CHARACTERISTICS OF DEBRIS FLOWS IN CENTRAL UTAH, 1983

by

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ABSTRACT OF THESIS

CHARACTERISTICS OF DEBRIS FLOWS IN CENTRAL UTAH, 1983

Several hundred debris flows and hyperconcentrated floods occurred in central Utah during the spring of 1983. This thesis provides detailed documentation of eight of the larger flows, including quantitative analyses of the material deposited during these events.

The debris flows studied are characterized by poorly sorted deposits supporting coarse angular clasts in a fine-grained matrix. Lateral levees, terminal lobate features, and woody debris oriented parallel to the flow direction are also characteristic of the deposits. Hyperconcentrated-flood deposits are generally better sorted than debris-flow deposits and may show stratification. Furthermore, they lack a fine grained matrix, levees, terminal lobate features, wholly supported large clasts, and have no preferred orientation of woody debris. The best sedimentological parameters for distinguishing between debris-flow and hyperconcentrated-flood deposits are mean grain size, sorting, kurtosis, and clay content.

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DEDICATION

This thesis is dedicated to my wife, Hazel, for her patience and understanding and to Earl Brabb, who gave me the opportunity to conduct this research.

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INTRODUCTION

In late May and early June of 1983, a rapid and sustained snowmelt triggered hundreds of landslides in the mountainous regions of Utah. Along the Wasatch Front, north of Salt Lake City, numerous landslides mobilized into viscous slurries of sediment, water, and entrapped air, referred to as debris flows. Many flows traveled several kilometers in the main stream channels and beyond the canyon mouths. Some flows were diluted by high runoff in the stream channels and became hyperconcentrated floods.

Both debris flows and hyperconcentrated floods caused extensive damage to the residential communities at and beyond the canyon mouths during this period (Kaliser, 1983). Further accounts of the landslides, debris flows, and floods occurring along the Wasatch Front during the spring of 1983 can be found in Wieczorek and others (1983, 1989), Lindskov (1984), Pack (1984), Pierson (1985a), Vandre (1985), Kaliser and Slosson (1988) and Brabb and others (1989). Several hundred landslides, debris flows, and hyperconcentrated floods also occurred during this period in the Wasatch Plateau region of central Utah (Anderson and others, 1984; Fleming and Schuster, 1985; Lips, 1985; and Brabb and others, 1989).

Purpose

Debris flows and hyperconcentrated floods have occurred in this region repeatedly in both historic and pre-historic times (Bailey and others, 1934; Croft, 1967; Keaton and others, 1988). The recent activity and recurrent nature of these events demonstrate the potential geologic risk to residential communities juxtaposed to mountainous regions. Important aspects of evaluating this risk are understanding the processes and being able to differentiate between the types of flows.

The purpose of this study is to provide a better understanding of debris-flow processes. The specific objectives are: 1) to provide documentation of eight of the larger debris flows which occurred in Utah during the spring of 1983, 2) to provide quantitative analysis of the deposits from these events, and 3) to provide quantitative distinction between the debris-flow and hyperconcentrated-flood deposits.

Previous Investigations

Debris flows, hyperconcentrated floods, and stream flows comprise a continuum of sediment-water processes. The rheologic properties of these flows can be either Newtonian or non-Newtonian depending in part on sediment concentration, sediment type, and particle distribution (Pierson and Scott, 1985). In order to evaluate hazard potential, it is important to distinguish between the types of sediment-water flows. Unfortunately, this distinction is sometimes difficult because different terminology and criteria have been used by different researchers. Flows are currently distinguished and classified on the basis of the sediment concentration and velocity, or on the basis of the morphology and sedimentology of the deposits.

Much of the terminology currently used comes from Sharpe (1938) who used relative velocity and relative sediment concentration to differentiate processes. Classification systems based on sediment concentration have been described by Beverage and Culbertson (1964), and more recently by Fan and Dou (1980), Takahashi (1981), Costa (1984), and O'brien and Julien (1985). Pierson and Costa (1987) have included velocity as well as sediment concentration into a classification system. Table 1 lists the sediment concentrations and classification of flows reported by these researchers.

Three problems exist in this type of classification system. First, there is little consistency in terminology of the flows, which makes comparison difficult. Second, there is a discrepancy in the reported values of sediment concentration that define the boundaries between types of flows. Third, sediment concentration and velocity are often only estimated from the deposits. Because of these limitations, sediment concentration and velocity are not in themselves adequate discriminators of the type of sediment-water flows.

Table 1. Classification of sediment-water flows

Concentration Percent by Volume (10, 20, 30, 40, 50, 60, 70, 80, 90, 100)

Reference				
Beverage and Culbertson (1964)	High	Extreme	Hyperconcentrated	Mud flow
Costa (1984)	Water flood	Hyperconcentrated	Debris flow	
O'Brien and Julien (1985)	Water flood	Mud flood	Mud flow	Landslide
Takahashi (1981)		Debris or Grain Flow	Fall, Landslide, Creep, Sturzstrom, Pyroclastic Flow	
Fan and Dou (1980)	Hyperconcentrated Flow	Debris or Mudflow		
Pierson and Costa (1987) Fast / Slow	Streamflow: Normal, Hyperconcentrated	Slurry Flow: (Debris Torrent), Debris and Mud Flow, Solifluction	Granular Flow: Sturzstrom, Debris Avalanche, Earthflow, Soil Creep	

The second primary method used to distinguish sediment-water flows is based on flow properties determined from the morphology and sedimentology of the deposits. Examples of the distinction between types of flows are found in the Committee on Methodologies for Predicting Mudflow Areas (1982), Bradley and McCutcheon (1985), Pierson and Scott (1985), O'Brien and Julien (1985), Smith (1986), Pierson and Costa (1987), Wells and Harvey (1987), and Keaton and others (1988). Although there is some discrepancy in terminology most researchers recognize debris flows, transitional (hyperconcentrated) flows, and stream flows as distinctly different processes. Commonly, the distinction is reported only based on a qualitative description of the deposits. Exceptions to this are Sharp and Nobles (1953), and Costa and Jarrett (1981) who use the Trask Sorting Coefficient; Bull (1962), and Pe and Piper (1975) who use textural characteristics; and Pierson (1985b), Pierson and Scott (1985), and Wells and Harvey (1987) who include mean grain size and sorting to distinguish types of sediment-water flows.

Although these studies do provide useful criteria, it remains uncertain if other sedimentological parameters of the deposits are significant discriminators of the type of flow. If other criteria can be found and used, identification of ancient deposits will be more precise. This will increase the ability to develop better models of transportation and deposition, and enable more accurate hazard identification.

Setting

The area investigated for this report is located in the north central part of Utah and is approximately bounded by the cities of Layton, Gunnison, Huntington, and Morgan (fig. 1). In the southern part of the study area the major physiographic feature is Sanpete Valley which is bordered on the east by the Wasatch Plateau and on the west by the San Pitch Mountains. The Wasatch Range is located at the central and northern end of the study area.

The climate ranges from semi-arid in the valleys to sub-humid in the mountains. Average annual precipitation generally ranges from 250 to 380 mm in the valleys and from 380 to 1015 mm in the mountains, locally reaching 2540 mm at the highest elevations. The majority of this precipitation occurs as snow from about November through April. The driest months are June through August, although brief cloudburst thunderstorms can make them the wettest months of a year in some locations.

Vegetation varies greatly in response to the wide ranges in precipitation and temperature. Many valleys are under irrigation, or are covered with scrub oak and sage brush. Riparian vegetation consists primarily of cottonwood, willows and tamarisk. In the mountainous regions, the lower hillsides are covered by varieties of scrub oak and maple, while the higher slopes support forests of conifers and aspen trees.

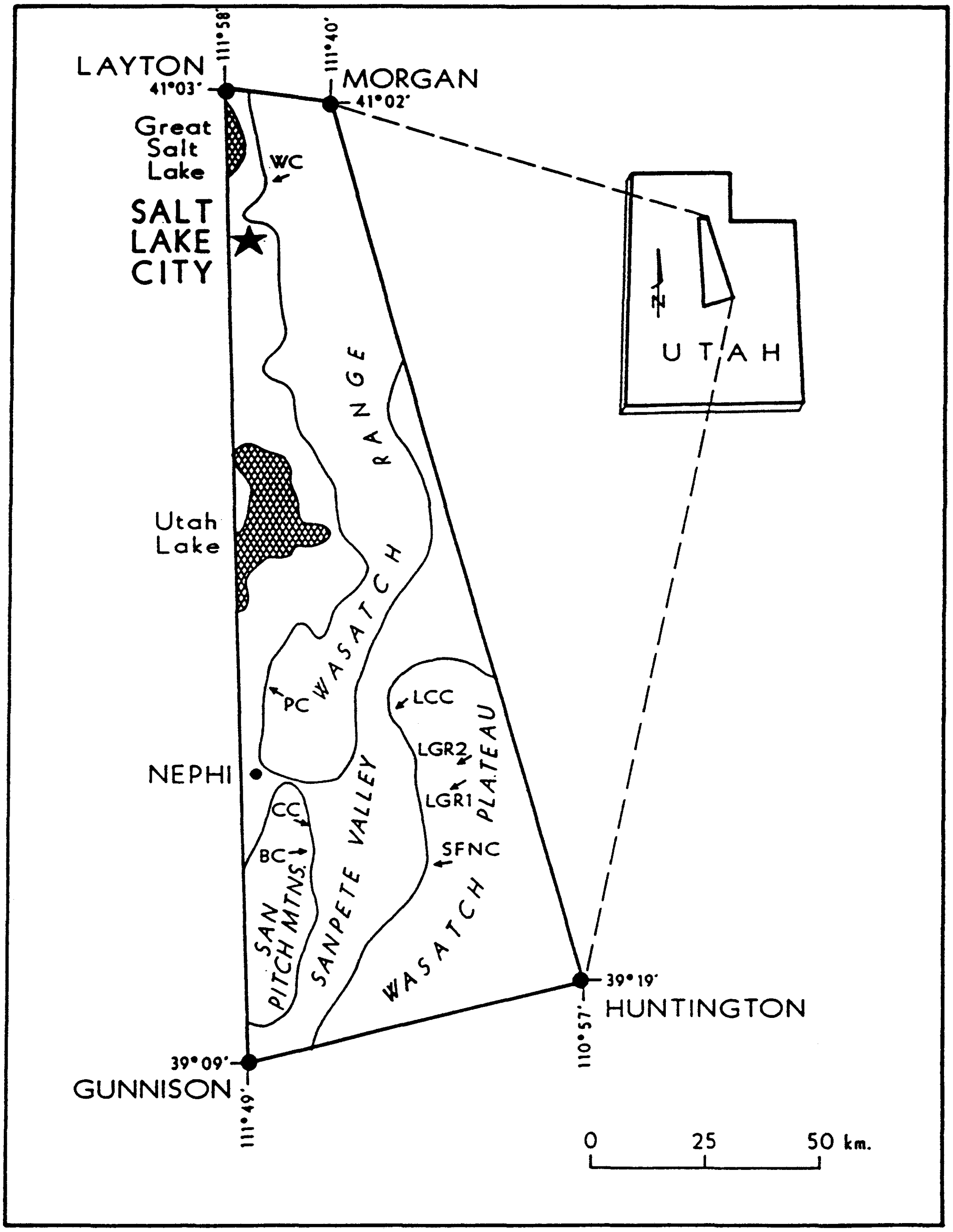


Figure 1. Location of study area, major physiographic features, and debris-flow sites. Debris-flow sites shown by small arrows are abbreviated as follows from north to south: WC, Ward Canyon; PC, Pole Canyon; LCC, Little Clear Creek; LGRII, Lower Gooseberry Reservoir-II; LGRI, Lower Gooseberry Reservoir-I; CC, Crooked Creek; BC, Birch Creek; SFNC, South Fork North Creek.

Along the northern Wasatch Range, the bedrock is composed principally of gneiss and schist of the Precambrian Farmington Canyon Complex (Davis, 1983). Mississippian and Pennsylvanian age sedimentary rocks occur at the southern end of the Wasatch Range. Cretaceous-age sedimentary rocks are present throughout most of the southern study area. Quaternary sedimentary units consist of landslide, alluvial, colluvial, and lacustrine deposits. In Sanpete Valley, Pleistocene and Holocene coalescing alluvial fan deposits reach aggregate thicknesses of up to 152 m (Robinson, 1971).

Method of Investigation

Sites were selected for detailed study from maps showing the locations of debris flows occurring in the spring of 1983. These maps were prepared from aerial reconnaissance of the state between June 15 and 19, 1983 (Brabb and others, 1989). The goal was to select a wide areal distribution of debris flow sites with varying geologic and topographic conditions. Debris flows were selected that had run their natural course without being significantly affected by man-made restrictions such as roads, houses, or modified stream channels. Larger debris flows were favored in order to study features that were less common in smaller flows. A final criterion was to find debris flow sites in a good state of preservation.

Based on these criteria, eight sites were chosen for detailed investigation. Aerial photographs were obtained in

August, 1983 for these sites at scales of either 1:6000 or 1:12,000. Debris-flow features were mapped in the field on enlargements of these photographs. At each site, several points observable in the aerial photos were surveyed by tape and level methods in order to determine the exact scale of the photo enlargements, and thereby establish precise horizontal control. Topographic maps were prepared photogrammetrically from the vertical aerial photographs using a Kern Stereo Plotting Instrument. Vertical control was established from points on USGS 7.5′ quadrangles identifiable on the aerial photos. These topographic maps were used for detailed mapping of debris-flow features. Historic episodes of debris flows were documented using aerial photographs dating back to 1946.

Topographic, hydrologic, and geologic data were collected and analyzed for each source area. The volume of material removed as the debris flows mobilized and the volume of partly-detached landslides were determined from vertical aerial photographs and surveys.

Gradients were surveyed in the main track using tape and level methods. Channel cross-sections were surveyed and the measurements were used to determine the coefficient of confinement. The coefficient of confinement is a measure which I developed to describe the degree to which the flow is confined by the channel, thus preventing lateral spreading. Figure 2 illustrates how the coefficient of confinement is defined. Locations and volumes of material

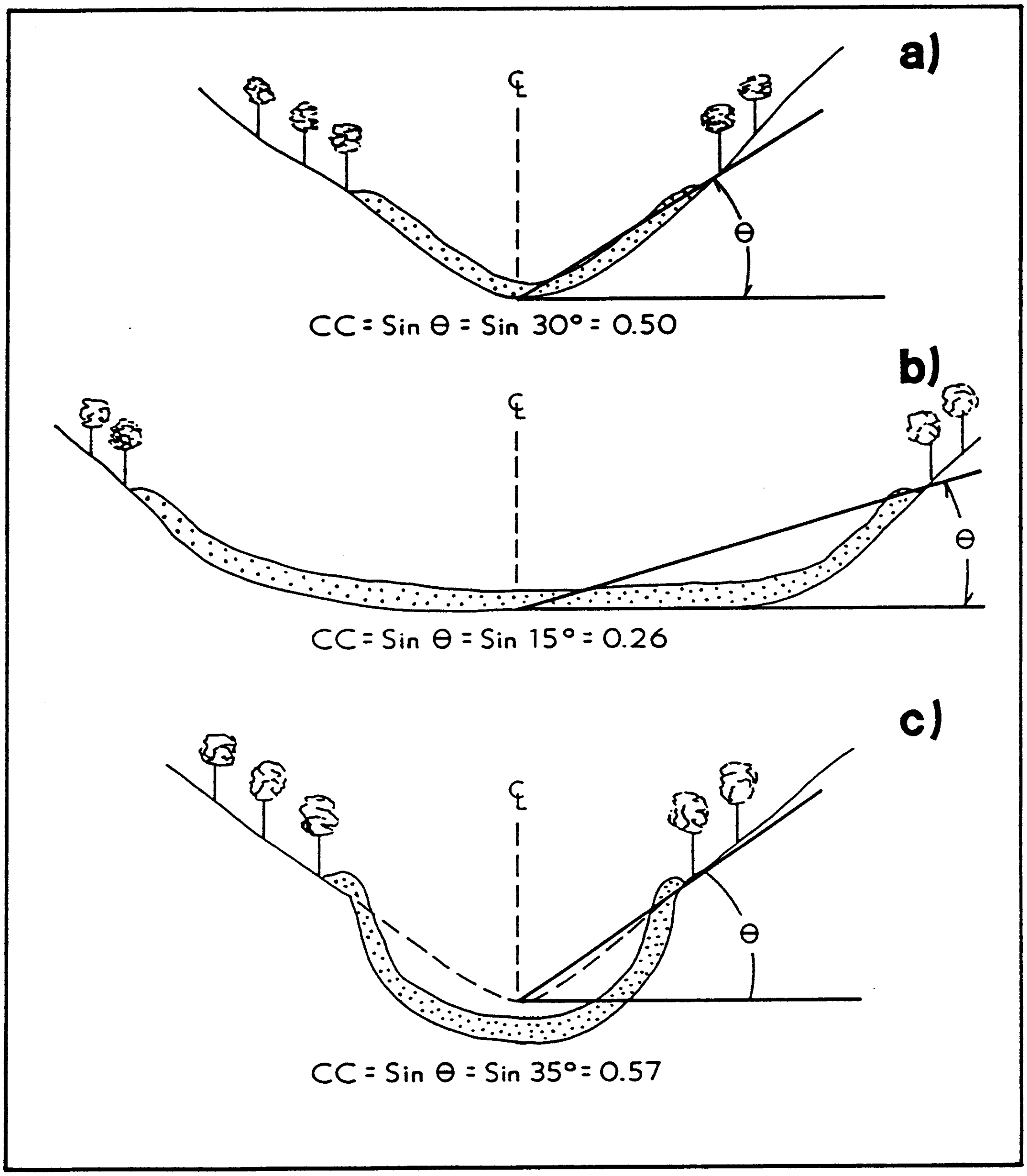


Figure 2. Sketch of channel cross-sections illustrating the coefficient of confinement, cc. cc is defined as the sine of the angle between the center of the channel and the highest point on the channel side where the debris flow passed. In (a) θ is equal to 30 degrees, therefore cc = 0.50. In (b) the flow depth is the same as in (a), but the channel is wider so the confinement is less; θ = 15 degrees, cc = 0.26. In (c) a channel scoured by a debris flow is shown; the dashed line represents the extrapolation of the assumed prior channel geometry.

deposited or removed from the channel by the debris flow were noted and measured. Flow depth was estimated by surveying the height of mud lines or lateral levees.

Deposits were mapped showing the areal extent, gradient, thickness, and locations of snouts or fronts composed of boulders or woody debris. Pre-existing deposits were exposed at three sites by channel incision. These were described, sampled, and at one site dated, using radiocarbon techniques.

Material properties were determined by analyzing samples collected at each site. Grain-size distribution parameters were determined by sieve and hydrometer techniques. The liquid limits, plastic limits, and plasticity indices as expressed by the Atterberg Limits were determined for several samples. From adaptation of existing methods, fives samples from each site were reconstituted in the laboratory to estimate the sediment concentrations and water content of the slurry at the time of flow.

SITE DESCRIPTIONS

The debris flows described in this study resulted from the mobilization of landslides occurring on steep hillsides. The debris flows traveled down the hillsides and quickly became confined to stream channels. Deposition of material dominated as the flows traveled beyond the canyon mouths onto alluvial fans. Based on these features, I have divided the flows into three geomorphic zones; the source area, the main track, and the depositional area. The processes in each of these zones are discussed below.

Source Area

The debris flows initiated as either rotational or translational slides. Mobilization of these slides into debris flows was either total or partial, the latter resulting in partly-detached landslides still in place on the slopes. Landslide volumes ranged between 167,000 m^3 and 1,800 m^3. Materials mobilizing into debris flows included soils and weathered bedrock, with depths of sliding ranging between 1 and 8 m. At six sites, landslides originated in soils and weathered conglomerates, sandstones, siltstones and shales. One slide initiated in soils and weathered gneiss and schist. One slide originated entirely within a pre-existing landslide deposit.

The landslides occurred primarily on west and south-facing hillsides between elevations of 2244 and 2829 m (2515 m average). All source areas are located between 75 and 1770 m (681 m average) below ridge crests. Gradients within source areas range between 0.25 and 0.97, with an average value of 0.50. Longitudinal profiles of the hillsides surrounding the source areas are convex at six sites and concave at two. Five hillsides are concave in transverse view, two are planar, and one is transversely convex. Table 2 provides a summary of the source area characteristics.

In all but one source area, seeps or springs were observed, or evidence existed that water had flowed from the source area subsequent to the mobilization of the landslide. I tried to determine if the water was originating within the surficial deposits or from bedrock, however, because of the partly-detached landslides and fresh debris-flow deposits this was not always possible. Because the debris flows occurred during a period of melting snowpack and high runoff, it is likely that the surficial materials were nearly saturated at the time of failure. Hence, initiation of the debris flows probably resulted from high pore-water pressures in the soils either from infiltration of the snowmelt, similar to the mechanism proposed by Campbell (1975), or from

Table 2. Summary of source area characteristics. Site designations match those on fig 1.

Site	Elev (m)	Distance Below Ridge Crest (m)	Aspect	Gradient	Geometry Profile/ Transverse	Source Mtrls	Initial Landslide Volume m^3	Partly-Detached Landslide volume m^3
BC	2427	725	south	0.36-0.42	convex/ concave	colluvium[1] over sedimentary rxs.	167,000 (±40,000)	105,000 (±25,000)
CC	2244	1640	southeast	0.30-0.49	convex/ planar	colluvium over sedimentary rxs.	8,500 (±1,000)	2,000 (±500)
LGRI	2829	330	west	0.27-0.58	convex/ concave	colluvium over sedimentary rxs.	17,250 (±5,000)	124,000 (±30,000)
LGRII	2799	485	west	0.57	convex/ concave	colluvium over sedimentary rxs.	2,950 (±1,000)	2,000 (±600)
LCC	2424	150	west	0.53	convex/ planar	colluvium over sedimentary rxs.	1,800 (±300)	None
SFNC	2634	75	west	0.62-0.97	concave/ planar	colluvium over sedimentary rxs.	45,000 (±15,000)	5,000 (±1,000)
PC	2268	1770	northwest	0.25-0.40	convex/ convex	pre-existing landslide	13,500 (±2,500)	440,000 (±280,000)
WC	2494	275	southwest	0.56	concave/ concave	colluvium over metamorphic rxs.	15,500 (±1,500)	1,000 (±100)
Mean	2515	681		0.50			33,900	97,000
S.D	221	663		0.14				

[1] Colluvium includes soil and weathered bedrock.

flow in bedrock fractures intersecting the base of the soils as proposed by Mathewson and Keaton (1986).

High groundwater levels can decrease slope stability and have been measured near debris-flow source areas by Wu and Swanston (1980) and Sidle and Swanston (1982). During the spring of 1983 and 1984 high groundwater levels were measured in granular soils and weathered bedrock near debris-flow source areas along the Wasatch Front (Pack, 1984). The concavity of the hillsides at most sites would be expected to further concentrate the flow of water in the surficial materials. The importance of topographic hollows as debris-flow source areas has been documented in northern California by Reneau and Dietrich (1987).

Main Track

Average gradients of the main debris-flow tracks range between 0.23 and 0.37. The debris flows were confined both by channel sides and locally by thick vegetation. Coefficients of confinement range between 0.0 and 0.75 in the main track. In some places, the flows overtopped the channel and flowed onto relatively flat hillsides. Flow depths range between 0.1 and 8.0 m. Thickness of material deposited range between 0.02 and 4.0 m and thickness of material scoured varies between 0.0 and 6.0 m. Table 3 provides a summary of the main track characteristics.

Flows within the main track typically followed tortuous channels and consequently, deposits are superelevated on the

Table 3. Summary of main track characteristics. Site designations match those on fig 1.

Site	Gradient Range	Gradient Ave	Cc	Flow Depth (m)	Mtrl Deposited (m)	Mtrl Scoured (m)	Length (m)	Relief (m)
BC	0.27-0.40	0.30	0.0[1] -0.49	4.3-6.0	0.5-4.0	3.0-5.0	1010	305
CC	0.25-0.45	0.29	0.51-0.75	2.3-8.0	0.03-0.5	1.0-6.0	981	280
LGRI	0.18-0.58	0.31	0.23-0.35	0.4-1.5	0.05-0.1	1.0-2.0	370	113
LGRII	0.15-0.56	0.26	0.03-0.40	0.1[2]	0.1	0.0	528	136
LCC	0.22-0.66	0.37	0.06-0.36	0.3-1.6	0.05-0.3	0.5-1.5	366	134
SFNC	0.33-0.53	0.30	0.0[1]	1.0-2.0	0.02-0.1	0.0-1.0	880	268
PC	0.21-0.31	0.23	0.05-0.24	2.8-4.5	1.0-2.0	0.0-2.5	254	58
WC	0.28-0.64	0.33	0.17-0.41	1.0-2.0	0.1-0.5	0.5-2.0	884	293

[1] Flow confined by vegetation on hillsides.
[2] Minimum flow depth.

outside of many bends. Based on measurements of the angle of superelevation and the radius of curvature of the bend, Johnson (1984) has derived the following equation for estimating the mean velocity of debris flows:

$$V = [g\ R\ \cos\ \delta\ \tan\ \beta]^{1/2} \qquad (1)$$

where V is the mean velocity of the debris flow, g is the acceleration due to gravity, R is the radius of curvature of the channel, δ is the channel slope, and β is the angle of superelevation. The average velocity of the Little Clear Creek flow is estimated from equation 1 to be 6.4 m/s.

At most sites, debris flows scoured the channels and incorporated significant amounts of additional material into the flows. Insufficient data were found to conclusively determine exactly the processes responsible for channel scour. Some possible mechanisms include: 1) scour due to the fluid at the waning end of debris-flow pulses (Takahashi, 1981); 2) low undrained strength conditions due to rapid loading of saturated channel materials as flows passed (Sassa, 1984); 3) scour caused by the increased tractive stress on the channel due to the fluid density being greater than water (Costa, 1984); and 4) scour caused by the erosive nature of the large clasts and boulders at the debris-flow front. The scour in channels commonly extended to erosion-resistant bedrock and was as much as 8 m deep. In most channels, both scour and deposition occurred concurrently although deposition was typically less than 50 cm. The thickest deposits of material are the levees observed on the lateral edges of the deposits. Often these levees contain accumulations of boulders or woody debris aligned parallel to the flow path.

The geometry of the channels eroded by the debris flows were U-shaped in cross-section and were superimposed on the original V-shaped channel which existed primarily as a result of fluvial processes (Johnson, 1970). Figure 3 shows an example of the superposition of a U-shape on a V-shaped channel at the Birch Creek debris flow. The resulting channel geometries, with steep to vertical side slopes, were relatively unstable and subsequent bank failure to a more stable configuration was observed for some channels during 1984 (Lips, 1985). The Lower Gooseberry Reservoir-II flow did not scour the channel probably because the flow occurred when the channel was filled with snow or ice.

Deposition of material became the dominant process as channel confinement typically decreased below 0.20 and gradients typically decreased to less than 10 degrees. This agrees with other investigators who have reported that debris flows stop where gradients generally decrease below 10 degrees: 2 to 9 degrees in Oregon (Benda, 1985); 3 to 10 degrees in Japan (Ikeya, 1981); 3 to 5 degrees in Japan (Mizuyama, 1981); 4 to 10 degrees in New Zealand (Pierson, 1980); 4 to 10 degrees in Oregon (Swanson and Lienkaemper, 1978); 8 to 12 degrees in Canada (Hungr and others, 1984);

Figure 3. Channel of Birch Creek showing modification due to scouring in the main track. The solid line represents the cross-sectional geometry. The channel has been scoured, as evident by the U-shape in the center being superimposed on, or cut into, the V-shape of the pre-debris-flow channel geometry.

and 11 degrees in southern California (Campbell, 1975). Based on the observations at the sites included in this study, as well as values reported in the literature, I have defined the point on the profile where the gradient decreases below 10 degrees as the boundary between the main track and the depositional area.

Depositional Area

Gradients within the depositional area range between 0.06 and 0.13. Coefficients of confinement are generally less than those in the main track and vary between 0.0 and 0.56. Deposits reach a maximum of 4.0 m, but are generally less than 0.5 m thick. The depth of scour was generally between 0.0 and 6.0 m, except for a deeply incised channel at the Birch Creek debris flow. Table 4 provides a summary of the depositional area characteristics.

Deposits thin and boulders decrease in size with increasing distance from the canyon mouths and as the flows spread laterally. This is consistent with observations and theory (Johnson, 1970) that as the shear strength, or capacity for carrying boulders decreases, the thickness of the flow decreases. Figure 4 shows the size distribution of boulders within the depositional area of the Lower Gooseberry Reservoir-I flow. As the flows thinned, they were easily diverted by vegetation and other obstructions in their path. This resulted in fingers of the deposit extending away from the lateral edges of the main flow.

Table 4. Summary of depositional area characteristics. Site designations match those on fig 1.

Site	Gradient Range	Gradient Ave	Cc	Flow Depth (m)	Mtrl Deposited (m)	Mtrl Scoured (m)	Length (m)	Relief (m)
BC	0.02 0.32	0.06	0.0-0.04	0.03-2.5	0.03-3.0[1]	0.0-20.0[2]	4691	287
CC	0.02-0.16	0.08	0.0-0.25	0.05-2.7	0.05-0.3	0.0	1823	150
LGRI	0.07-0.13	0.11	0.0-0.18	0.05-1.5	0.05-0.3	0.0-2.0	1086	119
LGRII	0.09-0.14	0.13	0.0-0.14	0.1-1.7	0.1-0.4	0.0	142	18
LCC	0.05-0.16	0.10	0.4-0.06	0.3-1.4	0.05-0.4	0.0-2.0	594	62
SFNC	0.05-0.07	0.06	0.0-0.53	0.5-5.0	0.1-0.5	0.0-6.0	3912	241
PC	0.12-0.14	0.13	0.02-0.31	2.3-4.7	1.5-4.0	0.0	511	67
WC	0.09-0.22	0.13	0.09-0.56	2.0-4.0	0.05-0.5	0.5-2.5	5079	658

1 Snouts and/or boulder fronts not extending across entire deposit.
2 Narrow deeply incised channel on alluvial fan.

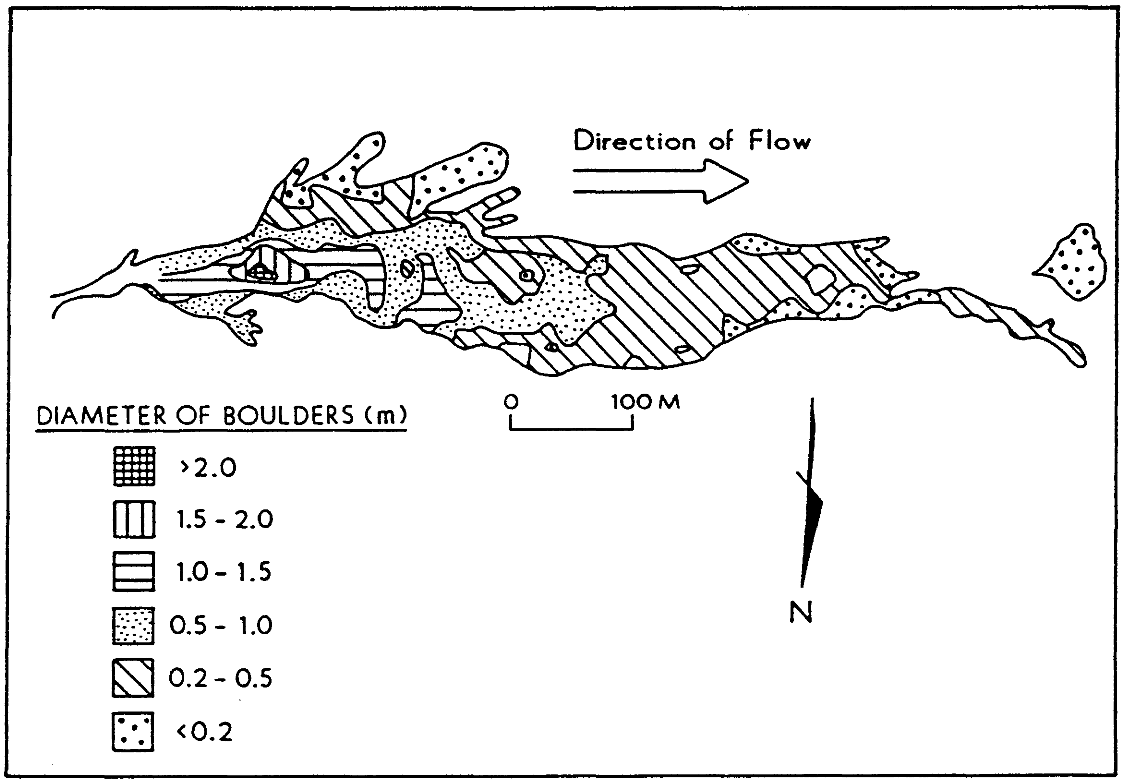


Figure 4. Map showing depositional area of the Lower Gooseberry Reservoir I debris flow showing the distribution of boulders. The largest boulders were concentrated in the center of the deposit and near the canyon mouth. As distance from the canyon mouth increased, the boulders decreased in size.

The lateral edges of the flows are easily discernable by levees, which are generally thicker than the adjacent flow and end in steeply sloping snouts, similar to a meniscus of water. Levees often contained woody debris oriented parallel to the flow direction due to differential shear stresses along the flanks of the flow. During shearing, large woody debris assume orientations parallel to the direction of flow indicating the stress field at the time of deposition. No differential shearing occurs at the flow front, so woody debris assume orientations perpendicular to the flow direction. Similar observations of pieces of tundra oriented perpendicular to the direction of downslope movement were reported by Mathewson and Mayer-Cole (1984).

Deposits at the Lower Gooseberry Reservoir-II site are found in scattered and isolated circular patches around the base of trees. The isolated deposits around the tree bases could have formed where the snow melted first leaving voids for the flow to fill around the trunks (fig. 5). Also, flow features in this deposit, such as levees or snouts at the lateral and distal ends of the deposit are indistinct, supporting the hypothesis that the deposits were later disturbed by melting snow. These features, as well as those observed in the main track, suggest that the debris flow occurred before the snow (or ice) had completely melted.

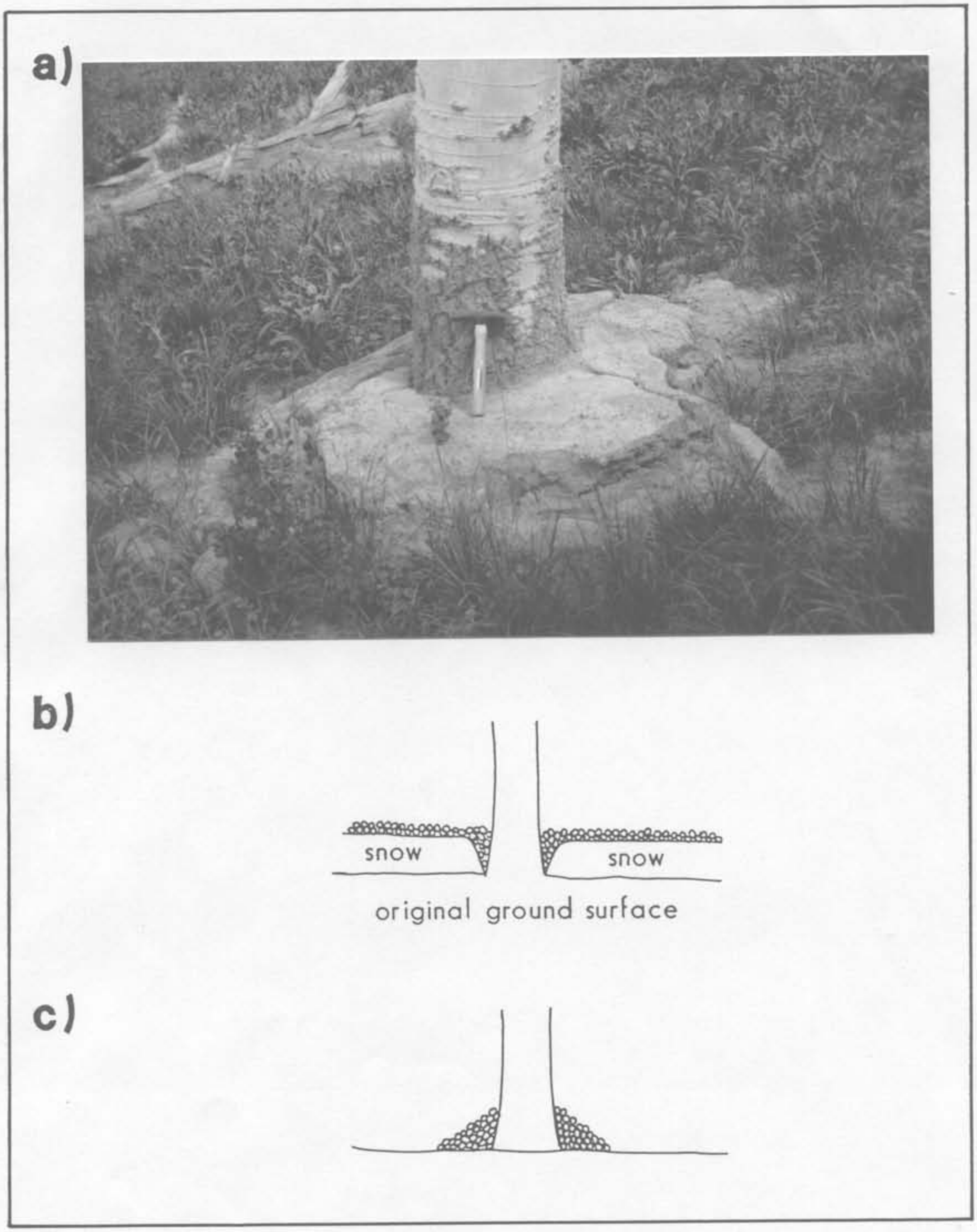


Figure 5. Isolated deposit in a circular patch around the base of a tree at the Lower Gooseberry Reservoir II debris flow (scale indicated by hammer). Illustrations (b and c) suggest explanation of deposits; (b) initial situation after deposition and (c) deposit after snow had melted.

Multiple Episodes and Pulses

Within the main tracks and depositional areas of several flows, evidence exists for more than one episode or pulse of debris flow. At some sites two distinct flow episodes are identified based on superposition and cross-cutting relations, as well as color and textural differences. The first episode is typically darker in color and contains large amounts of organic debris representing the initial flow which scoured the surficial materials from hillsides and channels. The second is typically more brown to yellow in color with less organic debris and is found on top of and confined within the first flow (fig. 6).

Accumulations of large boulders and/or woody debris within the main tracks and depositional areas define locations of debris-flow snouts; some of which have been breached, remobilized, or overtopped by subsequent pulses. These snouts probably represent pulses, or surges, within a single large debris flow and are not necessarily from temporally separate debris-flow episodes. Figure 7 shows a typical boulder-front snout at the Birch Creek site.

Further evidence for multiple pulses can be found in excavated sections of the 1983 deposits. At the Birch Creek site a sequence of nine deposits reveals alternating layers of debris-flow and hyperconcentrated-flood deposits (fig. 8). The hyperconcentrated-flood deposits could represent the fluid tail-end of debris-flow surges (Costa and Williams, 1984) or periods of flooding between debris-flow pulses.

Figure 6. One of the debris-flow paths at Birch Creek. Two deposits are separated by solid lines. The first deposit (outermost) was gray in color and had abundant woody debris; in contrast, the second deposit was yellow to tan in color and had very little woody debris.

Figure 7. A boulder-front snout in the upper depositional area of the Birch Creek debris flow. Boulders in this snout averaged 2 m in diameter; however, other snouts had boulders up to 4 m in diameter. For scale, largest boulders were approximately 2.3 m in diameter.

Figure 8. Excavated section of debris-flow deposits (dark layers) and hyperconcentrated-flood deposits (light layers) the Birch Creek debris flow where the flow crossed Utah State Highway 117. The darker-colored deposits were gray, massive, and unsorted consisting of clay to cobble-size material and containing abundant woody debris. The lighter colored deposits were light brown to tan, finely bedded, well-sorted sands containing almost no woody debris.

Recurrence of Debris Flows

Examination of aerial photographs reveals a lack of historic debris-flow activity in all but the Birch Creek site, suggesting that these events are historically infrequent in these particular canyons. However, on the basis of historic (140 yr) sedimentation, Keaton and others (1988) estimated recurrence intervals for the 1983 debris-flow events of two particular canyons along the Wasatch Front at 39 and 154 years. Thus, although no evidence for historic activity exists at the sites included in this study, it may not be reasonable to assume recurrence intervals greater than historic time.

Debris flows were identified in the stratigraphic deposits of three sites, indicating the recurrent nature on a geologic time scale. By dating deposits on the upper part of the alluvial fan at the Birch Creek site, the average recurrence interval for debris flows was determined to be 206 years during the period 4210 to 710 years B.P. At a point lower on the alluvial fan, where eight paleo-debris flows were identified, the average recurrence interval was established to be 296 years during the period 4470 to 2105 years B.P. Thus, there appears to be a period of time, beginning at about 4.5 ka, of frequent debris flows at the Birch Creek fan. This is in close proximity to the early Holocene period (> 6 ka) of heavy sediment accumulation along the Wasatch Front identified by Keaton and others (1988).

PHYSICAL CHARACTERISTICS OF THE DEPOSITS

The physical characteristics of the deposits were analyzed by considering the grain-size distribution, sediment-water concentration, and Atterberg Limits of the matrices. Only the matrices were considered because the rheologic properties of the flows are largely a function of the fine-grained fraction (Fisher, 1971; Middleton and Hampton, 1976). This assumption can not be made for all debris flows, particularly where inertial forces dominate as a result of grain-to-grain contact of the clasts (Bagnold, 1954; Takahashi, 1981). However, field evidence of laminar flow at these sites suggested that fluid motion was controlled primarily by viscous forces (Johnson, 1970). The error introduced in the analysis from the exclusion of the largest clasts will be discussed in a later section. For hyperconcentrated-flood deposits, there was no clear distinction in the field between the matrix and the entire deposit; therefore, the entire deposit was analyzed.

Grain-size Distribution

Samples were collected by excavating approximately 300 cubic centimeters of the deposit to include the material at the surface and to a depth of at least 10 cm. The largest clasts included in the samples were approximately 5 cm.

Grain-size distributions were determined in the laboratory by sieve and hydrometer techniques. Between six and fourteen sieves were used, ranging in size from 8 mm to 0.063 mm. Hydrometer readings were taken up to 24 hours, enabling determination of grain size down to 0.0013 mm. For the purpose of this investigation clay is defined as less than 0.004 mm; silt is between 0.004 and 0.062 mm; sand is between 0.062 and 2 mm; and gravel is greater than 2 mm in size. Grain-size distribution curves were generated by plotting percent coarser by weight versus grain size. Grain diameters were converted to Φ units (Krumbein, 1938). All curves were standardized to a maximum particle size of -1.0 Φ (2 mm), to exclude the gravel and coarser fraction.

Figure 9 shows envelopes of grain-size distribution curves for the debris-flow and hyperconcentrated-flood deposits (where they existed) at each of the eight sites. Two distinct groups of curves can be observed on these graphs. The first are the poorly sorted curves of the debris-flow deposits; the second are those from the deposits of the hyperconcentrated floods, which are visually better sorted. The grain-size characteristics were quantified by calculating the Graphic Mean, Inclusive Graphic Standard Deviation, Inclusive Graphic Skewness, and Graphic Kurtosis according to Folk (1965). Median grain diameter, Trask Sorting Coefficient, percent silt and clay combined, and

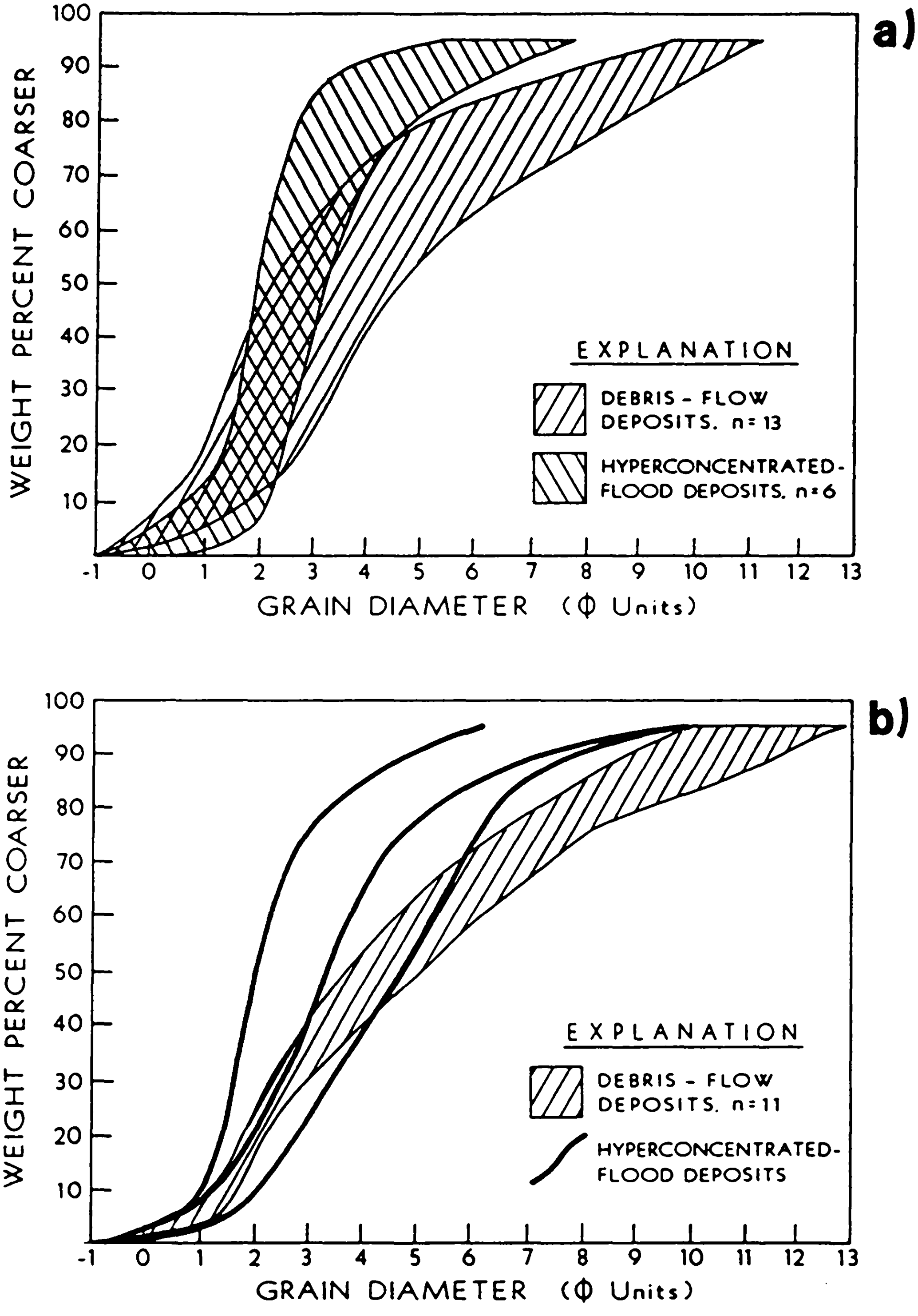
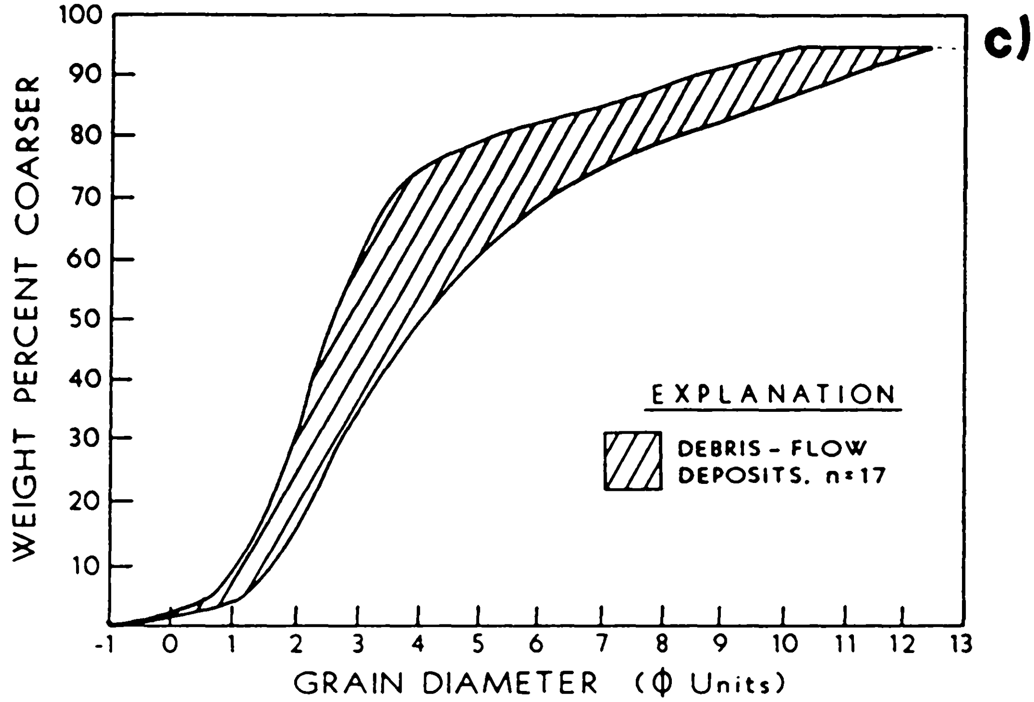


Figure 9. Grain-size distribution curves of the matrix from a) the Birch Creek debris flow, and b) the Crooked Creek debris flow.



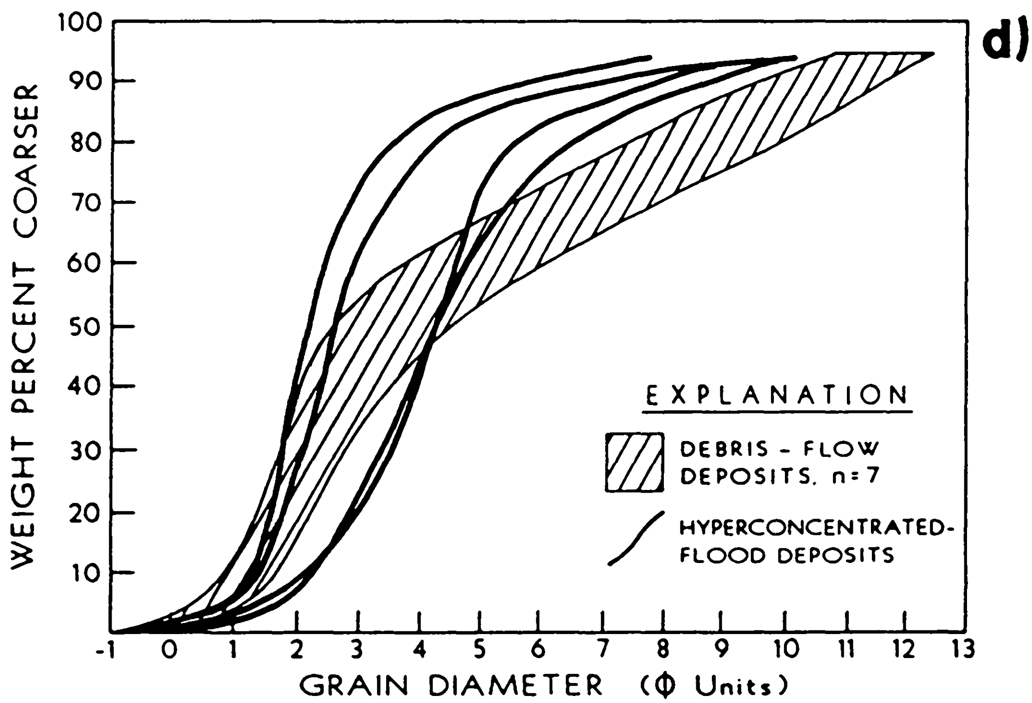


Figure 9. Grain-size distribution curves of the matrix from c) the Lower Gooseberry Reservoir-I debris flow, and d) the Lower Gooseberry Reservoir-II debris flow.

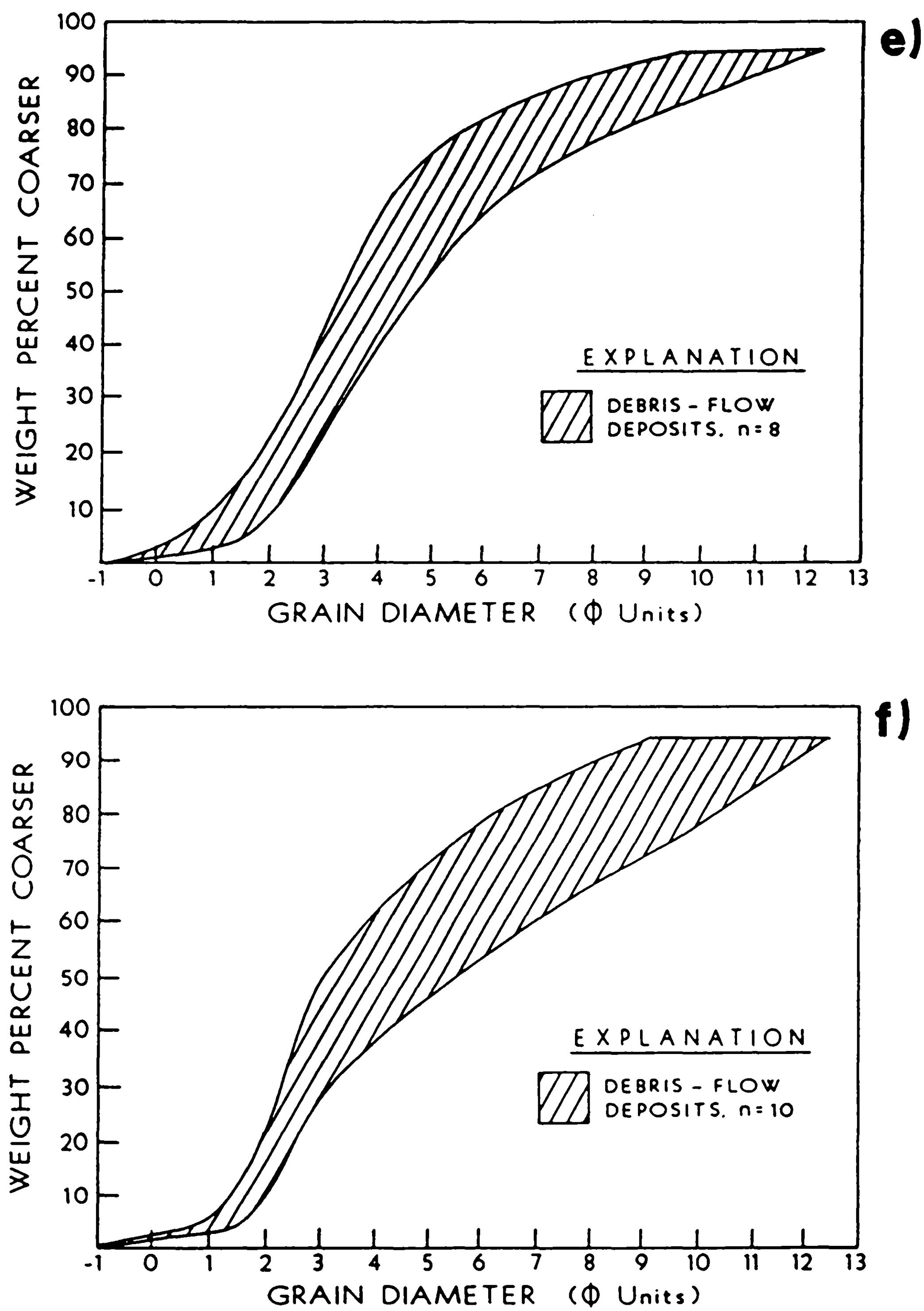
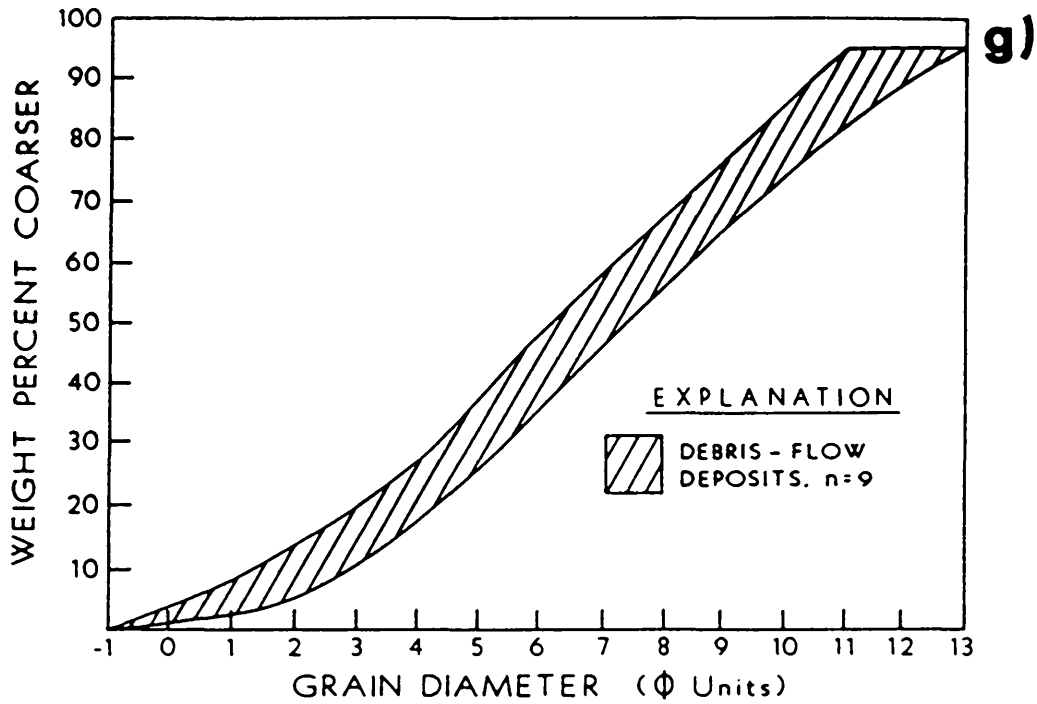


Figure 9. Grain-size distribution curves of the matrix from e) the Little Clear Creek debris flow, and f) the South Fork North Creek debris flow.



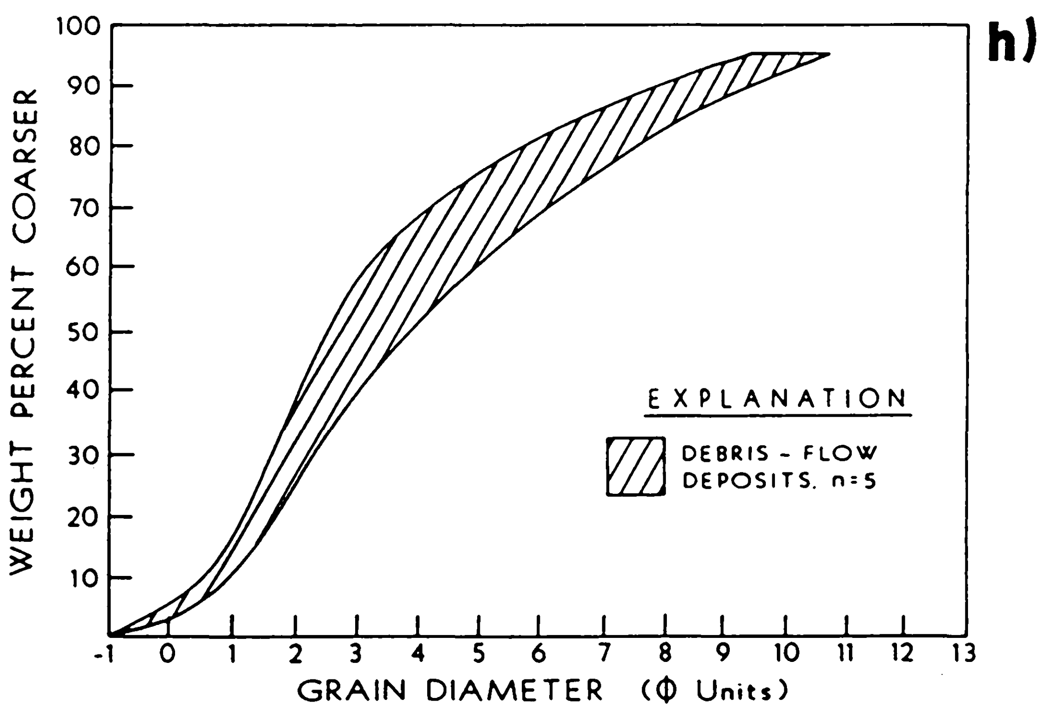


Figure 9. Grain-size distribution curves of the matrix from g) the Pole Canyon debris flow, and h) the Ward Canyon debris flow.

percent clay were analyzed in addition to the graphic statistics. The grain-size characteristics of the debris-flow and hyperconcentrated-flood matrices are summarized in tables 5 and 6.

The debris-flow matrices, for all but the Pole Canyon site, are very poorly sorted, strongly fine-skewed, and platykurtic to leptokurtic. The hyperconcentrated-flood matrices are poorly sorted, strongly fine-skewed to fine-skewed, and leptokutric to very leptokurtic. Because skewness measures the asymmetry of the distribution, the strongly fine-skewness of a debris flow indicates that the matrices have excess fine material (Landim and Frankes, 1968). Hyperconcentrated-flood matrices were slightly less skewed. Kurtosis measures the ratio of the sorting of the extremes of the distribution compared to the middle. The debris-flow matrices are nearly as equally well sorted in the extremes as in the middle, whereas the hyperconcentrated-flood matrices are better sorted in the middle. The samples from the Pole Canyon site are similar to those from the other sites except that the distribution curves are nearly symmetrical.

The debris-flow matrices have mean clay content ranging between 14 and 37 percent (table 5). This is a higher clay content than most values reported in the literature (table 7). The hyperconcentrated-flood matrices have mean clay content ranging between 3 and 8 percent (table 6).

Table 5. Summary of grain-size characteristics of debris-flow matrix. Mean value for each site listed, with standard deviation below, in parenthesis. Graphic statistical parameters from Folk (1965).

Site	Median Grain Diameter d_{50} (Φ units)	Graphic Mean M_z (Φ units)	Inclusive Graphic Standard Deviation σ_I (Φ units)	Inclusive Graphic Skewness Sk_I	Graphic Kurtosis K_G	Trask Sorting Coefficient S_o	% Si+C	%C
BC	3.44	4.33	3.08	0.41	0.92	4.75	46	17
n=13	(0.57)	(0.53)	(0.21)	(0.09)	(0.14)	(1.09)	(10)	(4)
CC	4.31	4.99	3.33	0.32	0.83	5.76	53	21
n=11	(0.37)	(0.35)	(0.23)	(0.07)	(0.05)	(0.77)	(4)	(4)
LGRI	3.23	4.28	3.06	0.53	1.21	3.49	38	16
n=17	(0.32)	(0.42)	(0.31)	(0.31)	(0.23)	(0.75)	(6)	(2)
LGRII	3.66	4.71	3.25	0.47	0.89	5.28	46	20
n=7	(0.59)	(0.48)	(0.29)	(0.09)	(0.10)	(1.40)	(7)	(4)
LCC	4.22	4.82	2.90	0.33	1.18	3.36	53	17
n=8	(0.38)	(0.56)	(0.24)	(0.06)	(0.18)	(0.64)	(6)	(4)
SFNC	4.07	5.11	3.39	0.45	0.89	5.91	50	22
n=10	(0.60)	(0.62)	(0.43)	(0.07)	(0.12)	(2.04)	(6)	(7)
PC	6.69	6.84	3.49	0.04	0.92	5.52	79	37
n=9	(0.39)	(0.41)	(0.24)	(0.09)	(0.05)	(0.58)	(3)	(4)
WC	3.05	3.84	3.06	0.41	0.96	4.62	39	14
n=5	(0.48)	(0.43)	(0.23)	(0.07)	(0.14)	(1.14)	(7)	(3)

Table 6. Summary of grain-size characteristics of hyperconcentrated-flood matrix. Mean value for each site listed, with standard deviation below, in parenthesis. Graphic statistical parameters from Folk (1965).

Site	Median grain diameter d_{50} (Φ units)	Graphic Mean M_z (Φ units)	Inclusive Graphic Standard Deviation σ_I (Φ units)	Inclusive Graphic Skewness Sk_I	Graphic Kurtosis K_G	Trask Sorting Coefficient S_o	% Si+C	%C
BC	2.32	2.49	1.48	0.31	1.76	1.64	15	3
n=5	(0.51)	(0.58)	(0.25)	(0.13)	(0.34)	(0.19)	(8)	(1)
CC	3.42	3.59	2.02	0.28	1.46	2.18	37	7
n=3	(1.09)	(0.89)	(0.41)	(0.17)	(0.26)	(0.49)	(20)	(3)
LGRII	3.32	3.61	1.97	0.39	1.79	1.93	39	8
n=4	(0.92)	(0.90)	(0.25)	(0.14)	(0.31)	(0.34)	(21)	(2)

Table 7. Clay content of sampled debris-flow deposits.

Location	Percent Clay	Reference
Wrightwood Canyon, California (1941 flow)	< 5	Sharp and Nobles, 1953
Western Fresno County, California (50 deposits)	12 - 76 median = 26	Bull, 1964
Mayflower Gulch, Colorado	1.1	Curry, 1966
Rio Reventado, Costa Rica	1 - 10	Waldron, 1967
Bullock Creek, New Zealand	4	Pierson, 1980
Pine Creek and Muddy River Lahars, Washington	< 2	Pierson, 1985
North Fork Toutle River Lahar, Washington	< 2	Pierson and Scott, 1985
Southern Rocky Mountains Colorado (14 Sites)	0.9 - 19.1 mean = 6.8 (< 0.002 mm)	Morris, 1986
Santa Cruz Mountains, California (8 flows)	21 - 33 mean = 26	Wieczorek and Sarmiento, 1988
Howgill Fells, England	11 - 15	Wells and Harvey, 1987

Sediment-Water Concentration

Five samples from each site were reconstituted in the laboratory to estimate their sediment-water concentration at the time they flowed. This method has been used by Pierson (1985b), Cannnon (1985), Pierson and Scott (1985), and O'Brien and Julien (1985). Although reconstitution is a subjective technique, Pierson (1985b) suggests that it is relatively accurate because slurry consistency is extremely sensitive to very small changes in water content.

Sediment-water concentrations of the reconstituted sample are measured when the sample exhibits characteristics which are assumed to be similar to debris flows. Cannon (1985) suggests that this occurs when the reconstituted mixture flows in a beaker tilted at 25 degrees. Pierson (1985b) suggests that this occurs when the reconstituted mixture flows easily, but still supports gravel-size particles. A change of water content between 5 and 7 percent by weight can either render the slurry too viscous to flow, or too runny to support a clast (Pierson, 1985b). The criteria used in this study were adapted from those of Cannon and Pierson.

Samples were reconstituted in a rectangular trough 31 cm wide by 47 cm long and inclined at 10 degrees to simulate natural gradients where flows were observed to stop. Water was added to the samples in 10 ml increments as the critical state was approached. Because the samples weighed approximately 2000 grams, the incremental change in water content was approximately 0.5 percent by weight. This small change increases the precision of estimating the water content at the time of flow. Solids concentration (by weight and volume), water content, and matrix density were determined when: 1) the mixture flowed easily to the end of the trough, 2) still supported 2 cm size clasts, and 3) had no free water running out of the slurry. The mean values and standard deviations of these properties are listed in table 8. The estimated solids concentration values obtained by this method agree well with values reported in the literature (see table 1).

The technique gave reasonable results with the exception of the hyperconcentrated-flood deposits from all sites as well as the debris-flow sample from the Pole Canyon site. The hyperconcentrated-flood samples contained 80 to 85 percent sand. When reconstituted, these samples were immobile unless the trough was vibrated or dropped inducing liquefaction. Also, water was seeping out of the sample before the slurry started to flow, resulting in a two-phased mixture. These observations suggest that the reconstituting method of estimating sediment-water contents is not suitable for these samples.

The samples from the Pole Canyon site were very difficult to reconstitute because they contained many dried clay clumps which had to be broken up during the reconstitution. The laboratory estimates of sediment-water concentrations are based on the assumption that all the

Table 8. Physical properties of the deposit matrices. Mean value for each site listed, with standard deviation below, in parenthesis. Cw = (weight of solids/total weight); Cv = (volume of solids/total volume); W = (weight of water/weight of solids).

Site	Estimated Solids Concentration by Weight Cw (%)	Estimated Solids Concentration by Volume Cv (%)	Estimated Water Content by Weight W (%)	Estimated Matrix Density D (gm/cm^3)	Liquid Limit[1]	Plastic Limit[1]	Plasticity Index[1]
Debris-flow Deposits							
BC	76	55	32	1.83			
n=5	(1.8)	(1.4)	(3.1)	(0.09)	30	25	5
CC	78	59	28	1.89			
n=5	(0.6)	(1.5)	(1.0)	(0.02)	26	18	8
LGRI	80	61	26	1.88			
n=5	(0.5)	(0.9)	(0.8)	(0.02)	19	18	1
LGRII	77	58	30	1.82			
n=3	(0.3)	(0.7)	(0.5)	(0.03)	23	18	5
LCC	74	56	35	1.72			
n=5	(1.1)	(1.2)	(2.0)	(0.03)	23	21	2
SFNC	76	56	32	1.80			
n=5	(1.0)	(1.5)	(1.7)	(0.02)	24	21	3
PC	71	48	42	1.75			
n=5	(1.8)	(1.9)	(3.6)	(0.04)	37	24	13
WC	84	66	20	2.09			
n=5	(1.3)	(1.9)	(1.8)	(0.06)	27	24	3
Hyperconcentrated-flood Deposits							
LGRII	78	58	29	1.89			
n=2	(1.8)	(3.1)	(3.0)	(0.02)	Non-Plastic		

[1] Based on one Atterberg test per site.

fine-grained material was separated at the time of flow. This assumption may not be valid if some of the material was intact from the source area. The evidence provided by the levees and shearing patterns of pulses of material in the deposit suggests that some material did remain intact from the source area, however, there is no way of knowing how much. The estimated concentration of solids by volume of 48 percent implies that this flow was at the lower end of the range for debris flows, or at the high end of the range for hyperconcentrated floods (see table 1). This would be inconsistent with all other field evidence. These combined observations indicate that reconstituted sediment-water estimates are probably not representative of those existing at the time of flow for this particular site.

Atterberg Limits

Atterberg Limits were determined on a single sample from each site. The purpose of the testing was to investigate the mobility of the flows based on the plasticity and liquid limits.

The plasticity indices (PI) of the samples vary between 1 and 13 (table 8) and would be classified as nonplastic to slightly plastic (Sowers, 1979). Materials with low PI change from a semi-solid to a viscous liquid with very small increase in water content. These PI values corroborate the observation of Pierson (1985b) that a decrease of only 2-3 percent in water content of reconstituted samples can make the slurry too viscous to flow. The highest PI value is from the Pole Canyon site, which also has the highest clay content. The PI values do not vary significantly between the other sites and were not investigated further.

The liquid limit (LL) of the samples (table 8) are lower than the water content estimated from reconstitution of samples. The matrices would therefore be described as viscous liquids (Sower,1979).

Debris-flow mobility has been investigated by Rodine (1974) and Johnson (1984) using water content as the principal determinant of slurry strength. Water content has also been shown to have the most effect on slurry strength by Trask (1959). Johnson (1984) defined the Mobility Index (MI) as the ratio of water content of the saturated inplace soils to the water content needed for that soil to flow. Ellen and Fleming (1987) have approximated the MI by defining the ratio of the water content of saturated inplace soil to its liquid limit. They found that soils having approximate mobility indices (AMI) greater than one have initial capacity to hold more water than their liquid limit, and when remolded would flow readily. These contractive soils would mobilize by liquefaction. Mobilization of the soil would be essentially instantaneous and complete because of the greatly reduced strength. Soils with AMI less than one must take on water in order to flow. These soils would mobilize by dilation, which is typically slower and less complete than liquefaction.

Although the AMI is defined for inplace soil, it may be reasonable to substitute the water content of a reconstituted sample for the saturated soil's water content. Making this substitution, AMI values are greater than one for all but one site. This suggests that mobilization was by liquefaction at these sites.

DISTINCTION BETWEEN TYPES OF DEPOSITS

The purpose of this analysis was to determine which parameters are the most significant in distinguishing between debris-flow and hyperconcentrated-flood deposits. Sedimentological parameters considered are, Graphic Mean, Inclusive Graphic Standard Deviation, Inclusive Graphic Skewness and Graphic Kurtosis (Folk, 1965). Other parameters evaluated are, median grain size, Trask Sorting Coefficient, percent silt and clay combined, and percent clay.

The samples from the Birch Creek, Crooked Creek, and Lower Gooseberry Reservoir-II sites were selected for statistical analysis because they include both debris-flow and hyperconcentrated-flood deposits. The deposit type was distinguished in the field based on morphology and observable sedimentological features. Debris flows were identified as poorly-sorted deposits lacking stratification and having angular clasts supported in a fine-grained matrix. They were further characterized by lateral levees, terminal lobate fronts, large clasts carried in suspension, and woody debris oriented parallel to the direction of flow.

The hyperconcentrated-flood deposits were identified on the basis of weakly developed stratification and a lack of a clay matrix, levees, and wholly supported large clasts. Woody debris present in these deposits showed no preferred orientation.

The mean values of each parameter were compared to statistically evaluate the difference in the deposits. The null hypothesis in this type of evaluation is that there is no difference in the mean values of a parameter. To show that there is a difference in the population means the null hypothesis must be rejected. This hypothesis test is two-tailed because the mean value of the hyperconcentrated-flood deposits can be either greater or less than the mean value for the debris-flow deposits. It may be appropriate to use a one-tailed test for some parameters. For example, hyperconcentrated-flood deposits are expected to have lower sorting coefficients and lower percent clay than debris-flow deposits. However, for most parameters no knowledge of the expected difference existed before the analysis, and therefore, the two-tailed test was used throughout.

The Wilcoxon Rank-Sum Test (Devore, 1982) was used to test the null hypothesis because I had no knowledge of the normality of the sample distribution. This non-parametric test is sometimes referred to as the Mann-Whitney U test (Devore, 1982). It has been shown (Mann and Whitney, 1947) that as the sample size increases, the distribution of U rapidly approaches the normal distribution. Siegel (1956) suggests that the Z statistic be used when the larger of the two samples is greater than twenty. Furthermore, Devore

(1982) suggests that when the size of both samples is greater than eight, the distribution of U can be approximated by the normal distribution. Therefore, because there are 31 samples of debris flows and 12 samples of hyperconcentrated floods, I evaluated the null hypothesis based on the normal approximation of U.

The hypothesis tests were performed on a computer using statistics software marketed by NH Analytical Software. This software performed the Wilcoxon Rank-Sum Test and also provided a Z-statistic for a normal approximation. Throughout this investigation, the null hypothesis is evaluated at the 0.01 significance level; i.e., the null hypothesis will be rejected when the computed Z-statistic is greater than or equal to $Z_{0.005}$, or less than or equal to minus $Z_{0.005}$. Table 9 lists the mean values and standard deviations of the parameters tested for the two types of deposits, and the corresponding Z-statistic for the hypothesis test.

The analyses for the median grain diameter and the Graphic mean indicate that only the Graphic mean is statistically significant in discriminating between the two deposits. However, field observations indicate that clasts up to boulder size were present in the debris-flow deposits, but not in the hyperconcentrated-flood deposits. A statistical difference in the median size of the samples would have been more likely if the sampling had included the

Table 9. Results of statistical analysis of the difference in the means of values of selected parameters of debris-flow and hyperconcentrated-flood deposits. The null hypothesis is evaluated at the 0.01 significance level, with a Z-statistic of 2.58.

	Debris flows (n = 31)		Hyperconcentrated floods (n = 12)			
Parameter	Mean	St. Dev.	Mean	St. Dev.	Z-statistic	Result
d_{50} (Φ units)	3.80	0.65	2.93	1.02	2.40	fail to reject Ho
Graphic Mean (Φ units)	4.65	0.56	3.14	1.00	3.97	reject Ho
Inclusive Graphic Standard Deviation (Φ units)	3.21	0.27	1.77	0.40	5.02	reject Ho
Inclusive Graphic Skewness	0.39	0.10	0.33	0.16	0.83	fail to reject Ho
Graphic Kurtosis	0.88	0.11	1.69	0.35	4.97	reject Ho
Trask Sorting Coefficient	5.23	1.18	1.87	0.42	5.02	reject Ho
Percent Silt and Clay	48.4	8.3	28.6	20.7	2.59	reject Ho
Percent Clay	18.9	4.2	5.6	2.7	4.98	reject Ho

large clasts in the debris flows. Sampling bias makes the result of this hypothesis test non-conclusive.

There are statistically significant differences in the mean values of the Inclusive Graphic Standard Deviation and the Trask Sorting Coefficient of the two deposits. The mean Inclusive Graphic Standard Deviation of the debris-flow and hyperconcentrated-flood deposits are 3.21 Φ and 1.77 Φ respectively. Pierson and Scott (1985) report Graphic Standard Deviations for debris flows, transitional flows, and hyperconcentrated streamflows as 3.0-5.0 Φ, 1.8-2.4 Φ, and 1.1-1.6 Φ respectively. The values for the debris flows in this study agree very well with their range. The values for the hyperconcentrated floods of this study agree very well with their transitional flows. The mean Trask Sorting Coefficient for the debris-flow and hyperconcentrated-flood deposits are 5.23 and 1.87 respectively. Costa and Jarrett (1981) report a range of Trask Sorting Coefficients between 3.9 and 11.5 for debris and mudflows, and between 1.8 and 2.7 for waterfloods.

The Z-statistic for the Inclusive Graphic Skewness indicate that there is not a statistically significant difference between the two types of deposits. Both sample means would be termed strongly fine-skewed. Again, this is a reflection of the sapling bias of only including the matrix of the deposits.

The analysis for the Graphic Kurtosis indicate that there is a statistically significant difference between the sample means of the two types of deposits. The debris-flow deposits are platykurtic and the hyperconcentrated-flood deposits are very leptokurtic. The physical meaning of the difference is that the debris flows are nearly normal (Kg = 1.0) with respect to the sorting in the middle of the distribution curve and the sorting in the extremes. The hyperconcentrated-flood deposits are better sorted in the middle of the distribution than at the extremes as indicated by the Kurtosis value significantly greater than 1.0. This well-sorted central part of the distribution curve for the hyperconcentrated-flood matrices are shown in figures 9a, b, and d.

The analyses for the percent silt and clay indicate that there is only a weak statistic difference between the mean values of the two deposits. However, there is a statistically significant difference between the percent clay in the two types of deposits. The debris-flow deposits have a mean value of 18.9 percent which exceeds reported values (10 percent, Pierson and Scott (1985); 11-15 percent, Wells and Harvey (1987)) of the necessary clay content to exhibit yield strength. The hyperconcentrated-flood deposits have a mean clay content of 5.6 percent which is below the values reported as necessary to exhibit yield strength.

The deposits can be further distinguished by examining scatter diagrams of selected parameters. Figure 10 shows a scatter plot of standard deviation versus mean grain size. Two distinct fields are evident on this scatter plot; one corresponding to the debris-flow deposits, and one to the hyperconcentrated-flood deposits. The hyperconcentrated-flood deposits are better sorted and have a smaller mean grain size than the debris-flow deposits. The deposits can also be visually separated into fields on plots of standard deviation versus clay content (fig. 11). This figure illustrates that hyperconcentrated-flood deposits are generally better sorted and have greater clay contents than debris-flow deposits. A scatter plot of kurtosis versus standard deviation (fig. 12) illustrates that hyperconcentrated-flood deposits are generally better sorted, particularly in the central portions of the distribution curves, than the debris-flow deposits.

Similar plots have been used by Pierson (1985a) and Wells and Harvey (1987) to distinguish between debris flows and hyperconcentrated floods. The distinctions visible on the scatter plots corroborates both the field observations and the statistical analysis discussed above.

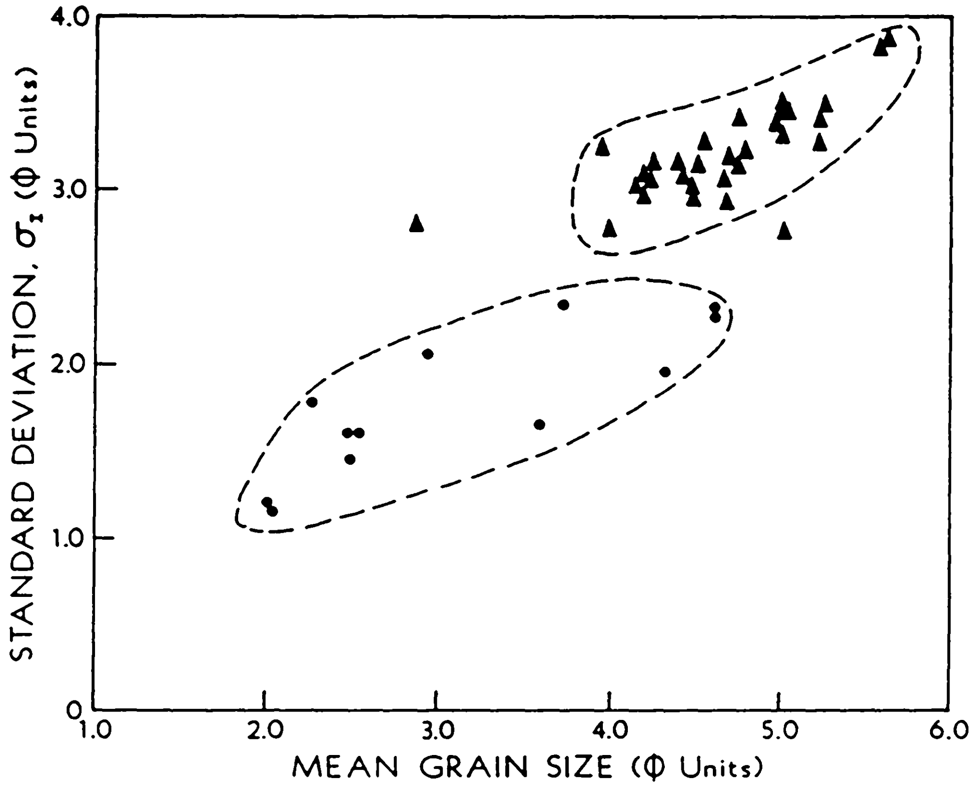


Figure 10. Scatter plot of standard deviation versus mean grain size showing distinct fields for debris-flow (triangle) and hyperconcentrated-flood (circles) deposits.

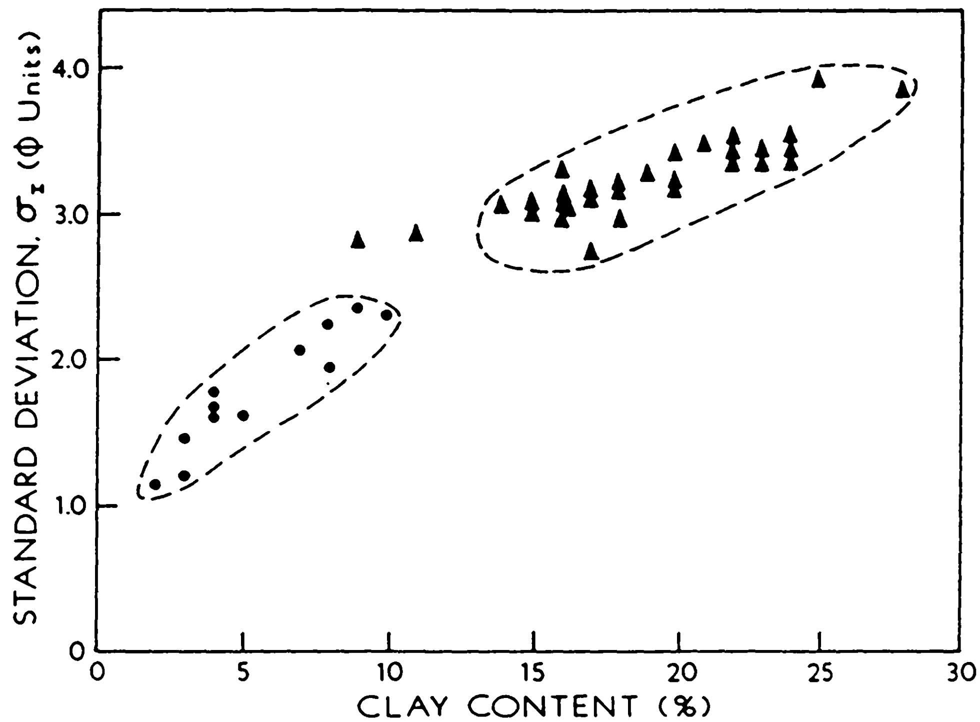


Figure 11. Scatter plot of standard deviation versus clay content showing distinct fields for debris-flow (triangles) and hyperconcentrated-flood (circles) deposits.

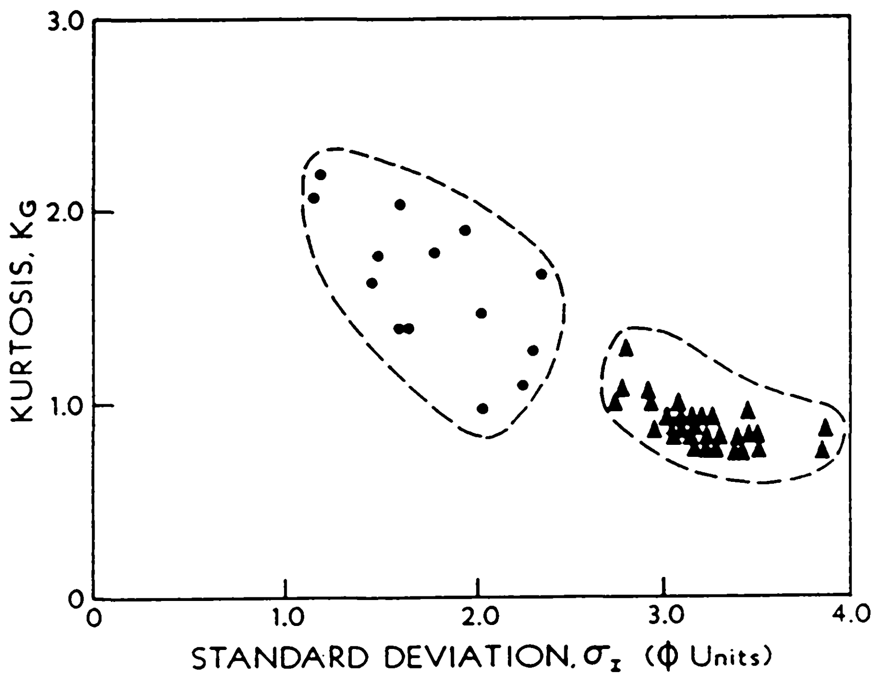


Figure 12. Scatter plot of kurtosis versus standard deviation showing distinct fields for debris-flow (triangles) and hyperconcentrated flood (circles) deposits.

SUMMARY AND CONCLUSIONS

Unusual climatic conditions during the winter of 1983 culminated in a rapid melting of above normal snowpack late in the spring. High pore-water pressures in soils and rock triggered numerous landslides, many of which fully mobilized into debris flows, others only partially mobilized and remained perched on the hillsides. Under favorable climatic conditions, it is likely that the partly-detached landslides could mobilize into future debris flows. Landslides along the Wasatch Front that became partly-detached during 1983 were statistically significant sources for debris flows in 1984 (Wieczorek and others, 1989).

In addition, many channels were oversteepened by scour during the 1983 events and are susceptible to accelerated rates of bank failures. Debris flows have been documented in other parts of Utah since the 1983 events as a result of mobilization of unconsolidated channel materials derived from bank failures (G. Kappessar, personal commun., July, 1984; Lips, 1985). Although partly-detached landslides and accelerated bank failures suggest debris-flow activity might increase, site visits to the source areas in the summer of 1984 indicated no movement of the partly-detached landslides.

The depositional areas were inspected in the fall of 1988, and no evidence was found to indicate debris flows since the 1983 events.

The landslides occurred on steep slopes within the drainage basins. From initial landslide source areas, debris flows traveled down hillsides and quickly became confined in first-order channels where they both incorporated new material and deposited thin veneers. Multiple flows occurred at some sites. The initial flows scoured soils and vegetation from channels making the channels deeper and more sharply defined. Subsequent debris flows traveling down these channels were more confined but could not scour as much. Greater confinement for these later flows may have increased the travel distance, while loss of additional volume of material decreased the travel distance.

Debris flows began to spread laterally and deposit material where gradients and coefficients of confinement decreased. As the flow depth decreased, the capacity to carry large boulders was reduced, and consequently, the largest boulders became grounded near the fan apex and were generally found in the upper reaches of the depositional area. Woody debris was carried on the surface of the flows to the distal ends of the deposits. Such debris were found oriented parallel to the flow direction and usually on the flanks of the deposit, except at the snouts, where they were oriented perpendicular to the flow direction. Debris-flow snouts consisting of large boulders and/or woody debris were found within the channels and depositional areas. The most distal deposits were from hyperconcentrated floods that either represented subsequent flood events or the more fluid tail end of debris flows.

Laboratory reconstitution of the deposits provides a means to estimate the sediment-water content of the flows. The material changed from a semisolid to a viscous liquid with very small changes in water content. This property of the material was also quantified by the low plasticity indices, as determined from Atterberg Limits. The approximate mobility index of the deposits suggests that mobilization was by liquefaction, and that the material took on additional water during mobilization. This mechanism could have resulted in a rapid mobilization, which would act to increase travel distance.

Field evidence indicates there is a distinction between debris-flow and hyperconcentrated-flood deposits. Debris flows are characterized by poorly sorted deposits supporting coarse angular clasts in a fine-grained matrix; they have well defined lateral levees and terminal lobate features, and woody debris oriented parallel to the flow direction. Hyperconcentrated-flood deposits are generally better sorted than debris-flow deposits and may show stratification. They lack a fine grained matrix, levees, terminal lobate features, wholly supported large clasts, and have no preferred orientation of woody debris. These features suggest distinctly different rheologic properties which were quantified by analyzing sedimentological parameters of the deposits.

The best parameters for distinguishing between debris-flow and hyperconcentrated flood deposits are mean grain size, sorting, kurtosis and percent clay. Debris-flow deposits are very poorly sorted, whereas, hyperconcentrated-flood deposits are poorly sorted. Debris-flow deposits have kurtosis values near 1.0 indicating even sorting between the middle and extreme parts of the distribution curve, whereas hyperconcentrated-flood deposits are better sorted in the middle part of the distribution than at the extremes. Debris flows have a greater clay content than hyperconcentrated floods.

Median grain size may be a useful parameter to distinguish between the two types of deposits if samples include the largest fraction of the deposits, which may be up to boulder in size. There is not a statistically significant difference in skewness between the two types of flows.

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