1970; Sparks 1976; Middleton and Southard 1977; Takahashi 1981; Fink et al. 1981; Pierson 1981; Costa and Jarrett 1981; Lowe 1982; Innes 1983; Costa 1984; Shultz 1984; Major and Voight 1986; Carey 1991; Battaglia 1993; Masson et al. 1993; Blair and McPherson 1994; Kohlbeck et al. 1994; Whipple 1994; Kim et al. 1995). Based on this assumption, methodologies have been developed to reconstruct physical properties of flowing debris from their deposits (e.g., Johnson 1984; Nemec and Steel 1984). Some studies, however, suggest that deposits from flowing granular debris, such as cataclysmic pyroclastic flows and huge volcanic debris flows, can result instead from prolonged incremental sedimentation (Fisher 1966; Smith and Lowe 1991; Branney and Kokelaar 1992; Vallance and Scott 1996; Kokelaar and Branney

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1996). These studies hypothesize that sedimentary textures in generally massive conglomeratic deposits may result from incremental rather than *en masse* deposition.

The capricious nature of many debris flows commonly hampers direct observations that may clarify the dominant depositional process. Observations (e.g., Jahns 1949; Okuda et al. 1980; Pierson 1980, 1986; Costa and Williams 1984; Zhang 1993), commonly made under adverse conditions, provide only a limited perspective of an event; rarely do observations cover an event from initiation to deposition. As a result few investigations link direct observation of flow behavior and depositional process to characteristics of deposits (e.g., Lawson 1982; Suwa and Okuda 1983); most interpretive studies of debris-flow deposits typically lack corroboration by direct observation of deposition.

Owing to the difficulties of directly observing natural flows and to the uncertainties involved in the interpretations of field deposits, analyses of debris flows have been augmented by experimental studies. However, existing experimental studies discuss results from small-scale flows; channels typically have been narrower than 20 cm and shorter than a few meters, volumes of source material have been limited to about 100 liters, and debris mixtures commonly have been restricted to clay, sand, or muddy sand slurries (Johnson 1965, 1970; Hampton 1975; Hooke and Rohrer 1979; Mizuyama and Uehara 1983; Van Steijn and Coutard 1989; Zimmerman 1991; Liu 1995; Whipple et al. 1995). Most natural debris flows, however, are very granular and typically contain a wide array of grain sizes but a restricted amount of fine material (<63 μm). Thus small-scale experiments are rarely representative of the natural process and have provided only limited insight on either the depositional process or characteristics of debris-flow deposits.

Expense and logistical difficulties have inhibited study of controlled experimental flows that approach the field-scale process. This paper presents results of experiments examining the depositional process, and the morphology, sedimentology, and stratigraphy, of deposits of several large, cohesionless experimental flows at a large debris-flow flume. This study is part of a broader experimental investigation of debris flows from initiation to deposition (Iverson et al. 1992; Iverson and LaHusen 1993; Iverson et al. 1996; Iverson 1997). This study attempts to determine whether an experimental basis exists to support the hypothesis that sediment emplacement by mass flows occurs incrementally, and if so, how that depositional process is manifest in deposit characteristics. The study provides the first large-scale experimental basis that permits linkage of flow behavior, depositional process, and deposit characteristics. Characteristics of the experimental deposits are compared with those of natural debris-flow deposits in China, because the Chinese deposits resulted from flows having transport characteristics similar to the experimental flows. The paper concludes with a discussion of the significance of the experimental results as they relate to interpretation of the sedimentology of field deposits and to methodologies for estimating the rheological properties of a debris flow from the characteristics of its deposit.

Large-Scale Debris-Flow Flume

The U.S. Geological Survey debris-flow flume (figure 1) in the H. J. Andrews Experimental Forest, Or-

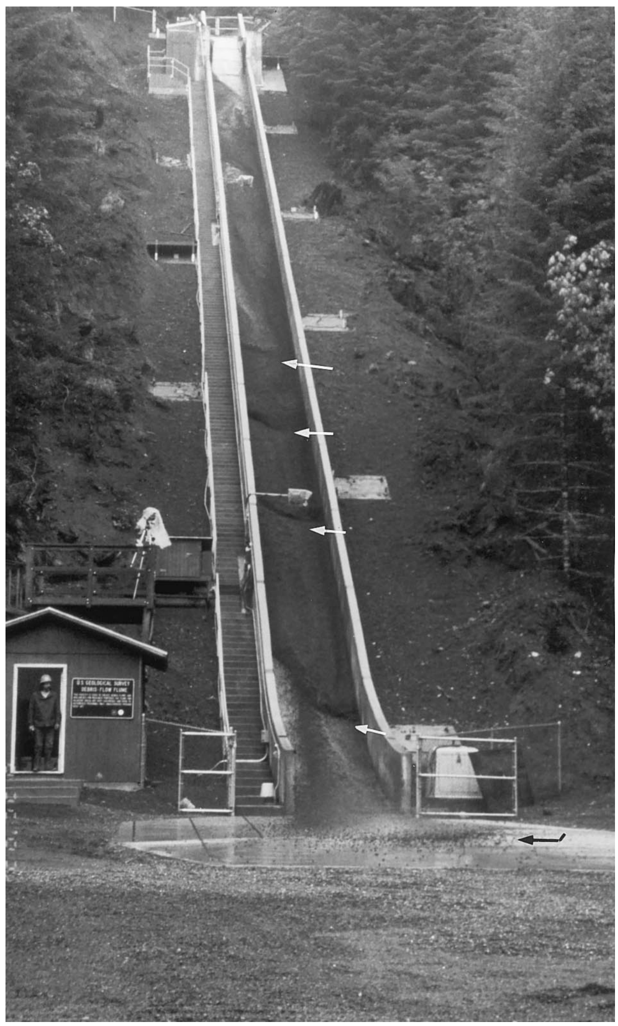

Figure 1. Experimental debris flow descending flume (experiment 4). Several surge waves develop (arrows) as flow descends flume. Note the runout surface beyond the flume. Flume is 95 m long, 2 m wide, and slopes 31°.

Table 1. Attributes of Experimental Debris-Flow Deposits

Number	Date (mmddyy)	Source debris[a]	Approximate degree of saturation (percent)	Source volume	Depositional area (unconfined) (m^2)	Length beyond flume mouth (m)	Length beyond confined channel (m)	Mean width (m)	Aspect ratio	Maximum thickness (m)	Source debris dry bulk density[b] (kg/m^3)	Deposit dry bulk density[b] (kg/m^3)
1[c]	052192	s,g	≪100	≈13	39.6	8.8	8.8	4.5	.51	.35	. . .	. . .
3	071692	s,g	≪100	7.4	23.4	6.3	6.3	3.7	.60	.36	1630	1720
4	092592	s,g	100	6.6	52.9	14.1	14.1	3.7	.26	.28	. . .	. . .
5	040793	s,g	100	6.2	38.8	11.9	11.9	3.2	.27	.24	2000	. . .
6	040893	s,g	100	6.5	46.4	10.0	10.0	4.6	.46	.20	. . .	. . .
7	050693	s,g	90	12.1	60.2	14.7	14.7	4.0	.27	.23	1820–2000	2520–2620
8[d]	072293	s,g	100	9.4	31.8	. . .	6.2	5.2	.84	.28	1630	1130–1610
9[d]	091593	s,g	90	11.5	46.7	. . .	9.0	5.2	.58	.44	1590–2010	1830–1870
10[d]	091693	s,g	100	10.8	48.9	. . .	7.4	6.6	.89	.43	1580–1720	1830–2020
11[e]	101993	s,g	100	10.0	64.1	30.3	15.8	4.1	.26	.26	1540–2210	1700–1870
12[e]	102193	s,g	100	8.9	20.0	21.3	6.5	3.1	.48	.25	1490–1630	1780–1880
13	041994	s,g	100	8.4	69.0	15.2	15.2	4.5	.30	.32	1630–1810	1870–1930
14	042194	s,g	100	9.2	65.8	16.7	16.7	3.9	.23	.24	1630–1960	1830–1940
15	052694	s,s,g	100	9.0	80.6	14.9	14.9	5.4	.36	.22	1400–1700	1630–2470
16[e]	072194	s,s,g	100	10.3	67.4	29.0	14.6	4.6	.32	.18	1480–1600	1630–1700
17[f]	083194	s,s,g	70	9.0	50.9	21.4	12.8	4.0	.31	.14	1340–1410	1680–2050

[a] s,g = sand and gravel mixture; s,s,g = silt, sand, gravel mixture.
[b] Collected at source debris and deposit surfaces (Iverson in press).
[c] From J. E. Costa (unpublished data).
[d] Curved-channel experiment.
[e] Channel confined across concrete runout pad; deposition primarily on gravel-covered runout surface.
[f] Channel confined 8.5 m across concrete runout pad.

egon, is a reinforced concrete channel 95 m long, 2 m wide, and 1.2 m deep (Iverson et al. 1992). The smoothly bedded structure slopes 31° along the upper 88 m and gradually flattens to a 3° runout surface across the lower 7 m (Iverson and LaHusen 1993). Ten meters below the head of the flume a steel gate is used to control the release of as much as 20 m^3 of debris. A smooth concrete runout surface extends beyond the flume mouth; beyond that is a gravel surface. Numerous instruments measure flow depth, basal normal forces, and basal pore-fluid pressures in both the channel and runout area (Iverson and LaHusen 1993; Iverson et al. 1992; Iverson 1997; Major 1996). Still and video cameras record the release, transport, and deposition of each experimental flow from several perspectives.

Experimental Debris Flows

To create a debris flow, sediment is loaded behind the steel gate at the head of the flume, soaked with water, and abruptly released. Sediment used in these experiments was obtained from a local commercial contractor and was derived chiefly from local fluvial sources. Several experiments used a poorly sorted mixture of sand and gravel, having clasts as large as 32 mm in diameter, that contained about 1% mud, particles <63 μm in diameter (table 1). A few experiments used a mixture of silt, sand, and gravel (table 1) to provide a greater quantity of mud, about 2 to 4 wt %. Thus even the finer-grained mixtures used at the flume were cohesionless (figure 2).

Sediment mixtures for the experiments were chosen on the basis of composition, size, and availability. One goal was to use realistic geologic debris (Iverson and LaHusen 1993)—debris flows can range in composition from relatively fine-grained silty-clay-rich slurries to coarse-grained cobble-boulder dominated flows (e.g., Costa and Williams

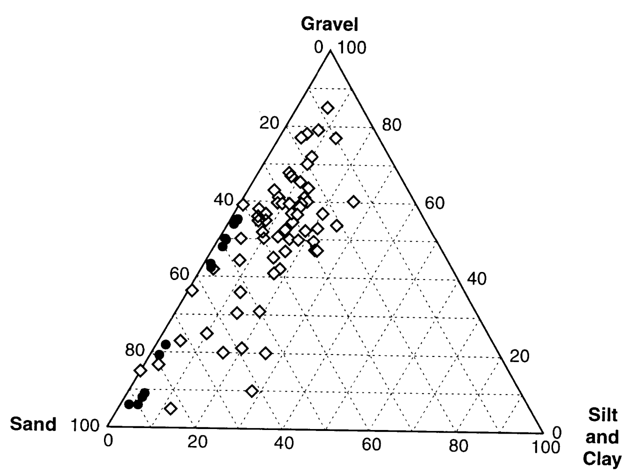

Figure 2. Ternary plot of grain-size distributions of source debris used in experiments (solid circles) and of various natural debris-flow deposits (open diamonds).

1984). Most are composed of some intermediate mixture that is dominantly granular and clay-poor (figure 2). The sediments in the experiments are poorly sorted mixtures of cohesionless debris that contain particles at least as large as pebbles. These mixtures avoid mechanical influence of cohesion owing to clay. However, even debris flows with relatively large proportions of clay (>5–10 wt %) are composed dominantly of interacting granular particles (e.g., Vallance and Scott 1996), and matrix cohesion may provide only a minor contribution to overall mechanical strength (e.g., Franz and Voight 1995; Major 1996). Mixtures composed solely of sand and gravel simulate the simplest system of cohesionless debris representative of realistic debris flows and therefore provide a logical starting point for experimental study. Silt was added to some experimental mixtures to study the effects of small amounts of mud. Particle size was restricted to ≤32 mm to avoid excessive wear of the flume bed and for safety reasons.

The experimental debris flows (figure 1) typically are thin, rapidly moving, unsteady, and nonuniform. After gate release, the source mass rapidly elongates and thins as it flows downslope (Iverson and LaHusen 1993). The leading edge of each flow commonly is marked by a diffuse "wave" of dry saltating, coarse particles. This diffuse wave is followed by a wet massive flow body. Flows invariably develop waves that surge down the channel (figure 1). These kinematic surge waves develop spontaneously along the channel within the massive body of the flows, but they do not develop systematically; nor do the same number of waves always develop. Larger, faster-moving surges commonly overtake and cannibalize slower-moving surges. Surge waves typically sweep down the flume at velocities from 6 to 13 m/s. At 67 m downslope from the release gate, surge waves in seven experiments had an average speed of 11 m/s and a period of 1 second (Iverson et al. 1994). Waves commonly were ~10 to 20 cm deep (crest to bed); flow depth between waves generally was thinner (Iverson et al. 1992, 1994). Detailed analysis of the surge waves is found in Schonfeld (1996).

The pulsing nature of the experimental flows is common in natural debris flows. Flow surges have been noted in a variety of physiographic settings, with periods that commonly range from a few seconds to several minutes or longer (Jahns 1949; Sharp and Nobles 1953; Hooke 1967, 1987; Morton and Campbell 1974; Wasson 1978; Costa and Williams 1984; Pierson 1986; Davies 1988; Davies et al. 1991; Cruden and Lu 1992; Harris and Gustafson 1993; Zhang 1993). Previous explanations for pulsing of debris flows include episodic input from multiple source areas (e.g., Sharp and Nobles 1953); piecemeal failure of a single source area (e.g., Sharp and Nobles 1953); episodic damming and release of debris within a channel (e.g., Gallino and Pierson 1985); and intrinsic fluid-mechanical instability (Davies 1986, 1988, 1990). The behavior of the experimental flows at the debris-flow flume shows clearly that surge waves can develop as a result of mechanical instability within a flow from a single source mass, and that they can form in the absence of any constrictions or blockages within a channel.

Large-Scale Experimental Debris-Flow Deposits

Analysis of experimental deposits included: (1) measuring deposit shape and thickness distribution; (2) mapping surface textures; (3) mapping tracer-particle distributions; (4) measuring near-surface bulk densities (Iverson 1997); (5) dissecting deposits to examine interior textures and collect sediment samples; and (6) reviewing video and still photographs of the depositional process. Deposits typically were removed from the runout area before a subsequent flow was released. In one set of experiments, however, deposits from two flows were accumulated in order to examine the effect of in situ debris on deposition by a subsequent flow and to examine the development of stratigraphy by multiple flows.

Individual Deposits. Experimental flows deposited sediment abruptly beyond the flume mouth on a smooth, gently sloping (3°) concrete surface. Flows not confined across the runout surface traveled as much as 17 m beyond the flume; flows laterally confined across the concrete runout surface traveled as much as 30 m beyond the flume. Deposits development was complex, a combination of shoving forward and shouldering aside debris from earlier waves as well as horizontal and vertical accretion. Deposits exhibited morphologic features common to many natural deposits, such as lobate platforms, steep, blunt margins, marginal levees, and arcuate surface ridges (figure 3). Deposits typically were <40 cm thick (figure 4) (table 1) and composed of a poorly sorted, massive, graded to ungraded mixtures of particle sizes.

The depositional process of each experimental flow was strongly influenced by the water content of the source material, whereas deposit platforms were influenced both by water and by substrate topography. Source debris was classified as saturated or unsaturated based on piezometric measurements of the position of a water table (Iverson 1997; Iverson et al. 1996). The objective in each experi-

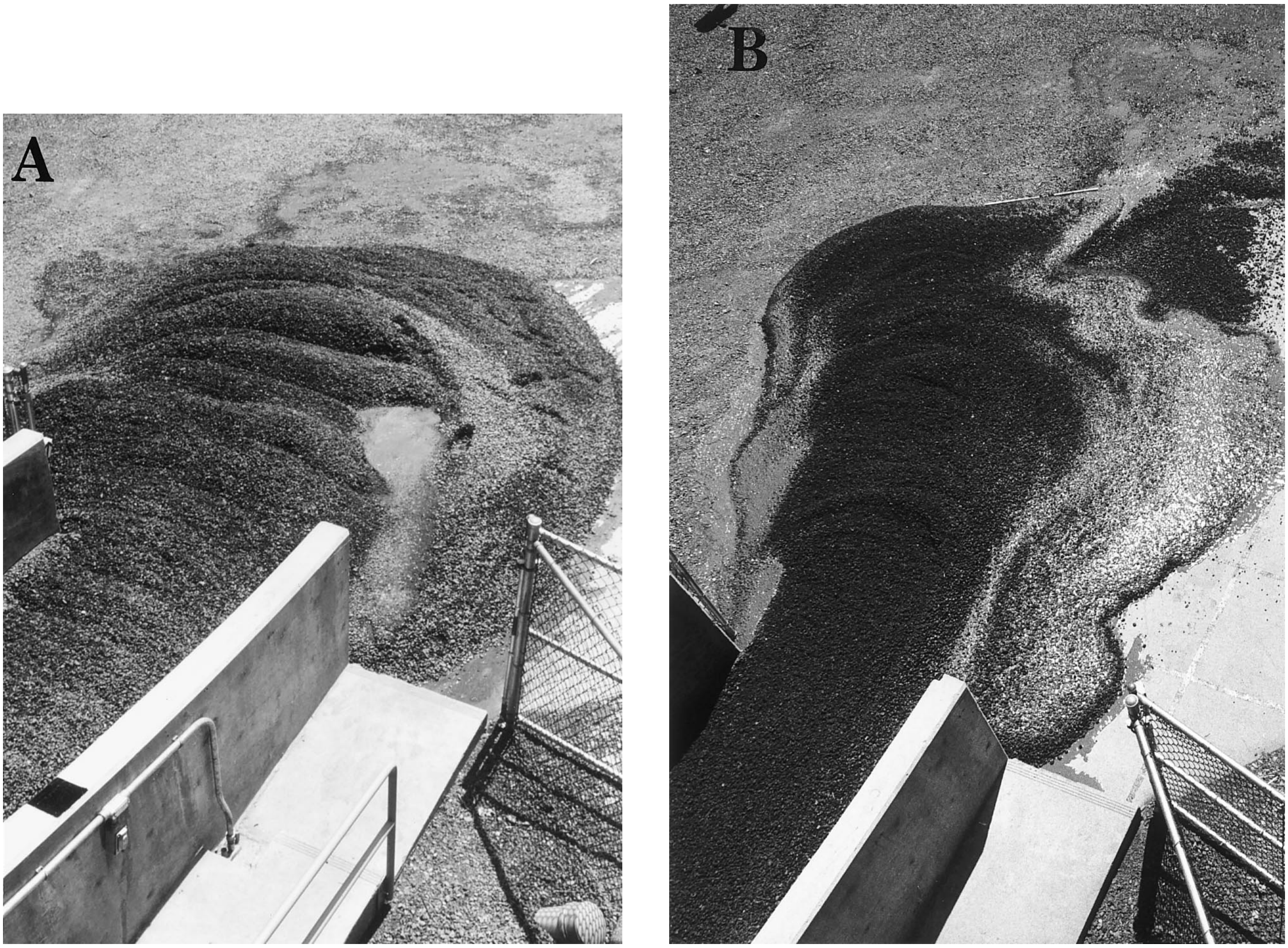

Figure 3. Experimental debris-flow deposits from unsaturated flows. Characteristic features similar to those in natural deposits include: lobate shapes, blunt margins, and concentrated surface gravel. Note the several prominent arcuate surface ridges on each deposit. *A.* Deposit of experiment 2. *B.* Deposit of experiment 3. Compare figure B with figure 5.

ment was to fully saturate the source debris; however, source debris in a few early experiments clearly was not saturated. Deposits from those early unsaturated flows accumulated substantially differently than those from later apparently water-saturated flows. The apparent degree of source material saturation (table 1) is only approximate, because water commonly leaked beneath the gate, and air remained trapped in interstices of the sediment.

Deposits from Unsaturated Flows. Deposits from unsaturated flows typically formed relatively thick lobes that had a high aspect ratio, the ratio of mean deposit width to maximum unconfined deposit length (table 1). Three deposits (experiments 1, 2, 3) had equant planforms, aspect ratios >0.5, and steep and blunt margins (figures 3, 4) (table 1). Mean thicknesses were 16–20 cm, maximum thicknesses about 35 cm (figure 4) (table 1). Subtle to prominent arcuate ridges a few to several centimeters high (figure 3) dominated surface morphology. Similar high-relief surface ridges are found on several natural deposits (Jahns 1949; Curry 1966; Shaller 1991). Gravels (8–32 mm diameter) dominated surface sedimentology (figures 3, 5). The deposit from a fourth source mass that was not fully saturated (experiment 17; table 1) (figure 4) was morphologically more characteristic of a saturated-flow deposit (discussed below). Volume contraction of source debris following gate release may have brought the ensuing flow to a nearly saturated state, which subsequently emplaced a deposit resembling that from a saturated flow. Near-surface dry bulk densities of the source debris and of that experiment's deposit suggest that the sediment may have densified 25% to 50% during transport (table 1).

Sequential photographs reveal that deposits from unsaturated flows formed mainly by succes-

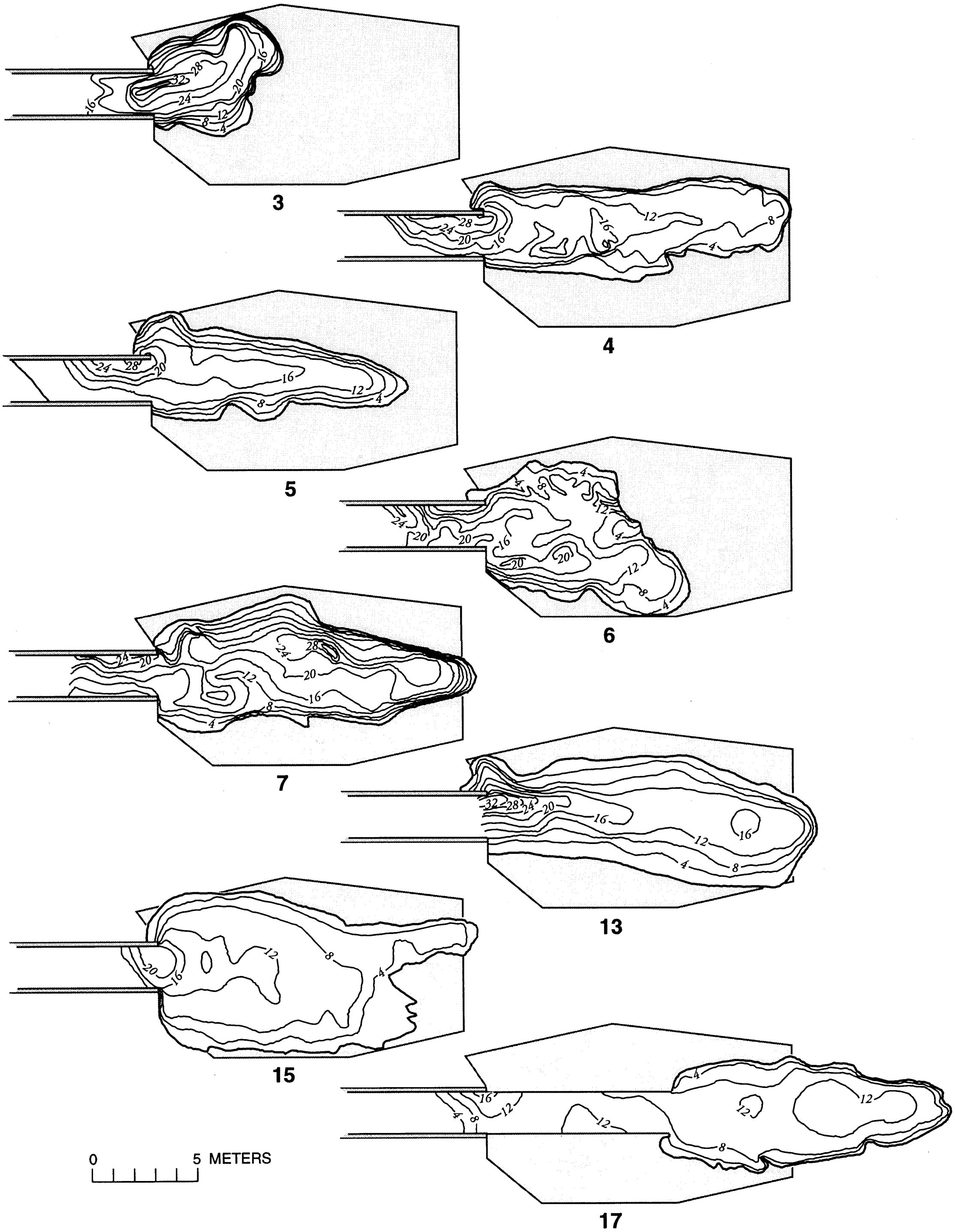

Figure 4. Isopach maps of experimental deposits. Contour interval is 4 cm. Experiment 1 data from J. E. Costa (unpub. data).

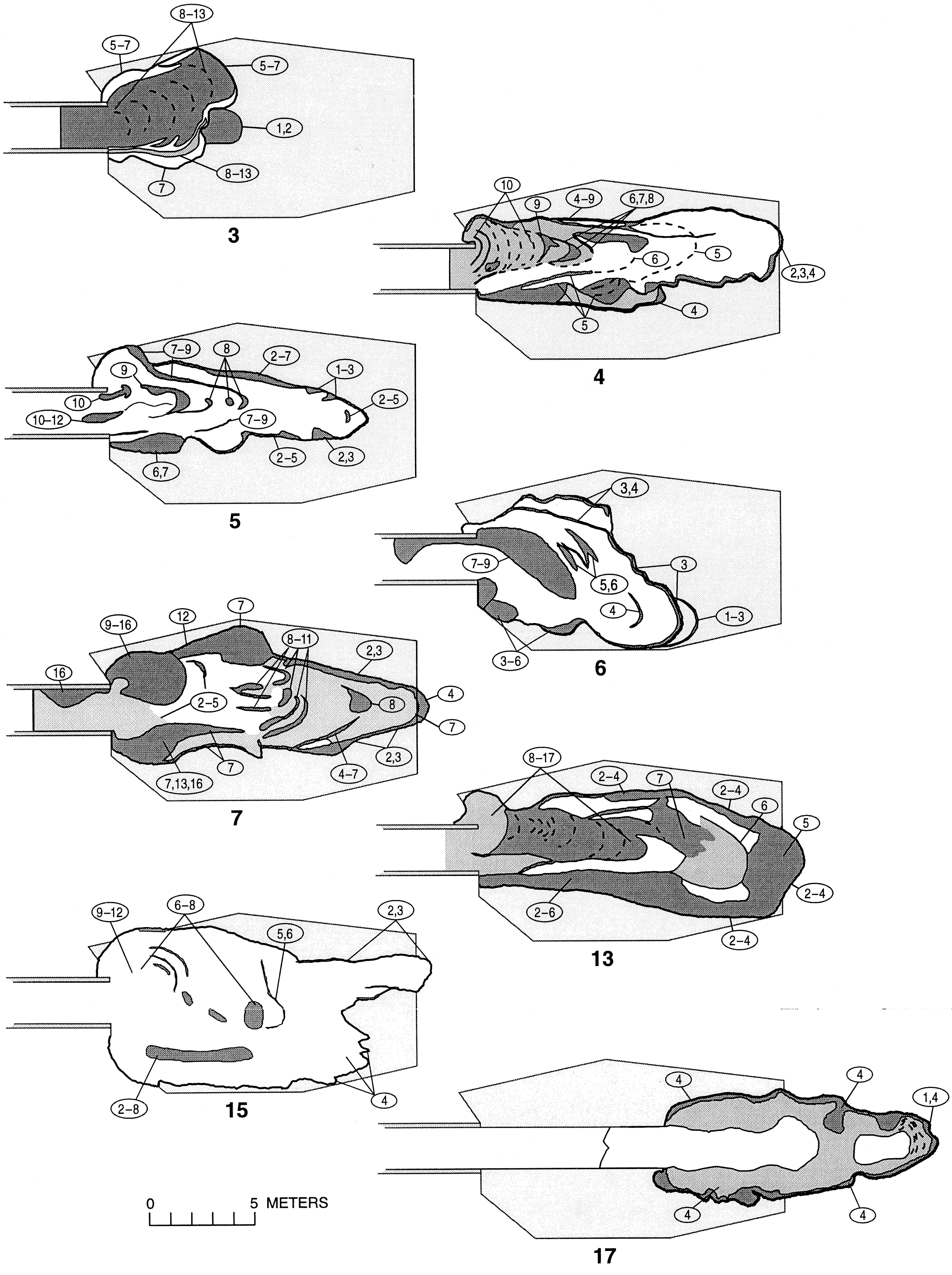

Figure 5. Surface textures developed on experimental debris-flow deposits. Dark stippled pattern represents dominantly gravel surface; light stippled pattern represents gravelly sand surface; white areas represent sandy surface. Dashed lines represent areas of positive surface relief. Numbers refer to surge or surges responsible for surface texture observed at that location. Deposit of experiment 3 is from an unsaturated flow. All others are from "saturated" flows.

sive surges partly overriding and partly shoving forward debris emplaced at the mouth of the flume by earlier waves (figure 5). Thus new material progressively accreted distally to proximally, gradually enlarging the deposit. Debris emplacement generally migrated from the toe of the deposit upslope as later surges pushed into and shouldered aside but generally did not override earlier-deposited sediment.

Sourceward accretion of sediment in unsaturated-flow deposits is revealed by colored tracer particles in the source material. Granule-sized tracer particles placed near the front of the source debris of experiment 1 were near the front and along the margins of the resulting deposit. Tracer particles placed near the rear of the source debris generally were near the rear of the deposit, within the lower confines of the flume (Costa 1992). The dispersal pattern of tracer particles within this deposit clearly indicates primarily horizontal rather than vertical accretion.

Deposits from Saturated Flows. Deposits from saturated flows were longer and thinner than those from unsaturated flows. Saturated-flow deposits typically were <30 cm maximum thickness and commonly had low aspect ratios, usually less than about 0.3 (figures 4, 6) (table 1). Deposits of unconfined flows with about 2–4% mud (notably experiment 15) had aspect ratios slightly larger than 0.3 and were notably thinner than those with less mud (figure 4).

Deposits from saturated flows typically had low-relief surface morphology and variably shaped margins. Surfaces usually were flat and had clusters and streaks of coarse clasts that distinguished surge boundaries (figures 5, 7). Margins locally had poorly developed levees; margin shapes ranged from steep and blunt, especially in distal reaches, to tapered and nearly wedge-shaped. This diversity attests to heterogeneity of strength within a single flow mass as it came to rest. Deposits of saturated flows did not develop the prominent surface ridges prevalent on unsaturated flow deposits.

Deposits from saturated flows developed mainly by incremental vertical, rather than horizontal, accretion of sediment transported by shallow (~10 cm deep), successively overlapping surges (figures 5, 7). Although later surges locally pushed into and shouldered aside some earlier-deposited debris, they more commonly overrode, or were deflected by, debris already emplaced. This mode of deposition contrasts with the depositional process of unsaturated flows. Nevertheless, the locus of deposition gradually migrated upslope as the mass and momentum of trailing flow diminished. The largest surge, regardless of its position relative to the flow front, commonly swept across the entire deposit (e.g., figure 7*E*–*J*).

Figure 6. Experimental debris-flow deposit from a saturated flow (experiment 7). Note elongate shape of the deposit and areas of accumulated clean gravel (light-colored).

Groups of colored tracer particles (16–32 mm gravel sifted from the source debris and painted) were placed in the source sediments of experiments 15 and 16. In each experiment, red particles were placed at the front base of the source and yellow particles near the centroid of mass. Black particles were placed on the rear surface of the mass in experiment 15. Locations and stratigraphic position of colored particles were mapped in the respective deposits (see Major 1996).

Locations of tracer particles in experiment 15 reflect a combination of vertical and horizontal sedimentation. Red particles placed at the lower front of the source mass were smeared along the length of the base of the deposit though concentrated in the distal half and in the "spray" of particles that had saltated ahead of the flow. Yellow particles were located mainly in the proximal half of the deposit and lay stratigraphically above red particles. Black particles were located mainly on the surface of the proximal one-third of the deposit. This dispersal pattern resembles that of the unsaturated-flow deposit from experiment 1 (Costa 1992). Overall, particles in the sediment mass retained their general horizontal position from the source debris. Yet elongation of the source mass during transport and vertical accretion by successively overlapping surges left a clear imprint on the resulting deposit. Tracer particles in experiment 16 demonstrate mainly vertical accretion of sediment. Surface and subsurface locations of tracer particles show that the source debris elongated during transport and that the center of mass overrode the front of the source debris. Red particles were found mainly in the proximal part of the deposit, whereas yellow particles were found along the length of the surface but were concentrated in the distal half of the deposit. This dispersal pattern contrasts strikingly with those in the deposits of experiments 1 and 15 and shows that source debris can exchange initial horizontal positions as a result of progressive sediment accretion. Vallance (1994) reports similar relations in laboratory experiments with glass beads.

Photographic analyses, surface morphology and sedimentology, and distributions of tracer-particles in deposits show clearly that deposition by a single debris flow can involve horizontal sourceward accumulation of debris as well as progressive vertical accretion. These data also show that deposit morphology and surface texture register the complex depositional history of debris-flow deposits and provide a link between deposit character and flow behavior. But do internal textures of debris flows faithfully register the depositional process? I now turn attention to an analysis of the internal sedimentology and stratigraphy of the experimental deposits.

Interior Texture and Sedimentology. Deposits were examined days to a few weeks after accumulation. Sedimentary features preserved were primary mass-flow features rather than secondary features resulting from alteration or reworking of the deposits. Areas disturbed by rainfall runoff or watery afterflow following an experiment were typically confined to narrow portions of the proximal few meters of the deposits. Each deposit was allowed to drain until trenching could produce vertically standing exposures.

No discernible vertically exposed sedimentary textures related to the observed sourceward accretion of debris by unsaturated flows. Deposits commonly exhibited inverse grading of particles >8 mm (figure 8*a*). Clasts at the surface were distinctly coarser and better sorted than were subsurface particles, and in general the basal 5 cm lacked the coarsest particle sizes. Otherwise the internal textures appeared to be massive and homogeneous. Well-sorted gravel commonly concentrated on the lee sides of surface ridges. Except for the concentrated surface gravel there was no difference in the interior sedimentary texture between ridges and intervening troughs. If the ridges are related to compressional deformation by impact of later surges, there is no internally preserved textural evidence of such compression, such as detectable displacement along shear planes. Systematic bulk sampling throughout the deposit also failed to detect textures indicative of sourceward accretion. The experimental deposits had bulk particle-size distributions everywhere identical to source materials. No detectable longitudinal or lateral sorting of particle sizes occurred.

Deposits from saturated flows typically lacked discernible internal texture related to the observed vertical accretion of debris. These deposits locally exhibited inverse grading of particles >8 mm (figures 5, 8*B–D*). Where locally graded, the deposit subsurface was more poorly sorted than the surface, and the subsurface mean particle size was substantially finer than the surface mean particle size. Similar observations have been made in natural deposits (e.g., Suwa and Okuda 1983). Where distinct surface gravel clusters (figure 5) were absent, deposits typically were massive, homogenous, and unsorted; there was little vertical variation in grain size characteristics (see Major 1996). Clusters of surface gravel are related primarily to emplacement of surge fronts. In vertical section gravel clusters are scanty sedimentologic evidence of deposition by multiple surges. In these experiments there is little if any discernible subsurface texture to indicate deposition by vertical accretion. The only clear evidence in vertical section that deposits resulted from multiple surges is found near deposit margins where finer-grained, poorly sorted debris locally overlies well-sorted gravel deposited by the leading edge of the debris flow (figure 8*D*). I detected no significant bulk grain-size variation longitudinally and irregular variation laterally, which generally represented smeared-out, well-sorted gravel deposited by the leading wave of saltating particles. The general lack of spatial variation of grain-size distribution results from the short runout distance and rapid deposition by the experimental flows. Longer runout distances and prolonged event durations

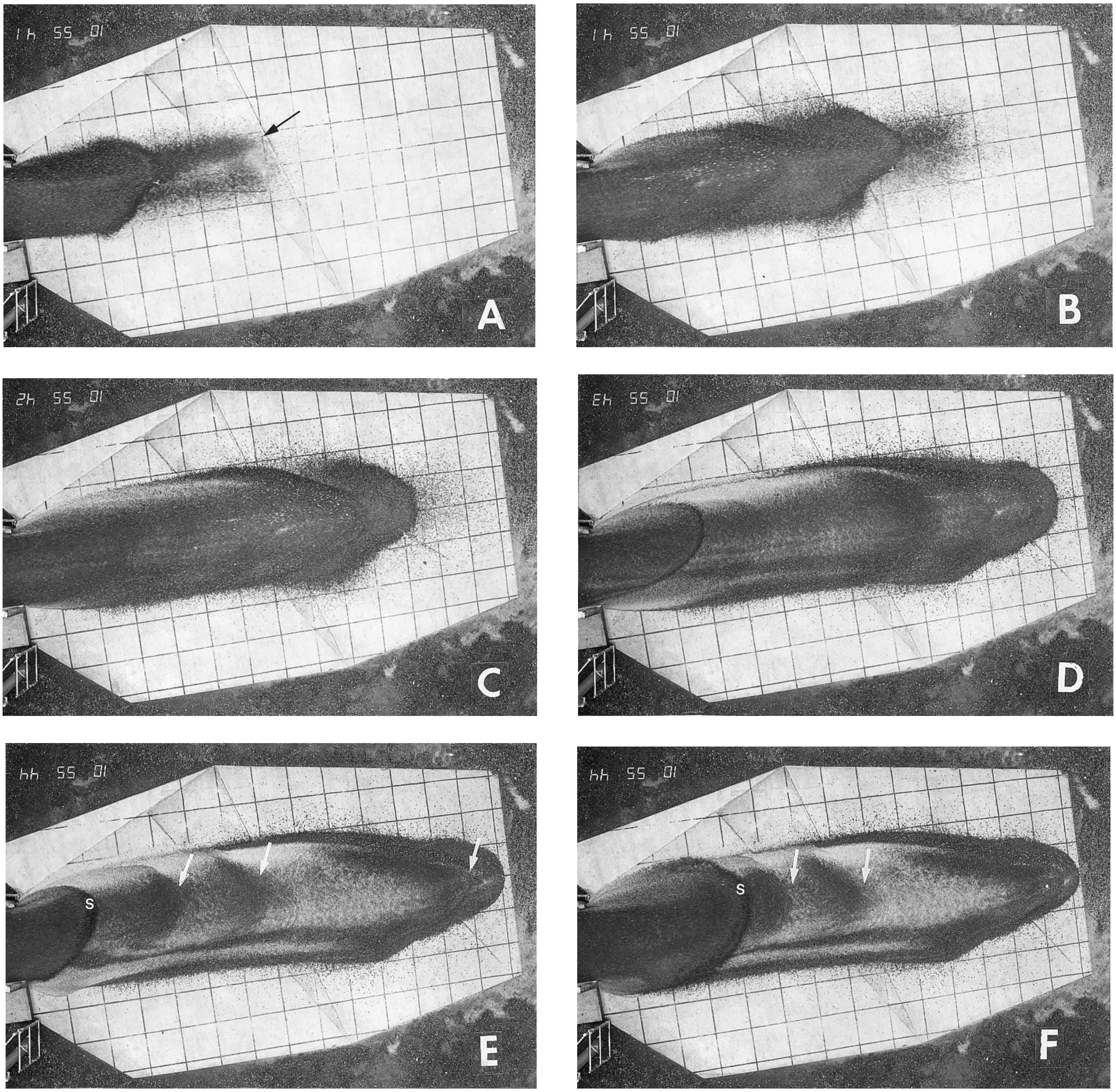

Figure 7. Sequence of vertical photographs illustrating debris-flow deposit forming by progressive vertical accretion of sediment transported by successively overlapping surges. The sequence encompasses approximately 9 seconds. A region of saltating dry particles (arrow) precedes the main flow body (*A*). Note how one large surge (s) sweeps completely over earlier-deposited material (*E–J*). Lobate morphology and concentrated patches of surface gravel (arrows in *E, F*) identify surge margins. Compare this sequence of photographs with figures 5 and 6 to link depositional process with deposit character. A 1 m^2 grid provides scale.

can lead to detectable variations in grain size within deposits from a single flow mass (e.g., Pierson and Scott 1985; Vallance and Scott 1996).

Multiple Deposits. To gain further insight on interior textures and relations between debris deposited by separate flows, the deposits from two identical flows released on consecutive days (experiments 5 and 6) were allowed to accumulate (figure 9). The deposit of experiment 5 accumulated in the manner typical of saturated flows, emplaced incrementally by a series of shallow, closely spaced surges. The deposit was widest where it left the flume and gradually tapered to its distal end (figures 4, 5). The deposit was convex in cross-section, had rounded margins, and a flat surface. Deposit margins were dominated by well-sorted gravel; clusters

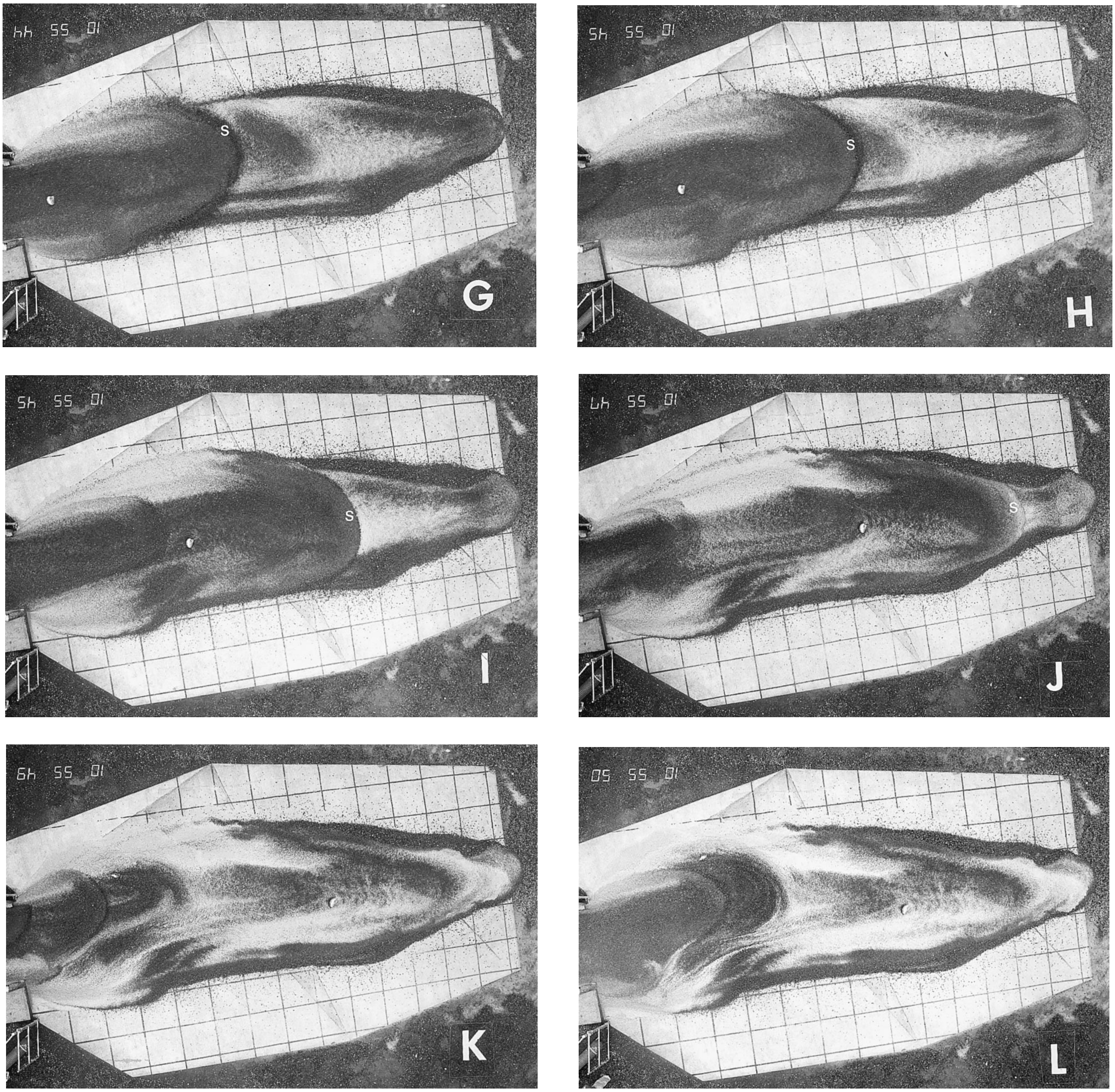

Figure 7. (*Continued*)

and streaks of well-sorted gravel related to individual surges dominated surface texture on the proximal half of the deposit (figure 5).

Before release of the second flow a distinctive beach sand marker layer was spread about 1 cm thick across the surface of the first deposit (figure 9) to provide an unambiguous and easily detectable contact between major depositional units. The sand covered all but an 8 m^2 patch near the proximal end of the deposit. The uncovered area provided a location to examine direct contact between the major depositional units.

Emplacement of the second deposit was affected strongly by in situ debris. The leading edge of the second flow slammed into and flowed over the proximal end of the first deposit, then smoothed out and flowed passively over its surface. Sediment accumulated against the inner left wall at the mouth of the flume while the topography of the first deposit beyond the flume (figure 4) directed the second flow toward one side of the runout area (figures 4, 5, 9). The in situ debris enhanced bed roughness felt by the second flow. Because of enhanced bed roughness and redirection of flow to-

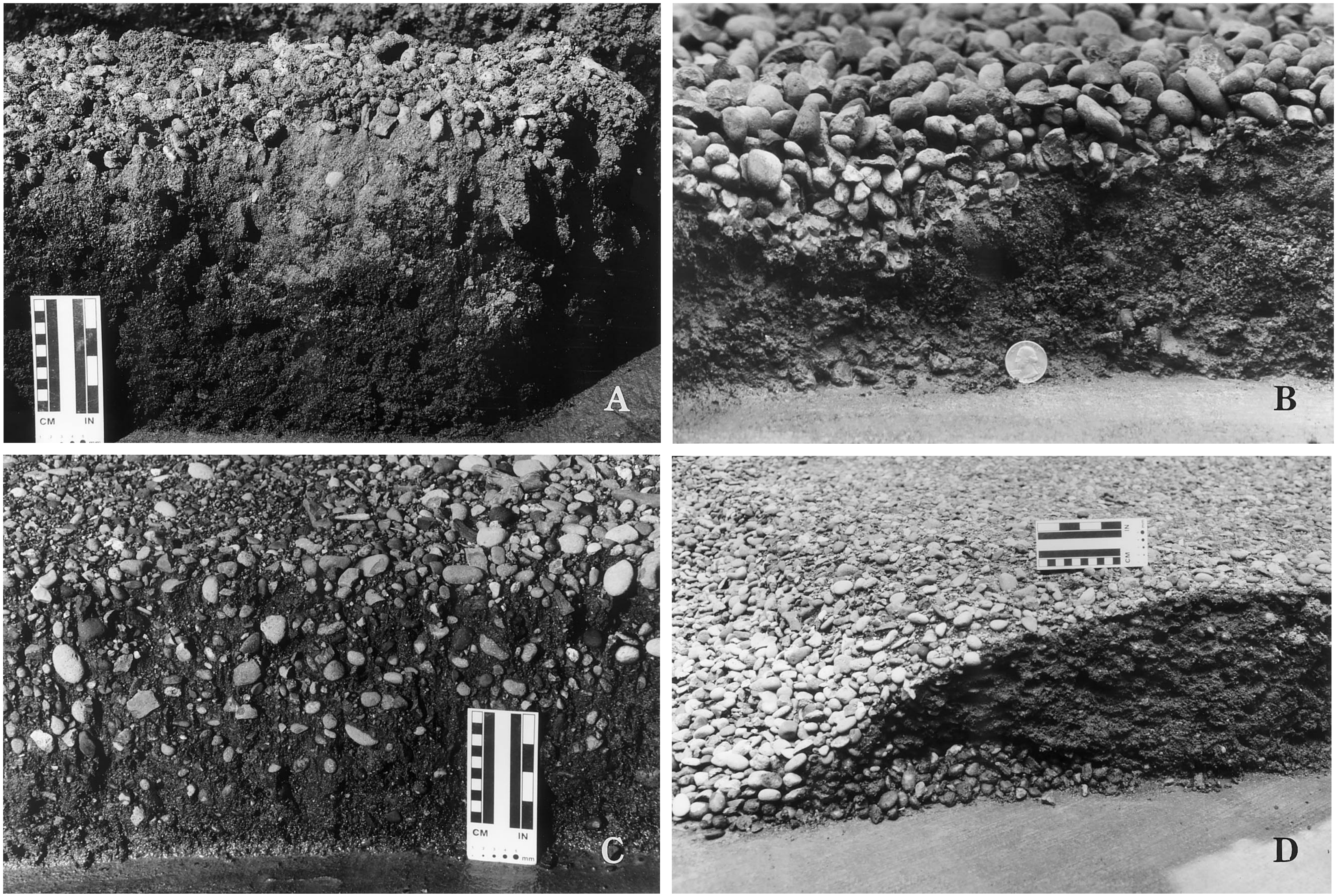

Figure 8. Typical interior textures of experimental debris-flow deposits. *A*. Deposit from unsaturated flow (experiment 3). *B, C, D*. Deposits from saturated flows (*B*. Experiment 4; *C*. Composite deposit of experiments 5 and 6; *D*. Experiment 7) Trough-like structure in (*B*) is related to subsequent surge emplacement. Gravel lens near margin of deposit in (*D*) was emplaced by an early surge; massive homogeneous body was emplaced by three surge waves. Scale units in inches (right) and centimeters.

Figure 9. Superposed deposits from two flows (experiments 5 and 6) accumulated at mouth of flume. Light-colored sand was used as a marker horizon, spread across surface of the deposit of experiment 5.

ward the side of the runout area, the second flow did not travel as far beyond the flume mouth as did the first, and it left a much less elongate deposit (figure 4) (table 1).

Sediment textures on the surface of the second deposit were mapped before the composite debris fan was trenched. Like the underlying deposit, it exhibited clusters of well-sorted gravel along its margin and on its surface (figure 5). Again, clusters of well-sorted gravel marked boundaries of flow surges. Thickness of the second deposit was comparable to that of the underlying deposit (figure 4), but maximum thickness was skewed toward the side of the runout area.

In vertical section the two deposits were indistinguishable except by the marker bed (figure 10). Each deposit appeared massive and homogeneous, and in the area lacking the marker sand the compound deposit could be misinterpreted easily as the product of a single flow. Figure 10*A*, which shows deposit texture and stratigraphy adjacent to that in figure 10*B* (about 30 cm apart), illustrates clearly that the lower deposit was not scoured by the second flow. Thus erosion of the first deposit did not obscure or destroy the contact between the two deposits.

Each of the two deposits, as well as the compound deposit, was sampled at several locations to determine if spatial variation in size distribution is a useful method of distinguishing similar, but separate, deposits. Samples from each unit show no systematic variation of grain-size distribution in either lateral or longitudinal transects (see Major 1996). Minor differences in bulk samples of each deposit are attributed to minor differences in size distributions of source debris. The compound deposit was sampled vertically at 6-cm intervals at six locations. At all six locations the coarsest particles (16–32 mm in diameter) in the first deposit were concentrated in the upper, rather than in the lower, part of the deposit. The second deposit exhibited a similar size grading at only three of the six locations.

Vertical variations of grain-size in the compound

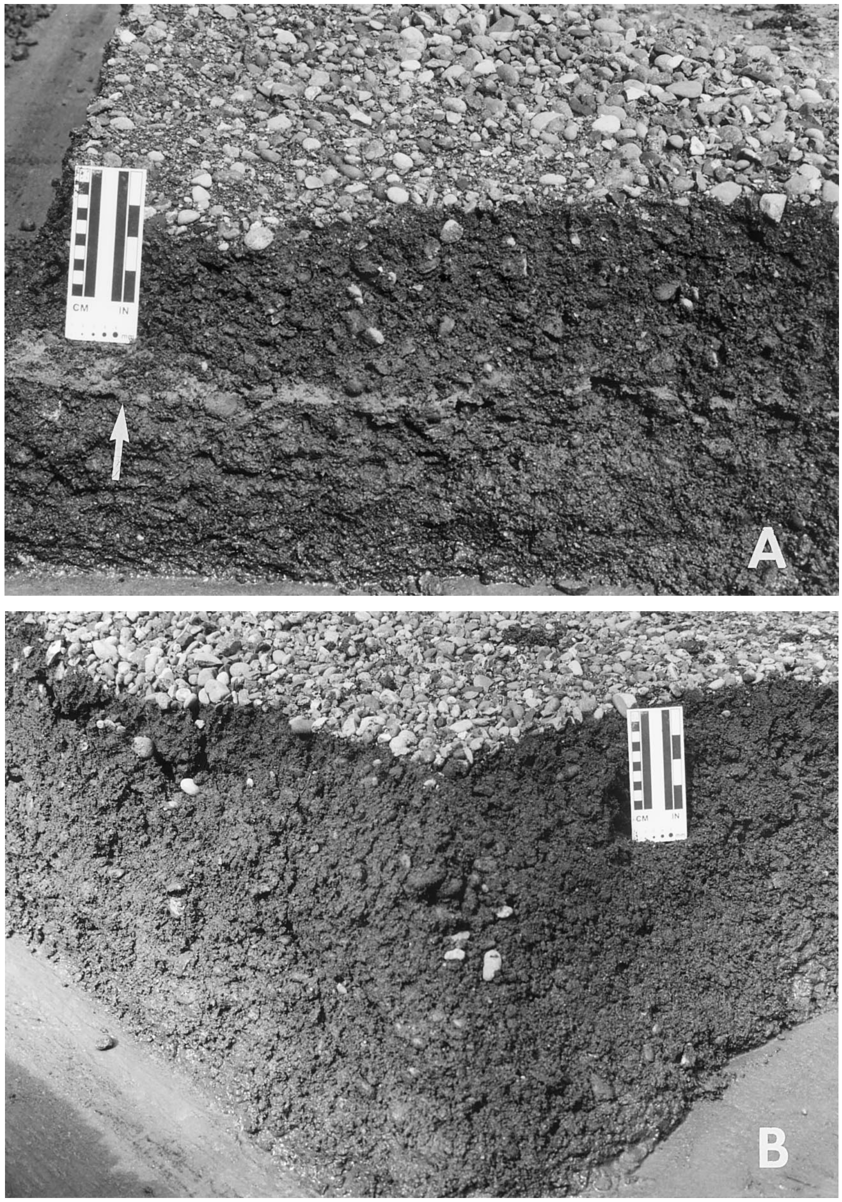

Figure 10. Interior texture of composite deposit shown in figure 9. *A*. Texture where marker sand (arrow) is present: deposit above marker sand is of experiment 6; deposit below marker sand is of experiment 5. *B*. Texture where marker sand is absent. Note the homogeneity of the compound deposit; the two separate beds amalgamated into one. The two exposures are about 30 cm apart.

deposit did not effectively distinguish the individual deposits. The two deposits could be distinguished at only three of the six sites using relative weight percentages of the coarsest particles in the upper part of the first deposit and the lower part of the second deposit as the criterion for distinction. Of those three sites, the marker sand was present at two to provide verification of the inferred distinction. Without a priori knowledge of two distinctly separate deposits, it would be difficult to conclude from grain-size analyses that the compound deposit resulted from emplacement of more than one flow.

Difficulty in distinguishing deposits from separate, but temporally related, debris flows is not unique to these experiments. In December, 1984, Weirich (1989) saw two debris flows emanate, within minutes of each other, from different watersheds in the San Dimas Experimental Forest and flow into San Dimas Reservoir. The reservoir was drained the following summer. The proximal deposits from these flows were unstratified, matrix-supported mixtures of organic and inorganic debris readily distinguishable from the reservoir substrate but not distinguishable from each other. Only after the flows had mixed sufficiently with reservoir water farther downslope, and had segregated their organic and inorganic debris, could their respective deposits be distinguished.

Natural Debris-Flow Deposits

Field debris-flow deposits in Jiangjia Gully, China (a tributary to the Xiaojiang River in the Yunnan

Province, about 200 km northeast of Kunming) were studied to determine whether insights from the experimental deposits were applicable to a natural setting. This site was selected because (1) the valley is inundated annually by numerous rainfall-triggered debris flows (Li et al. 1983; Zhang 1993); (2) each debris-flow ''event'' lasts for several hours and is characterized by numerous surges (Li et al. 1983; Zhang 1993); and (3) nearly all debris flows in the past 30 years have been observed and documented from an established observation post (Zhang 1993). This site provided an opportunity to study recent, unreworked deposits from well-documented events. It also provided an opportunity to analyze deposits from debris flows having kinematic behavior similar to that of the experimental flows (i.e., many surges), but which emanated from finer grained (as much as 7–10 wt % clay) source materials, which had substantially longer flow durations (Zhang 1993), and which traveled much farther distances from source.

Debris-flow deposits along Jiangjia Gully were examined in late July, 1994. Individual deposits from flows on June 16, June 25, and July 19, 1994, were well preserved along the channel; older deposits from flows in 1983 and 1992 were well preserved on and within a dominant terrace that occupies a vast proportion of the valley. Like the experimental deposits at the USGS flume, the morphology and surface sedimentology of deposits in Jiangjia Gully record the intermittent nature of the source flows. Several deposits consist of thin lobate landforms (figure 11) that have undisturbed surface ridges, clusters of coarse clasts, and aligned particles.

Deposits from several individual debris-flow events typically exhibit a massive, homogeneous, matrix-supported texture (figure 12), which may or may not show grading of the coarsest stones, despite sediment accumulation during several surges. Although not every surge reached the floodplain, many did, and video recordings show clearly that depositional areas commonly are inundated by numerous surges. Similar to the experimental deposits, the sedimentology of several single-event field deposits in vertical section did not faithfully record the intermittent nature of discrete debris-flow events.

Sediment emplacement by separate flow events likewise can develop massive deposits not easily recognized as the product of multiple flows (figure 13). Overlapping flow deposits having similar source debris, clearly known to have occurred days apart in June, 1994, were difficult to distinguish in vertical section, similar observations of multiple experimental deposits. At least five flows during the 1983 monsoon season are claimed to have deposited the assemblage of sediment shown in figure 13*B* (Dr. Wang Yuyi, Chinese Academy of Sciences, pers. comm. 1994), yet it is difficult to distinguish individual units.

Stratigraphic breaks between major depositional units are sometimes obvious, such as fluvially reworked deposit surfaces and subtle-to-obvious textural changes. In general, however, the terraces and floodplain of Jiangjia Gully comprise a monotonous assemblage of massive debris-flow sediments and only rare fluvial or fluvially reworked deposits. Chinese researchers who study debris-flow deposits here and in several other river valleys in southwest China use fluvially reworked surfaces, obvious textural changes, clay accumulations thought to result from ponded surface water, and clean stones (thought to have been washed by surface flow) to delineate stratigraphic breaks. While some of these criteria are clearly reliable, others are subtle and subjective, and their effectiveness is debatable.

Discussion

Large-scale flume experiments show that debris-flow deposition can occur by incremental accretion, yet produce massively textured, matrix-supported deposits. These results challenge the common assumption that sediment deposition occurs *en masse* and limit interpretations regarding behavior and physical properties of debris flows that can be made from their deposits. Although these experimental results are valid strictly for rapid, near-source deposition of cohesionless sediments from relatively small-magnitude flows, they are the first well-constrained experimental observations of debris-flow deposition that approaches a field-scale event. These reproducible experiments provide a basis against which inferences drawn only from field analysis may be compared and are significant beyond their relatively limited scale. Many natural flows exhibit surging behavior (e.g., Davies 1986, 1988). Deposits from farther-traveled, longer-duration, clay-rich flows having kinematic characteristics similar to the experimental flows, such as in Jiangjia Gully, exhibit sedimentologic features similar to those observed in the experimental deposits. Although the experimental debris is cohesionless, recent work suggests that cohesive strength may provide only limited influence on overall mechanical behavior of debris flows (Middleton 1990; Iverson 1997), even in some clay-rich debris flows such as the Osceola Mudflow from Mount Rainier volcano, Washington (Franz and Voight 1995; Major 1996). Hence rheological and depositional behavior of the experimental debris

Figure 11. Lobate debris-flow deposits in Jiangjia Gully, China. Individual deposits commonly are thin and many lobes overlap.

Figure 12. Debris-flow deposit of July 19, 1994, Jiangjia Gully, China. Deposit resulted from flow having numerous surge waves (as recorded on video), yet deposit texture is massive and homogeneous.

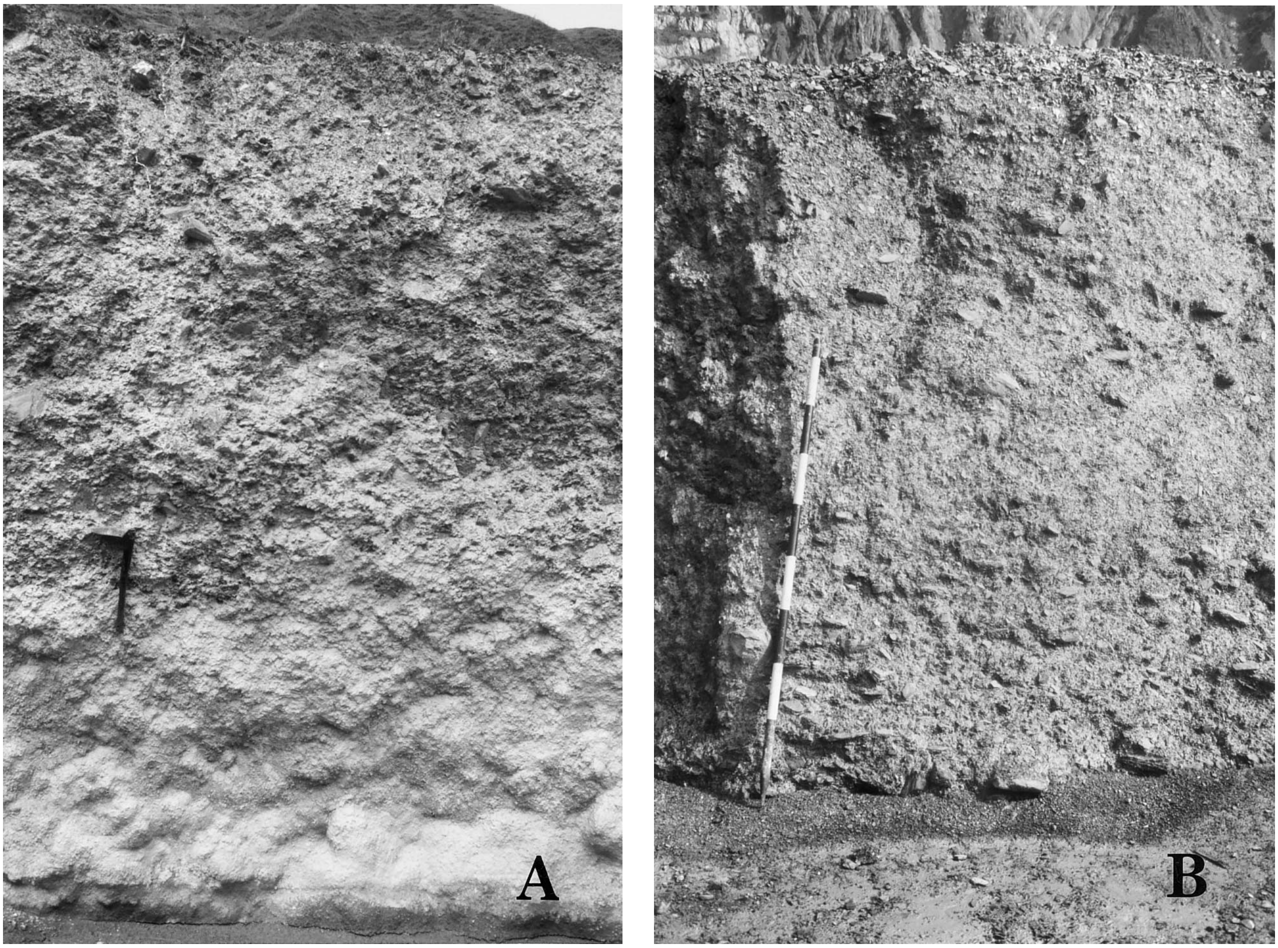

Figure 13. Debris-flow deposits exposed in terraces along Jiangjia Gully, China. Deposit sequences generally appear homogeneous and massive despite deposition by numerous, temporally distinct debris flows. Shovel and surveyor's staff for scale.

flows may not differ greatly from many natural debris flows.

The experimental flows generated deposits that had many features in common with natural debris-flow deposits. Deposits were lobate, having steep blunt margins and marginal levees, and were composed of the typically unsorted, unstratified, matrix-supported sediments that commonly result from flows having exceptional sediment concentration. Clear evidence that the experimental deposits resulted from incremental accretion of multiple surges typically was recorded in deposit morphology and surface sedimentology only. Surface clusters and streaks of well-sorted gravel marked boundaries of individual surges. Analogous clusters of coarse clasts were identified on bedding planes of Cretaceous debris-flow deposits by Kim et al. (1995), who inferred that such clusters reflected gravels deposited during flow surges. Arcuate surface ridges, resulting from sequential sediment emplacement, occurred only on deposits from unsaturated flows, which suggests that ridges may be used as indicators of relative water content of source flows.

Despite the unequivocally incremental nature of sediment accumulation, the sedimentologic and morphologic characteristics of the experimental debris-flow deposits can be misinterpreted as having resulted from *en masse* emplacement from a single surge. Internal textures of the experimental deposits did not faithfully record the progressive nature of deposition. Indeed, not only were individual surges from a single flow not faithfully recorded, but superposed deposits from similar yet separate debris flows formed a compound deposit having little stratigraphic distinction. Incremental accretion may be difficult to interpret from examination of interior sedimentology of debris-flow deposits, although through careful analysis of deposit stratigraphy and sedimentology a few studies have documented incremental accretion during prolonged deposition (e.g., Vallance and Scott 1996).

Mingling of sediments deposited over a relatively short period of time by different surges from a single debris flow mutes stratigraphic contacts. Mingling occurs when subsequent surges encounter unstable, nearly liquefied sediment deposited by earlier surges and plausibly explains the apparent lack of stratigraphic contacts within sediments known to have resulted from multiple surges. It also suggests that debris deposited by various surges must maintain a low effective-stress state over time, when compared to the typical period of surges or duration of a debris flow (Major 1996).

Despite their complex behavior, geologists commonly infer the kinematic behavior and physical properties of most debris flows from deposit characteristics, from mudlines along channels, and from evidence of physical interactions with channels. Many post-event interpretations are guided by assumptions that debris flows behave rheologically as viscoplastic materials (Johnson 1965, 1970) and that massively textured deposits result from sediment deposition that occurs *en masse* (e.g., Cas and Landis 1987; Ghibaudo 1992). Rheological properties of debris flows, such as yield strength and plastic viscosity, commonly are estimated from deposit characteristics (e.g., Johnson 1984). Some investigators use relations between maximum particle size and bed thickness to infer processes of sediment deposition, grain-support mechanisms, and strength properties of sediment gravity flows (e.g., Nemec and Steel 1984; Walton and Palmer 1988; Collinson and Thompson 1989; Arguden and Rodolfo 1990); others use inferred rheological properties to reconstruct estimates of paleoslope gradients (e.g., Kim et al. 1995). Assessments of geologic processes assume particular significance when used in geologic hazards evaluations. For example, estimates of debris-flow yield strength and viscosity are used in some numerical models that predict debris-flow inundation areas as part of flood-hazard assessments on alluvial fans and urban floodplains (O'Brien et al. 1993; Whipple 1994).

Inferences drawn from debris-flow deposits regarding the hydraulic behavior and rheological properties of flow are suspect. Although parts of debris-flow deposits may locally from *en masse*, the experimental results clearly illustrate that the full thickness of a debris-flow deposit need not result in this manner. Because debris-flow deposits generally are assumed to result from simple *en masse* sedimentation, it has been common practice to infer debris-flow yield strength from deposit thickness or from large clasts apparently suspended in deposits (e.g., Johnson 1970, 1984; Pierson 1980, 1985*b;* Fink et al. 1981; Li et al. 1983; Voight et al. 1983; Costa 1984; Major and Voight 1986; Van Steijn et al. 1988; Rodolfo et al. 1989; Whipple and Dunne 1992; Cruden and Lu 1992; Kim et al. 1995). When deposition is dominated by vertical accretion, however, the resulting deposit thickness has little bearing on flow strength (see figure 10). Instead, deposit thickness and shape merely reflect *deposit* strength (Kokelaar and Branney 1996), which is greatly influenced by sediment permeability, pore-fluid pressure, and frictional strength along deposit margins (Major 1996). Indeed, the finest-grained experimental flows produced the thinnest deposits (figure 4). In the context of a viscoplastic model, this suggests that the finer-grained debris flows had the lowest plastic yield strength, contrary to expectations based on relations between slurry yield strength, composition, and sediment concentration determined in laboratory experiments (e.g., Major and Pierson 1983). Thus relations between thickness and composition of the experimental deposits are incompatible with deposition by a simple viscoplastic material.

Relations between maximum particle size and bed thickness (e.g., Nemec and Steel 1984) and computation of flow strength from the size of the largest supported particle are subject to similar skepticism. Vertical accretion of sediment by surges can produce beds that appear to "support" oversized particles that were emplaced instead as tractive bedload. For some active sediment flows at the Matanuska Glacier, Lawson (1982) had difficulty distinguishing particles transported by traction (observed through a plexiglass wall) from those actually suspended in flow. Thus large particles apparently suspended within a debris-flow deposit were instead transported by traction. Inferences and computations regarding flow strength based on relations between clast sizes and bed thickness are not compatible with a progressive depositional process.

The experimental results demonstrate that multiple deposits of similar sediment can accumulate without obvious stratigraphic contact, particularly if there is little time between events, if source materials are similar, or if travel distances are short. Experimental results and analysis of field deposits suggest that distinctive source materials, facies variations over long travel distances, prolonged deposition by longitudinally sorted flows (e.g., Vallance and Scott 1996), or sufficient time for development of unconformities or marker horizons generally are required to differentiate most debris-flow units under natural conditions. Even if sedimentary features delineate stratigraphic contacts between massively textured sediments, such contacts may represent breaks between sediments deposited by multiple discrete flows rather than breaks between individual flows. Evaluations of debris-flow hazards and reconstructions of geomorphic histories commonly utilize estimates of debris-flow frequency and magnitude. Results presented here suggest that event frequency may be underestimated and that event magnitude, defined as the volume of debris transported by a single debris flow (Hungr et al. 1984), may be overestimated.

Conclusions

Recent large-scale flume experiments reveal that massively textured, unsorted debris-flow deposits can result from progressive incremental deposition rather than from simple *en masse* deposition. The experimental flows and resulting deposits best simulate debris flows that occur in small, steep catchments rather than large-magnitude debris flows from volcanic eruptions. Results of these experiments are valid strictly for rapid, near-source deposition of cohesionless sediment. However, recognition that cohesive strength may not be important in many debris flows, the similarity between kinematically similar deposits of clay-rich debris flows (such as in Jiangjia Gully, China) and the experimental deposits, and recent recognition of progressive emplacement of a massive volcanic debris-flow deposit (Vallance and Scott 1996) suggest that these experiments of debris-flow depositional process have broader application.

Sedimentologic and morphologic evidence of progressive incremental deposition of debris-flow deposits were found to be subtle and therefore potentially misinterpreted. Locally preserved coarse gravel, transported near the front of each debris flow, overlain by poorly sorted, massively textured debris provided the only internal sedimentologic indication of progressive sedimentation in the experimental deposits. Instead, evidence of progressive aggradation during a single event was preserved primarily in deposit morphology and in surface sedimentary textures. Clusters and streaks of surface gravel commonly delineated deposition from individual, or amalgamated, surges.

Deposition of sediment by similar, yet separate, debris flows produced homogeneous, massively textured, poorly sorted, matrix-supported deposits having little stratigraphic distinction. Superposed deposits from separate experimental flows could not be identified without aid of an introduced marker horizon. Likewise, natural debris-flow deposits in southwest China that resulted from flows that occurred days to weeks apart were indistinguishable in vertical section; deposits from more temporally distinct flows also were difficult to distinguish in vertical section.

Emplacement of debris-flow deposits through progressive accretion severely complicates inferences of flow rheology reconstructed from deposit characteristics. Estimating flow properties from deposit thickness for from relations between particle size and bed thickness are suspect when incremental accretion leads to homogeneous, massively textured deposits. Although parts of a deposit may result from *en masse* emplacement locally by a single surge, this does not require that the entire thickness of a deposit at all locations forms in that manner, and effective distinction of these disparate depositional processes may be difficult. Similarly, lack of distinction of individual debris-flow deposits in sedimentary sequences can lead to underestimates of debris-flow frequencies and overestimates of debris-flow magnitudes on floodplains and alluvial fans, even in near-source regions where most events likely remain preserved.

The results discussed in this paper provide experimental support for an alternative hypothesis regarding the process of emplacement of massively textured debris-flow deposits. With the insights obtained from these experiments in mind, careful field analysis of massively textured deposits may find evidence to support these results and to successfully interpret the process of emplacement of sediment by debris flows and kindred mass-movements.

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