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DEBRIS FLOWS–GEOLOGIC PROCESS AND HAZARD

ILLUSTRATED BY A SURGE SEQUENCE AT JIANGJIA RAVINE, YUNNAN, CHINA

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COVER PHOTOGRAPH

Head of alluvial fan of Jiangjia Ravine. Rice fields on the deposits of debris flows (occurring in the 1980's). Photo by K.M. Scott.

DEBRIS FLOWS—GEOLOGIC PROCESS AND HAZARD

ILLUSTRATED BY A SURGE SEQUENCE AT JIANGJIA RAVINE, YUNNAN, CHINA

By Kevin M. Scott and Wang Yuyi

A study and video recording of debris flows at Jiangjia Ravine in Yunnan Province, China. This rugged and remote site is famous for the annual occurrence of debris flows that present serious risks to those living in this mountainous region.

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CONVERSION FACTORS

Multiply	By	Obtain
millimeters (mm)	0.03937	inches (in.)
centimeters (cm)	0.3937	inches (in.)
meters (m)	3.281	feet (ft)
cubic meters (m^3)	0.028	cubic feet (ft^3)
kilometers (km)	0.6214	miles (mi)
square kilometers (km^2)	0.3861	square miles (mi^2)
meters per second (m/s)	3.281	feet per second (ft/s)
meters per second (m/s)	2.237	miles per hour (mph)
kilometers per minute (km/m)	37.28	miles per hour (mph)
cubic meters per second (m^3/s)	35.31	cubic feet per second (cfs or ft^3/s)
hectare–10,000 m^2 (ha)	0.405	acres–43,560 ft^2 (ac)

Debris Flows–Geologic Process and Hazard

Illustrated by a Surge Sequence at Jiangjia Ravine, Yunnan, China

By Kevin M. Scott and Wang Yuyi[1]

ABSTRACT

Debris flows are slurries of sediment and water that are both an important geologic process and a major hazard. They present large risks to those living in mountainous areas, as well as downstream from volcanoes in the case of the flows known as lahars that may travel 100–200 kilometers (62-124 miles). The accompanying video records a series of debris flow surges at Jiangjia Ravine, in Yunnan Province in southern China. This rugged and remote site is famous for the annual occurrence of debris flows triggered each summer by monsoonal rains. The video illustrates the unique characteristics of debris flows, how they behave, and why they cause large losses of life and property in China and many other parts of the world. This report is a summary for those wishing more information than is presented in the video, and for the specialist we include dynamical data on the flows and textural data on their deposits.

INTRODUCTION – WHY STUDY DEBRIS FLOWS?

The Chinese Academy of Science studies the recurring debris flows at Jiangjia Ravine (fig. 1) in order to define their origin and behavior and thereby find ways to reduce the risks of debris flows to life and property (Kang, 1989; Cui, 1992; Du and others, 1995). Huge sediment yields—volumes of sediment discharge per unit area—are moved by debris flows. These high sediment yields can markedly reduce the capacity of downstream flood-control and power-generating facilities. Among these is the Three Gorges Dam, the world's largest dam scheduled for completion on the Yangtze River about 2010, located approximately 1,000 km (620 mi) downstream from Jiangjia Ravine. We use metric units throughout our discussion, with their customary ("inch-pound") equivalents for some measures of distance, velocity, and volume.

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[1] Institute of Mountain Hazards and Environment, Chengdu, China

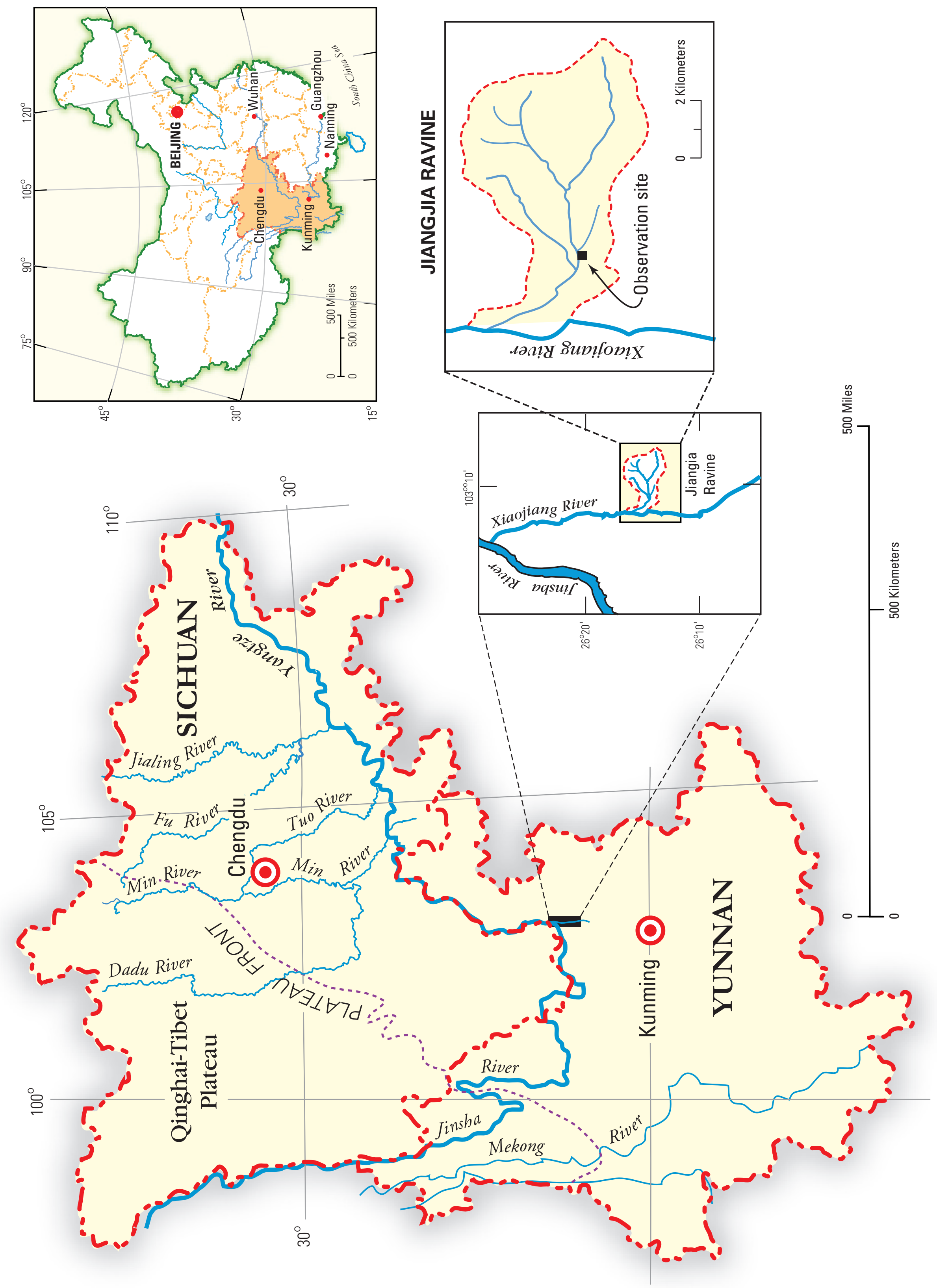

Figure 1. Index map showing location of Jiangjia Ravine.

Mountains comprise 33 percent of China's land area of 9.6 million km^2 (3.7 million mi^2). Jiangjia Gou (Ravine or Gulley) is one of approximately 50,000 small mountain watersheds called "sediment highways" that yield debris flows in China (Ou, 1999). Ravine or gulley, the best translations of *gou*, are overly diminutive, but there is no really analogous term in English. The drainage area (figs. 1 and 2) is 48.6 km^2 (19 mi^2), and the main channel is 13.9 km (8.6 mi) in length. Relief is from 1042 to 3269 m.a.s.l. (3,419 to 10,722 ft). The sparse rainfall, with 85 percent concentrated in monsoonal storms from May to October, has ranged from 307 to 886 mm/yr (12.1 to 34.9 in/yr) in recent years (table 1). Consequently, vegetation has not recovered from long-term deforestation, and erosion rates are high. Nearly all the sediment discharge from the drainage occurs as what can be described as episodic "express trains" of debris flow (Cui, 1999). In spite of the harsh environment, many small villages survive tenaciously throughout the basin, subsisting on rice grown on the debris flow deposits in the main channel (the only green areas in the video), and on other crops from upland areas. Most intermediate altitudes are too steep for humans or domestic animals.

The flows at Jiangjia Ravine (fig. 3) are very similar in their behavior and physical properties to their huge analogs, lahars, that occur in volcanic terrains and from volcanoes. Although the Peoples Republic of China has few volcanoes of the type that produce lahars, elsewhere around the circum-Pacific "Rim of Fire" lahars have taken many thousands of lives in recent decades. Case histories of catastrophic examples, with recommended mitigation strategies, are described by Scott and others (2001).

Figure 2. Photo showing video site (arrow) in Jiangjia Ravine and location of the Dongchuan Debris Flow Research and Observation Station (DDFROS). Note rice field development on recent debris flow deposits, upper left. Photo by R.J. Janda.

Table 1. Annual sediment yields of debris flows in Jiangjia Ravine. Data from Dongchuan Debris Flow Observation and Research Station. Total sediment discharges estimated for 1965 to 1981 range from 820,000 in 1971 to 3,530,000 m^3 in 1965 (Wang and others, 2000).

Year	Sediment Discharge (m^3)	Number of Periods of Debris Flow	Annual Precipitation (mm)
1982	1,920,000	14	408
1983	3,980,000	15	653
1984	3,690,000	7	528
1985	5,850,000	14	788
1986	1,800,000	5	478
1987	1,710,000	7	352
1988	290,000	4	307
1989	2,000,000	14	389
1990	2,560,000	10	580
1991	6,590,000*	22 *	697
1992	1,190,000	5	497
1993	260,000	2	524
1994	2,000,000	6	739
1995	3,740,000	13	775
1996	3,150,000	14	620
1997	6,570,000	18	810
1998	2,150,000	10	514
1999	2,340,000	8	484
2000	600,000	8	735
2001	3,732,000	21	886 *

* Peak of record (only during the period listed here for annual precipitation)

Debris Flows in Southwest China

Debris flows are a widespread means of sediment transport in the mountainous and semiarid parts of Southwest China (Du and others, 1995; Ou, 1999). In recent years, the annual economic loss from debris flows has exceeded 2 billion yuan (US$ 235 million), and the annual loss of life from debris flows and landslides, many of which are actually debris flows, is estimated at between 500 and 1,000. Facilities periodically damaged by debris flows include 150 cities, 1,200 towns and villages, 36 railway lines, 50,000 km (31,000 mi) of highways, 120,000 ha (300,000 ac) of farmland, and large numbers of mines, secondary roads, and hydroelectric facilities. In addition to the death and destruction from moving debris flows, their deposits remain to reduce flood conveyance in channels and the water-storage capacity in the region's reservoirs. More than 360 small-to-medium-scale hydroelectric stations and more than 50 reservoirs were destroyed by 1991, and at least 1,000 reservoirs had lost significant capacity primarily as a result of debris flows [IMHE—Institute of Mountain Disasters (renamed Hazards) and Environment, 1991].

Jiangjia Ravine is tributary to the Xiaojiang River (fig. 1) which has 106 other tributaries that yield debris flows. The watershed of the Xiaojiang River is known in China as the "World's Natural Museum of Debris Flows" (Cui and others, 1999a). That description is not an overstatement. Debris flows would be common in the Xiaojiang watershed under natural conditions, but they are larger and more frequent in part because of progressive deforestation that began during the Tang Dynasty (A.D. 618-907) and intensified during the last 300-400 years for the smelting of copper from local mines (Wieczorek and others, 1987).

The Xiaojiang is the main southern tributary of the Jinsha River (the fabled "River of the Golden Sands" in Chinese literature), which joins the Min River to form the upper Yangtze River, here known as the Chang Jiang (Long River). Northwest of the provincial capital of Chengdu (of Sichuan, north of Yunnan; fig. 1), the Min River descends from the Qinghai-Tibet Plateau, an area of high relief and frequent debris flows, to disgorge sediment as coarse as boulders (particles with diameters >256 mm, or about 10 in). At this point, famed engineer Li Bing designed the first large-scale, hydraulically sophisticated system for flood control and irrigation in the 3rd century BC. The system still functions exactly as he designed it, utilizing the natural flux of coarse sediment toward the inside of a large bend to separate it from flow with low concentrations of sediment toward the outside of the bend. Relatively clear water is then decanted from the outside of the bend through a bedrock weir (named "Neck of Precious Bottle") into low-gradient canals that irrigate the Sichuan Basin, the so-called Granary or Rice Basket of China.

The Great Rivers of China and Erosion of the Landscape

The two large rivers of China—the Yellow River of the north and the Yangtze of the south—are strikingly different. The Yellow River transports approximately 3 times as much sediment as the Yangtze on average, whereas the Yangtze discharges approximately 20 times as much water as the Yellow River (Jordaan, 1992). Sediment yields and erosion are intense

Figure 3. Photo of surge front on June 15, 1990. Note spray of ejected particles from surge front, especially at right margin (left bank). Width of surge is 20 m (66 ft). Photo by K.M. Scott.

throughout most of the Yellow River watershed, due in significant part to widespread deposits of loess, or windblown silt. Slopes covered by or cut into loess readily fail, and the disaggregated material may move as a debris flow. In contrast, high sediment yields and erosion rates are mainly confined to the rugged headwaters of the Yangtze watershed. There, the active mountain-building processes that have elevated the Qinghai-Tibet Plateau have formed a steep and unstable landscape where debris flows are common. For example, the annual sediment yield (volume of sediment only) from Jiangjia Ravine is typically from 1–4 million m^3 (35-140 million ft^3). Table 1 summarizes the annual sediment yields and the numbers of flow episodes at Jiangjia Ravine from 1982 to 2001. The maximum recorded annual yield is 6.6 million m^3 (230 million ft^3), which corresponds to an astounding denudation rate—equivalent to lowering the entire area drained by Jiangjia Ravine *in a single year*, by over 13.6 cm (more than 5 in)!

WHAT CAN WE LEARN FROM THE VIDEO?

The video illustrates the features of debris flows that make them an important geologic process and hazard—their content of rock particles (sediment), high velocities, ability to move huge boulders, and other unique attributes described under the following headings. We recorded most of the first 24 in a sequence of 77 rainfall-triggered surges lasting over 3 hours and 45 minutes in Jiangjia Ravine on July 9, 1990. The site is renown for similar flow episodes, lasting between 30 minutes and over 10 hours, that have occurred here with summer rainstorms between 5 and 28 times annually and a total of 427 times from 1965 to 2001. Segments of this video appear in many television documentaries on natural hazards, including those dealing with lahars. Except for their lack of coarse boulder snouts or fronts, explained below, the flows in Jiangjia Ravine are typical, in appearance and characteristics, of debris flows as they occur in steep terrain around the world.

The characteristics and dynamics of the surges seen in the video were recorded by the staff of the Dongchuan Debris Flow Observation and Research Station (DDFORS), part of IMHE (Zhang and Xiong, 1997). Flow episodes consist of as many as 100 or more surges, each separated by less than one to tens of minutes. Each surge is a separate wave of moving rock fragments and water. Table 2 includes data for all the surges in the video, to and including surge 29, the second of 2 surges in the series that were sampled for sediment content. Complete data for the 77-surge series appear by surge number in DDFORS records (Zhang and Xiong, 1997, p. 105-106). Figure 2 shows the DDFROS facilities and the location at which the video was made. A complete narration of the video, for reference by educators and keyed by surge number, is included in the appendix.

Flows of Water and Rock Particles Comprise a Spectrum of Increasing Sediment Content from Floods, to Hyperconcentrated Flows, to Debris Flows

Floods consist of water containing less than 20 percent sediment by volume—fine sediment that moves in suspension and coarser particles that roll and saltate along the bed (bedload). The properties of debris flows, in which a slurry of sediment moves a subordinate amount of entrained water, are less well known but are the object of intense experimental study (cf., Iverson, 1997). Debris flows typically contain about 65 percent sediment by volume, and may be defined as containing at least 60 percent sediment by volume (cf., Pierson and Costa, 1987). Least well known are the properties of the flows between these two end members—hyperconcentrated flows, which contain sediment in the range of 20 to 60 percent by volume, or 40 to 80 percent by weight. The occurrence and deposits of hyperconcentrated flow are rarely recognized, but may actually be common in the steeplands of volcanic and

Table 2. Data for surges seen and sequential with those seen in the video. Data for all 77 surges in series from Zhang and Xiong, (1997, p. 105-106). Surges 13 and 29 were sampled (data in figure 8).

Surge number	Time code on video*	Time at start of observation reach (hr: min: sec)	Height (m)	Velocity (m/s)	Discharge (m^3/s)	Unit weight (t/m^3)	Surge volume m^3
1	2-13/14	13:13:19	0.40	3.23	25.8	1.700	2141
2	2-14/15	13:14:44	0.90	6.78	128.1	2.000	2626
3	2-16/17	13:16:01	1.00	7.63	167.9	2.100	4785
4	2-17/18	13:17:15	0.65	7.84	117.2	2.100	2051
5	2-18-19	13:18:00	1.21	8.16	246.8	2.200	4196
6	2-19-20	13:19:41	1.15	8.33	239.5	2.200	9221
7		13:21:27	2.58	9.09	609.8	2.200	13100
8	2-23/24	13:22:52	2.83**	9.30**	710.6**	2.200	23450 **
	(Only the surface of flow 8 is shown)						
9	2-24/25	13:24:30	1.66	8.16	338.6	2.200	5926
10	2-25/26	13:25:38	2.29	8.33	496.0	2.200	10168
11	2-27	13:26:46	2.06	8.00	412.0	2.200	7004
12	2-28	13:27:34	1.68	8.00	336.0	2.200	7392
13 ***	2-29/30	13:29:02	1.63	8.89	362.3	2.262**	5072
14	2-30/31	13:29:50	1.55	8.89	344.5	2.262**	6718
15	2-31/32	13:31:19	1.56	7.27	283.5	2.262**	4394
16		13:32:17	2.01	7.35	369.3	2.262**	4616
17		13:33:05	1.64	7.41	303.8	2.262**	5164
18		13:34:09	1.39	7.04	244.6	2.262**	4280
19	2-35/36	13:35:35	1.75	7.30	319.4	2.262**	8304
	2-37/38	(No data for small surge seen between surges 19 and 20, in the process of being overriden by surge 20)					
20	2-38/39	13:37:48	1.70	8.70	369.7	2.262**	7948
21	2-40/41	13:40:03	0.85	6.78	144.1	2.262**	2666
22	2-41/42	13:40:48	1.31	5.88	192.6	2.262**	3274
23	2-42/43	13:41:42	1.41	7.41	261.2	2.200	6269
24	2-43/44	13:43:35	1.20	7.14	214.2	2.200	3748
25		13:44:38	0.80	8.89	177.8	2.200	2845
26		13:45:42	1.22	6.25	190.6	2.200	3526
27		13:47:01	1.70	7.14	303.4	2.200	10468
28		13:48:49	1.15	5.56	159.8	2.200	3276
29 ***		13:50:20	1.40	7.69	269.2	2.180	076

Series contained 48 more surges. Peak surge velocity in the remainder of the series was 8.33 m/s; peak height was 1.99 m; peak unit weight was 2.200 t/m^3. Surges 75-77 were hyperconcentrated flows.

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* The time code is one hour in advance of local time; the relative times between surges, as measured from the time codes and used for correlation with the data of Zhang and Xiong (1997), are accurate.

** Peak values of the entire series.

*** Samples taken from these surges; sample reported from surge 14 by Zhang and Xiong (1997) is from surge 13.

semiarid terrains (cf., Pierson and Scott, 1985; Scott, 1988).

Surge 1 in the video is a hyperconcentrated flow (data in table 2). Note that the high sediment content causes it to resemble dirty, turbulent motor oil in appearance. The body of surge 2 is a debris flow, but note that it is pushing hyperconcentrated flow that has remained in the channel ahead of the surge peak. Some of the flows in the video by Costa and Williams (1984) have the same appearance and behavior and are probably also hyperconcentrated flows.

Debris Flows Can Move Huge Boulders

Debris flows are widely cited as capable of moving huge boulders. In fact, most of the debris flows in the western United States and other parts of the world have a characteristic snout or front of boulders, the concentration of which may act like a "moving dam." Examples of flows with boulder-dominated fronts are recorded in the video by Costa and Williams (1984). This common feature is not present in the debris flows in our video, only because little sediment as coarse as boulders is present at Jiangjia Ravine—the bedrock readily disaggregates to small fragments. The boulder seen rolling in the flow between surges 6 and 7 is near the maximum size recorded at the site, over 1 m (about 4 ft) in maximum dimension.

Forming Rivers of Rock

The Jiangia Ravine watershed is underlain by highly fractured, metasedimentary and volcaniclastic siltstone and shale that disaggregates directly to pebble-size clasts. The smaller particles are predominantly elongate, or prismoidal, in shape. This material is continuously supplied to the main channels from hill- and valley-side slopes, by small landslides, dry sliding, and in the summer by wet creep at a visibly obvious rate (fig. 4). Bank erosion of previous debris flow deposits (fig. 5) adds to the surge volumes (flow bulking). During the storms that trigger the flows, slope stability throughout the steep source areas of Jiangjia Ravine is so low that access and direct observations are not prudent (and were not permitted in 1990). Nevertheless, our observations during clear weather suggest that the source of the flows is the gradual mobilization or flushing of the "reservoir" of deposits, during storm runoff, that have accumulated in the channel network since the last flow episode. The surges generally do not form by progressive upstream slope failures, as observed in some areas of recurrent debris flow.

Debris Flows are Faster than Flood Waves

At similar discharges, slurries of debris flow travel about twice as fast as water flows. Velocities of the surges typically range from several m/s to 10 m/s, about 10 to 33 ft/s or 7 to over 20 mph–the range of those we see in the video. Velocities of most debris flows fall in this range. The velocity of the fastest surge in the video (surge 8) is 9.3 m/s (table 2), equivalent to 30.5 ft/s or 20.8 mph. The maximum surge velocity recorded at the site is 18.18 m/s (July 9, 1998)–*over 40 mph!* The values are based on the travel times, measured by stopwatch, of the surge fronts in the straight, 200-m reach upstream from the observation point (fig. 2). In the calculations of flow and sediment discharge, discussed below, it is assumed that the debris flow surges are translatory waves of moving material rather than of form—that is, that the particles in the wave are moving at the speed of the wave, as opposed to oscillatory surges in which the wave form moves faster than the material within it [see the video of Costa and Williams (1984) for an example of a wave form moving through nearly stationary sediment]. The dominantly translatory nature of the surges at Jiangjia Ravine, where sediment moves with the flows, is clear in the video. We designate surge velocity in the video as *c*, celerity—the velocity of a wave form independent of sediment movement.

The channel retains a significant volume of flow between the surges, and this material may cease to flow, as seen in the video, or it may flow continuously. Note the stationary material in the channel as it is overrun by all of the surges following surge 3.

Figure 4. Photo of tilled debris flow deposits in Jiangjia Ravine (note texture in rice-field levee at left) and debris cones of sediment flowing from the steep valley-side slopes. Note patterns on cone surfaces, indicating mass flow, in some instances at visibly detectable rates during summer dry periods. Photo by K.M. Scott

Figure 5. Photo of debris flow in channel, incorporating mass of material derived from bank failure (arrow). Note texture of deposit surface, in cutbank and on surface at lower left. Photo by K.M. Scott.

Flow Geometry—Depth and Width—and Channel Slope

The heights of individual surges typically range from 1–2 m (3.3–6.6 ft). The largest surge in the video (surge 8) is 2.83 m (9.3 ft) high. The highest peak recorded at the site through 2001 was 5.5 m (18 ft). The flows range in width from 20.0 m (66 ft), the width of the channel bottom, to 27.0 m (89 ft) for surge 8. Slope of the reach at the site is 0.06.

How Much Flow and Sediment are Moved by the Surges at Jiangjia Ravine?

The largest peak discharge of any surge in the video (table 2; no. 8) is 710.6 m^3/s (25,000 cfs). The largest peak discharge measured for any surge at Jiangjia Ravine through 2001 is 2,913.5 m^3/s, or 103,000 cfs (July 9, 1998). Total sediment yield (the volume of sediment discharged from the watershed) of the 77 surges, including the hyperconcentrated flows, is 243,000 m^3 (over 8 million ft^3). The most sediment discharged by any single flow series is 2 million m^3, or about 70 million ft^3 (Ou, 1999, p. 37). The sediment-yield volumes are derived from the total discharges of the surges and their measured or estimated sediment concentrations.

Maximum sediment transport rates for each surge are not listed in Table 2, but values range between 29 t/s (surge 1) and 1,370 t/s (surge 8)—the largest transport rate for any of the 77 surges in the series.

Why Debris Flows Destroy Manmade Structures–Powerful Impact Forces

The ability of debris flows to crush many structures results from their high impact forces—they are literally rivers of flowing rock fragments with interstitial water. The maximum unit weight of a surge in the video is 2.26 t/m^3 (surges 13 to 22), compared to 1.0 for pure water, only slightly less than the maximum recorded value at the site of 2.37 t/m^3, corresponding to 81 percent sediment by volume (Wang, 1989, p. 237; Ou, 1999, p. 37). Thus the flows are more than twice as dense as pure water (as well as flowing at twice the velocity, as noted above). The unit weight of the solid sediment at Jiangjia Ravine is taken uniformly as 2.65 t/m^3 (a density of 2.65).

Like Wet Cement

Debris flow behavior is strongly influenced by a highly viscous, nearly incompressible pore fluid composed of water with suspended fine sediment (Iverson, 1997). Although the property of viscosity does not strictly apply to granular mixtures, like most debris flows, viscosity has been measured or estimated for some flows. The viscosities of debris flows themselves are reported at over 1,000 times that of pure water at 20° (Pierson, 1980). Viscosity of 20–30 poises is reported by Li and others (1983) for the flows at Jiangjia Ravine. That range compares with viscosities reported for mayonnaise, 6.3 poises, and wet cement, 24 poises (see table 2 of Costa, 1984).

Why Multiple Surges?

Prolonged episodes of debris flow commonly occur as a series of separate surges, both at Jiangjia Ravine and elsewhere (see the video of Costa and Williams, 1984). Explanations include flow instability, which causes uniform flow to evolve into a series of waves (Davies, 1986; Liu and Mei, 1990). Based on research at Jiangjia Ravine in the month following the surges in our video, Davies and others (1991, 1992) observed that surges form with the continuous inflow of material from upstream into downstream, wider, and less-steep reaches that already contain a large volume of static debris (such as the 200-m reach upstream from the video site; fig. 2). Discharge of a surge from those reaches is triggered periodically at some critical point, temporarily depleting them, and setting the stage for another cycle of continuous upstream inflow that will again trigger episodic outflow. Between surges, flow commonly ceases entirely, as we see in the video.

Ballistic Clast Ejection—Estimating Flow Velocities from Runup Heights

The fronts of the surges contain clasts as coarse as small boulders, but the dominant size class is the pebble (4-64 mm) fraction. Grain-to-grain collisions are intense, and pebbles are constantly ejected from the moving front, at times as a spray of material (fig. 3). The spray appears to be mud, but it is mainly if not entirely mud-coated particles, based on the direct observations of the authors during this flow series. Ejection is intense when flow impacts the channel side or a barrier at a high angle, and cataclasis (breaking and crushing) of the pebbles occurs. The ballistically ejected, mud-coated clasts yield mud-splatter deposits that extend above those that are formed as the flows “run up” an obstacle or superelevate against the outside of a channel bend. Thus, based on deposits after the fact, applications of the energy-balance equation (assuming conversion of kinetic to potential energy) at this site could yield velocities that are too large. The distance (h) a flow runs up an obstacle is related to velocity (c) by the energy-balance relation, $c = [2gh]^{1/2}$, where g = gravitational acceleration (cf., Pierson, 1985). However, in a large-scale flume, Iverson and others (1994) found that the measured velocities of moving debris flow exceeded those obtained from application of the energy-balance equation to the runup height (where not affected by mud splatter) by about 30 percent.

Estimating Cross Sections of Debris Flows

Instantaneous debris flow discharges are commonly estimated by obtaining velocities from runup as described above, as well as by the superelevation of the flow surface (Δh) in a bend due to centrifugal force (cf., Pierson, 1985). Velocity (c) is related to Δh by the relation, $c = [g\Delta h r_c / b]^{1/2}$, where r_c = centerline radius of curvature, and b = channel width. The velocity estimate is then multiplied by the cross sectional area to yield the rate or discharge of flow.

Webb and others (1989) found that unrealistically high discharge values of debris flows were obtained from bends, when compared with corresponding values for the same flow in straight reaches. Compared to both upstream and downstream sites, the cross-sectional areas at bends were 1.3 to 3.6 times larger (Webb and others, 1989). In each location, the flow surface and thus the cross-sectional area was reconstructed by connecting the peak flow levels as indicated by deposits on both sides of the channel with a straight line. This large difference in discharges could not be explained, but one suggestion was the presence of static material in curves. The video indicates the probable cause of the discrepancy in discharge values–the flow surface in bends is markedly concave (fig. 6). This conclusion corresponds with observations of bend-surface concavity during flume experiments (Iverson and others, 1994). Figure 7 shows the interpretations (assuming straight flow surfaces) of the cross sectional area in a case where the discharge obtained from a bend is twice that of a discharge from a straight reach.

Knickpoints

Knickpoints are vertical, transverse “falls” in channel elevation that are scoured by erosion and which commonly migrate upstream. Knickpoints as much as 1–1.2 m in height form during the surge series at Jiangjia Ravine. They were observed but not photographed during the late stages of the flows of July 9, 1990. As described by Davies and others (1991 and 1992), they are probably associated with channel incision. However, during the series in the video and a previous series on June 15, 1990 (fig. 3), they were transient features developed in deposits only temporarily in the channel, and they did not result in any notable change in mean bed elevation.

Why and How Do We Seek to Identify the Deposits of Old Debris flows?

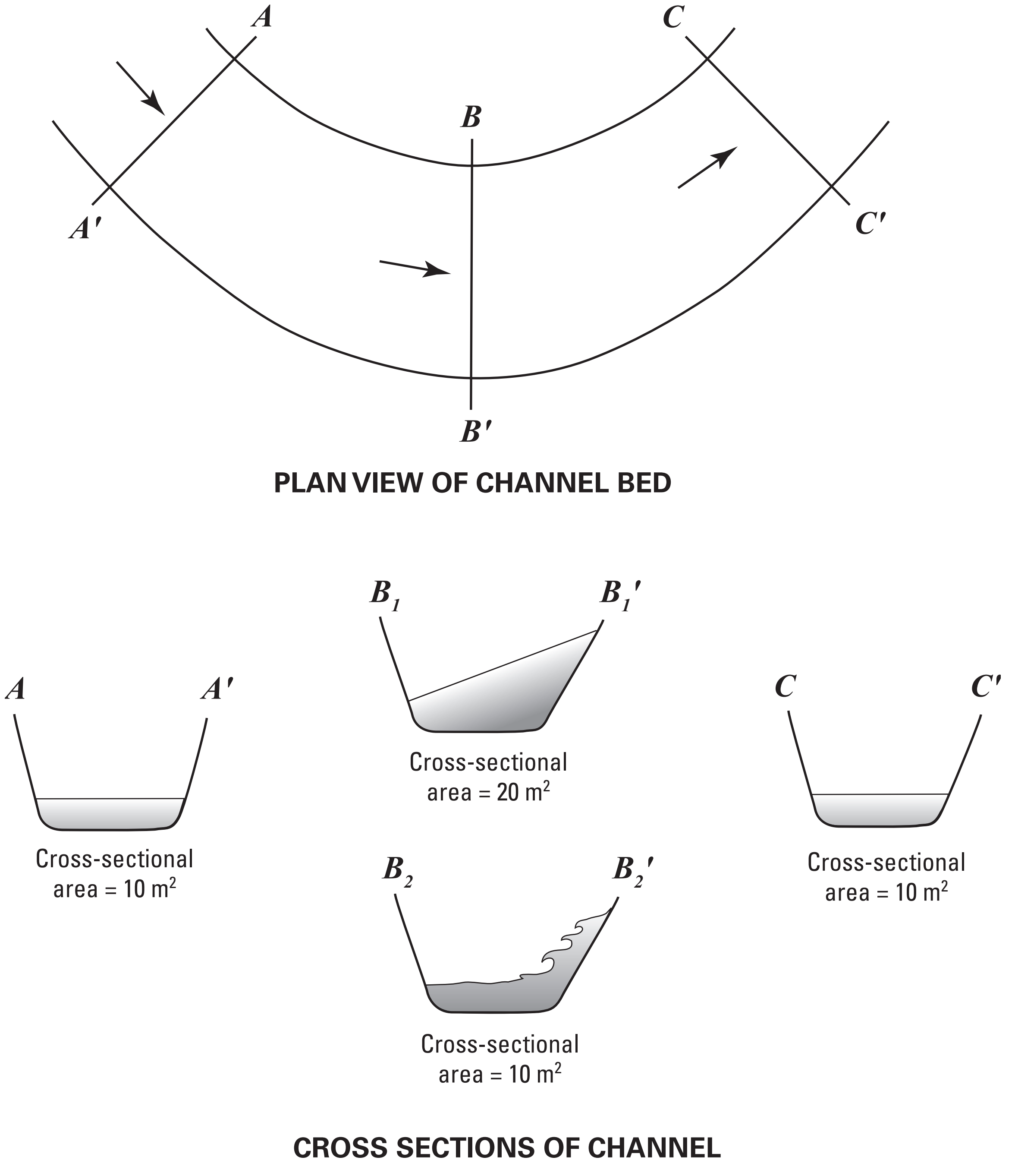
Debris flow occurrence is rarely as frequent and predictable as at Jiangjia Ravine. Elsewhere, potential flow hazards may be evident only from the deposits of previous flows. How can

Figure 6. Photo of longitudinal roll waves and concave surface of right-to-left flow in bend on June 15, 1990. For scale, this bend is visible in the video—for example during surge 10. Observer in left foreground does not indicate scale. Photo by Kang Zhicheng

we recognize these deposits, and thus their past as well as the possible or even probable future occurrence of debris flows?

1. They have a fine-grained, commonly muddy matrix. Debris flows are commonly called mudflows because of their content of fine sediment [mud = the total of silt-size sediment (0.004–0.0625 mm) and clay-size sediment (< 0.004 mm; < 0.005 mm in Chinese data)]. The flows and deposits at Jiangjia Ravine typically contain 2 to 5, and as much as 10 percent clay-size sediment by weight (Kang, 1989). Figure 8 shows histograms of sample A, a complete analysis of all size fractions in a flow in Jiangjia Ravine; B and C are the partial analyses of surges 13 and 29. The samples of moving flows were taken with a suspended sampler with a restricted orifice, thereby excluding the coarsest fractions. In addition, the fine fractions of the two samples were not analyzed. Otherwise, the distributions in B and C would be similar to that of A.

The amount of silt- and clay-size material is useful for determining debris flow origin, and samples D and E of figure 8 are deposits that are cohesive (or muddy), and noncohesive (or granular), respectively. These two textural subpopulations help us distinguish lahars of landslide and meltwater origins, respectively, at volcanoes (Scott and others, 2001). However, facies of lahars with mainly cohesive deposits may have very little fine sediment, as in the boulder-rich bars of the channel faces of the 1980 lahar in the North Fork Toutle River (Scott, 1988, fig.15). R.M. Iverson (written commun., 2002) has noted formation of a fines-free levee facies at



PLAN VIEW OF CHANNEL BED

CROSS SECTIONS OF CHANNEL

Figure 7. Diagrammatic cross-sections of flow illustrating the differences in cross-sectional area (and thus, discharge) as they depend on reconstruction of the flow surface from deposits. Case B_1–B_1’: assumption of straight line connecting highest deposits on each side of channel; case B_2–B_2’: observed concave surface at Jiangjia Ravine, yielding cross-sectional area in accord with those from upstream and downstream cross-sections A–A’ and C–C’.

the large-scale flume noted above. Typical alpine debris flows that move with boulder-rich fronts, as noted above in contrast to the flows at Jiangjia Ravine, also leave lateral levees dominated by boulder-size clasts.

2. <u>They are commonly bimodal (two peaks in histograms of sediment size).</u> For example, sample D in figure 8 has a primary mode or peak in a cobble-size fraction of the size distribution–between 128 and 256 mm, and a secondary mode in a sand fraction–between 0.125 and 0.25 mm. The coarse mode represents particles in the "dispersed phase;" the finer mode is sediment in the muddy matrix or "continuous phase." The coarse mode is like the plums dispersed throughout a plum pudding. With the other features listed here, we can identify debris flow deposits from this bimodal, "plum-pudding" texture.
3. <u>They contain a large range of sediment sizes; that is, they are poorly sorted (high values of σ_G; fig. 9)</u>. In figure 9, several of the samples in figure 8 are plotted as cumulative curves on a graph with a probability ordinate, on which normal distributions (a bell-shaped distribution in a histogram) plot as straight lines. Note that, excluding the primary mode, sample D is close to a normal distribution, as seen both in the histogram in figure 8 and the nearly straight line in figure 9.

   The fewer the fractions in a sediment sample, the more steeply the line representing their cumulative distribution is sloped and the better the sorting (low values of σ_G; fig. 9). Note the better sorting of flood deposits represented by samples G and H. Sample G is a deposit of coarse gravel resulting from bedload transport in flood flow, and sample H is the deposit of a sand layer deposited by a flood. For comparison, with both the poorer sorting produced by debris flows and the better sorting of flood deposits, sample F is the deposit of a hyperconcentrated flow. Figure 10 shows the deposit of a debris flow overlying that of a flood or hyperconcentrated flow.
4. <u>They are commonly massive (without stratification)</u>. The multiple surges at Jiangjia Ravine, where they spread over a downstream flood plain (fig. 11), yield single massive, matrix-supported units, analogous to the successive surges of material from a large debris flow flume (Major, 1997). The series of texturally and compositionally homogeneous surges yield massive composite units without obvious stratigraphic breaks, indicating a need for caution when interpreting flow magnitudes and frequencies from stratigraphy, particularly in alluvial fan environments.

Because the stratigraphic units are commonly of composite construction, and therefore relatively uniform, graded bedding is poorly developed. Wang and others (1999) note the occurrence of normal grading (upward fining) in some units.

Can People Be Warned That a Debris Flow is Coming?

Warning times of 20-45 minutes at the observation site are based on threshold values of rainfall intensity and antecedent precipitation (Ou, 1999). For predictive purposes, rainfall data are telemetered from recording stations high in the watershed. The flows in the video occurred with little precipitation at the observation site.

Various devices for event warnings (flow is occurring) have been tested at this location (e.g., Kang, 1990). They include Acoustic Flow Monitors (AFM's)—solar-powered, microprocessor-based field computers linked to exploration-model geophones that detect the specific frequency of moving debris flows (LaHusen, 1998). Arrays of AFM's are widely used for detection of lahars. In addition, lives can be saved by educating the residents of vulnerable areas–like the many towns in the valleys of mountainous southern China–to recognize ground vibrations as the possible signal of an approaching debris flow, and to go to high ground immediately. With this knowledge—Education for Self Warning and Evacuation

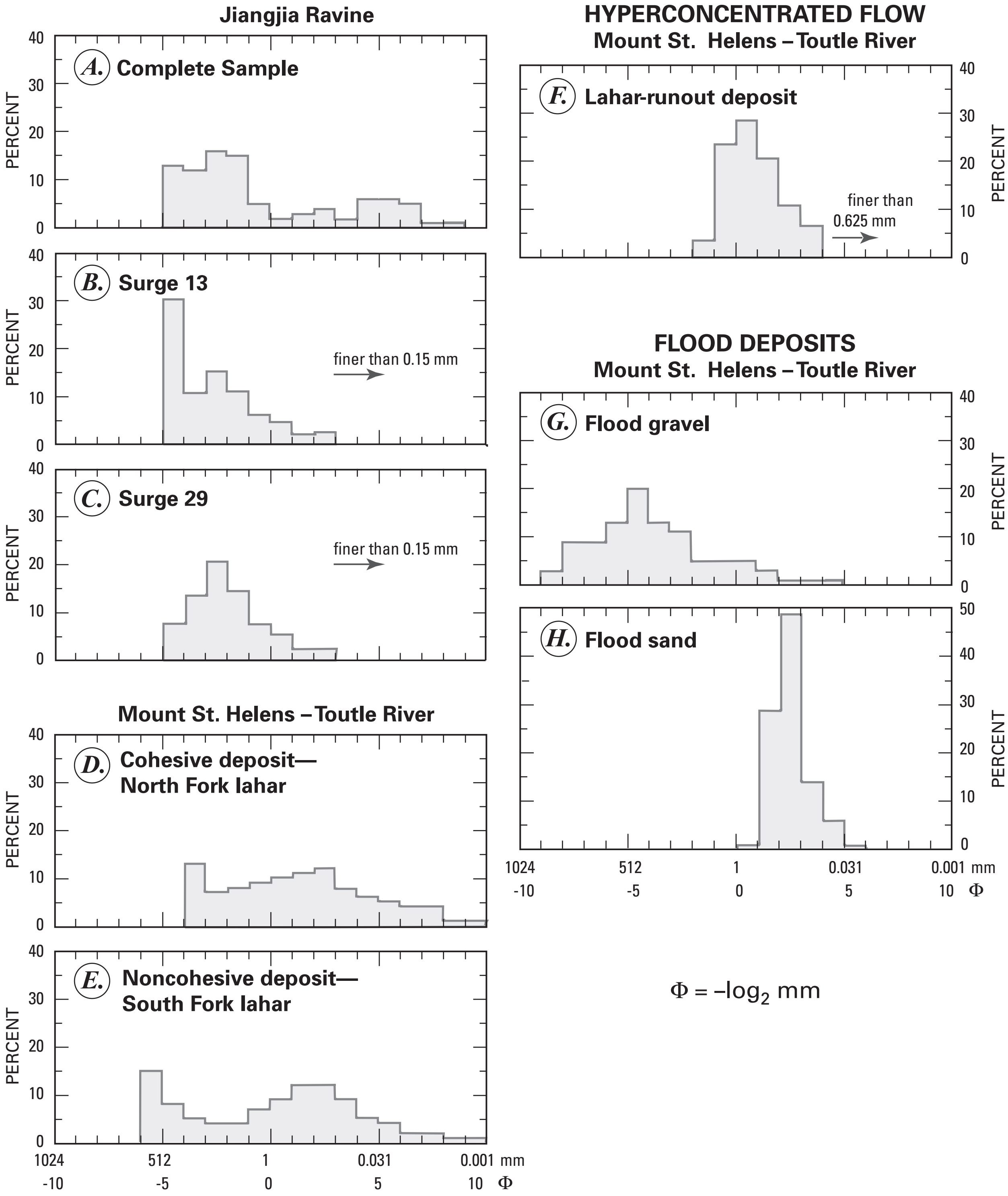


Figure 8. Texture (particle size distribution) of debris flow deposits, shown as histograms. A, Debris flow at Jiangjia Ravine (Li and others, 1983); B, Surge 13; C. Surge 29; D, Cohesive (muddy) debris flow deposit in North Fork Toutle River—peak flow facies of 1980 lahar from Mount St. Helens (fig. 17, Scott, 1988); E, Noncohesive (granular) debris flow deposit in South Fork Toutle River—1980 lahar 35.6 km downstream from Mount St. Helens (fig. 20, Scott, 1988); F, Lahar-runout flow, 1982 in Toutle River (fig. 41, Scott, 1988); G, Fluvial gravel representing bedload in Toutle River ("pre-lahar alluvium," fig. 22, Scott, 1988); H, Fluvial sand in 1980-81 flood berm of Toutle River (fig. 41, Scott, 1988).

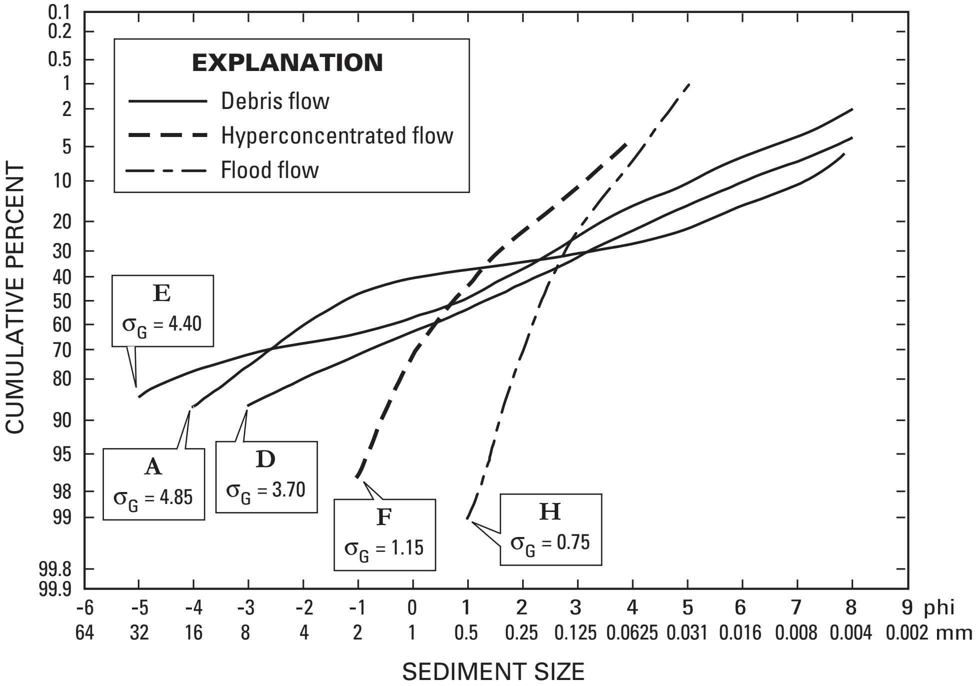


Figure 9. Selected data in figure 8 plotted as cumulative curves of the size distributions. Values of sorting (σ) as the graphic standard deviation of Folk (1980), $\sigma_G = (\Phi_{84} - \Phi_{16})/2$. Φ values defined as in Figure 8.

(ESWEV)—people can, in effect, be their own AFM's (Scott and others, 2001).

Mitigation and Countermeasures

The video records the flows as they pour from a mountain front across an alluvial fan. The rugged topography indicates the difficulties in stabilizing slopes and reducing the sediment flux into channels. In order to maintain its function as a natural laboratory, no formal engineering works are present in the upstream portion of the main channel of Jiangjia Ravine. However, in addition to a national program of soil conservation, measures that specifically target other watersheds that yield debris flows include planting trees and constructing plant hedges to stabilize hillslopes and retard flows. Engineering measures are primarily check or sabo dams, and flumes that

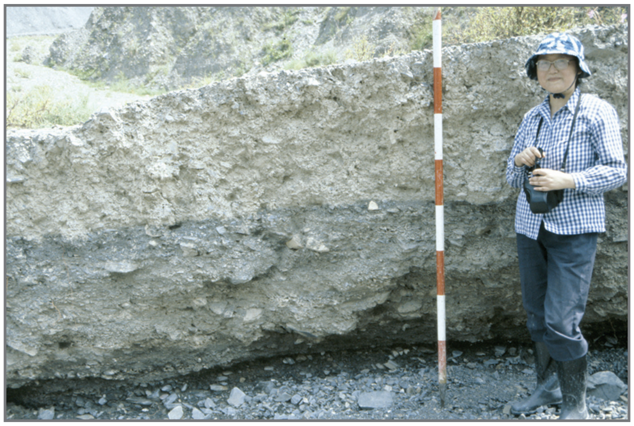


Figure 10. Photo of cutbank showing lighter-colored debris flow deposit overlying deposits of flood or hyperconcentrated flows. Photo by J.J. Major.

function as "drop structures," diverting flow to lower gradients in order to reduce erosion. In one cited example (Ou, 1999) of 29 watersheds, a total of 12 towns, 100 villages, 15,300 hectares of farmland, 16,000 people, and property valued at 1.1 billion yuan (US $130 million) have been protected by these measures at a total cost of 45 million yuan (US $5 million).

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Figure 11. Photo of downstream reach of Jiangjia Ravine where debris flow surges spread and deposit lateral levees. Photo by J.J. Major.

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APPENDIX

APPENDIX

Narration. *A.* During introductory black-and-white film segment showing flows and sampling at Jiangjia Ravine.
B. During remainder of video/DVD.

A. Debris flows are slurries of rock and water that flow like wet concrete. They are an important way that sediment is transported in mountainous areas. Debris flows are also a significant geologic hazard.

Each summer, in arid and mountainous SW China, debris flows are triggered by rainstorms. Each episode may consist of more than 100 separate waves, or surges, lasting over several hours. In the 1960's, sampling procedures were primitive (narrated as technician runs from surge front).

B.

SURGE NUMBER AND VELOCITY (c) IN M/S	**NARRATION WITH SURGES, BY NUMBER**
1 $c = 3.23$	This is the first of 77 surges. Each series may begin with surges of water or, as here, a type of flow called hyperconcentrated flow. Hyperconcentrated flow is a mixture of water and sediment. It has more sediment than a flood but less than a debris flow. Debris flows look like wet concrete; hyperconcentrated flows look like motor oil.
2 $c = 6.78$	The second surge, beginning as debris flow, pushes and mixes with the hyperconcentrated flow already in the channel.
3 $c = 7.63$	As surge 3 leaves the mountain front, note the emerald green areas. These are fields of rice and sweet potatoes cultivated on the deposits of larger debris flows during the 1980's. The debris flow fronts are the deepest part of each surge. The fronts contain the coarsest clasts in the flow. At this site, surges occur at regular intervals, from one to several minutes. A single series of surges may continue for over 10 hours.
4 $c = 7.84$	Grain-to-grain contact in the turbulent front is intense. Masses of mud that seem to be splashing from the front are actually ballistically ejected, mud-coated pebbles. A spray of ejected pebbles precedes the surge. By this time, flow ceases between the surges. The channel remains full of slurry waiting to be remobilized.

B. (Continued)

SURGE NUMBER AND VELOCITY (c) IN M/S	**NARRATION WITH SURGES, BY NUMBER**
5	Note how fast the surges travel–about twice as fast as the same size of water wave. We are seeing the flows at actual speed.
$c = 8.16$	Debris flows are more than twice as dense as water without sediment.
	These two factors–very dense flows moving very fast–create the high impact forces that enable debris flows to destroy many manmade structures.
6	As the series builds initially, each surge is larger and faster.
	Flow now splashes to the top of the main terrace.
$c = 8.33$	
Between 6 and 7	Debris flows can move huge boulders.
	Here the size is limited by the bedrock of the watershed, which is mainly weak, easily broken shale.
	This boulder is over 1 m or nearly 4 ft in length.
	Note the people on the bank for scale.
7 [not photographed]	
8	This is the surface of the largest and fastest surge in the entire series.
	Velocity of the front is over 9 m/s, or 20 mi/h.
$c = 9.30$	Debris flow sediment, seen here between surges, consists of two phases–coarse particles, mainly pebbles in these flows, that are dispersed and suspended in a matrix of sand, silt and clay.
9	We are looking directly at the front of the flow.
	As it hits the bank, we can sense the impact force.
$c = 8.16$	A barrage of pebbles is ejected.
	The ground vibrations of approaching large debris flows can be detected by instruments known as Acoustic Flow Monitors, and a warning signal can be radioed downstream in time for evacuations.
10	Longitudinal waves form as the flow rolls up or superelevates against the bank on the inside of a bend.
$c = 8.33$	

B. (Continued)

SURGE NUMBER AND VELOCITY (c) IN M/S	**NARRATION WITH SURGES, BY NUMBER**
11 c = 8.00	In the film from the 1960’s at the beginning of this video, this channel had not been cut, and flows spread across the entirely valley. That film was made at this location.
12 c = 8.00	Mud, the term for particles of silt and clay size, causes debris flows to be widely known as mudflows. Scientists prefer the term debris flow because mud is generally less than 25% of most debris flows, and some have only a few percent mud. The streaks in the flow, parallel to the banks, are lines of shear as flow approaches the channel boundary.
13 c = 8.89	Surge 13 has as high a unit weight as any in the series–2.26 t/m^3 vs. 1.0 for pure water. That value is only slightly less than the maximum value recorded for any debris flow at this site–2.38 t/m^3.
14 c = 8.89	In contrast to the dangerous techniques of the 1960’s, samples are now taken by lowering the torpedo-like cylinder into the flow with a steel cable.
15 c = 7.27	Note how the flow is disturbed by irregularities in the bank. Measurements of runup or superelevation height after the fact, in order to estimate velocity, can be highly variable.
19 c = 7.30	As we watch the final surges recorded on video, we will review some characteristics of debris flows. As surge 19 begins, note that the upstream terrain is steep, barren, and climate is semiarid. Worldwide, debris flows are especially common in areas with these characteristics.
Between 19 and 20	Debris flows are slurries of water and sediment. They consist of coarse fragments dispersed or seemingly floating in a fine-grained matrix.

B. (Continued)

SURGE NUMBER AND VELOCITY (c) IN M/S	**NARRATION WITH SURGES, BY NUMBER**
20 *c* = 8.70	Debris flows contain more than 60 percent sediment by volume. Flow with less sediment, seen in the first two surges, is described as hyperconcentrated flow. It contains less than 60 but more than 20 percent sediment.
21 *c* = 6.78	The fronts of each surge are turbulent, like surge 21. The front contains the coarsest material. Cobbles and boulders collide violently in the front, extruding smaller particles.
22 *c* = 5.88	Debris flows have high impact forces that can destroy many structures and crush most buildings. This is because they are more than twice as dense as water, and nearly twice as fast as a surge of water the same size.
23 *c* = 7.41	Debris flows are an important process of sediment transport. In a single year, episodes of flows like these have removed enough material from this watershed to lower its entire 19-square-mile surface by 5 inches.
24 *c* = 7.14	Debris flow are also an important geologic hazard. Debris flow, along with landslides, many of which are viscous debris flows, take an average of 500-1,000 lives each year in China and cause hundreds of millions of dollars in damage.

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Scott, K.M., and Wang, Y.—

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