Developing a Method of Debris-Flow Hazard Zonation Along the Wasatch Front, Utah

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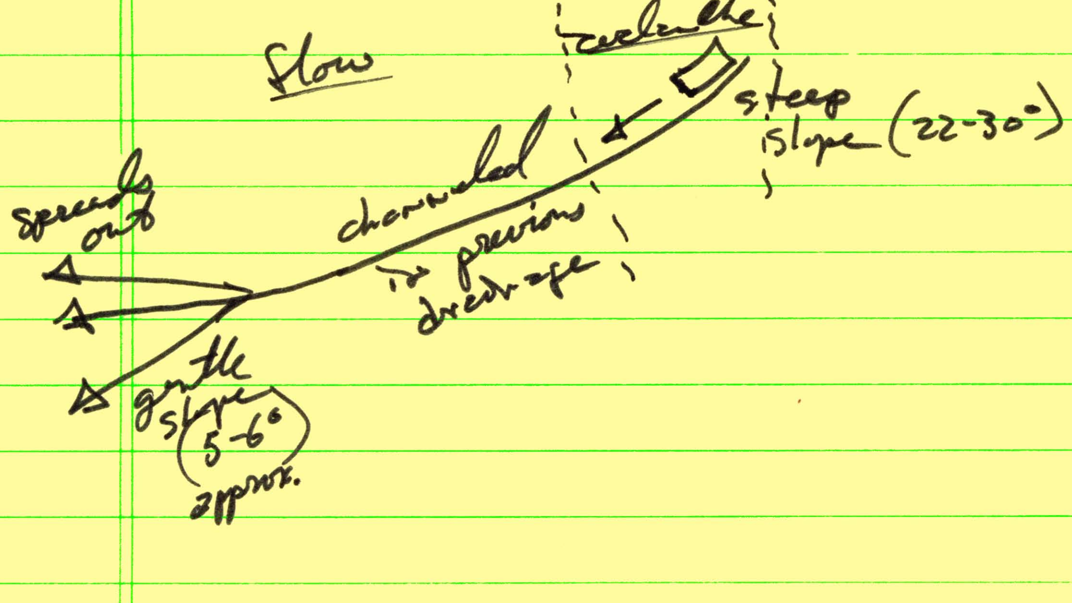
factors related
degree of associated hazard

(Johnston)

Debris flow
- slope (22-30°) { <22°: slope too gentle; >30°: colluvium too thin }
- slope length & thickness of colluvium
- clay content
- size distribution
- pre-event ground sat.
- interstitial pore-pressure
- channelization of flow
- length of runout
- nature of flow front
- recurrence interval
- correlation w. weather condition
- velocity of flow

Campbell 1975
Rodine PhD thesis Mechanics of D. Flow
critical ∡ 5-6° where debris flow spreads out



Presentation to UGMS - Topic: Developing a Method of Debris-Flow Hazard Zonation Along the Wasatch Front, Utah

Outline

I. Perception of debris-flow hazards in Utah prior to 1983
   - A. History of "flash flood" events in Utah 1850-1938; Woolley (1946)
   - B. U.S. Forest Service and Civilian Conservation Corps response (1930-40) solves the problem (?); contour plowing and debris basins
   - C. Davis County Experimental Watershed - research activities: snowmelt, precipitation, runoff monitoring within rehabilitated watersheds; U.S. Forest Service - Croft (1967, 1981)
   - D. Conditions for cloudburst and snowmelt floods (Marsell, 1971); 1952 spring floods along Wasatch Front
   - E. Recognition of Debris-flow hazards-maintenance and modification of debris-flow basins in Davis Co.

II. Climatic and debris-flow events during the spring of 1983 in Utah
   - A. Similarity to climatic conditions for spring flooding identified by Marsell (1971)
   - B. Debris flows during late May - early June, 1983 in Utah

III. Method developed in 1983 for evaluating potential debris flow and debris flood along the Wasatch Front
   - A. Assumptions made for developing method
   - B. Questions remaining for a more accurate evaluation
   - C. Implementation of recommendations for mitigative measures along the Wasatch Front

IV. Subsequent debris-flow studies in Utah
   - A. Detailed site studies of 1983 debris-flow runout along the Wasatch Front and in central Utah (Lips and Wieczorek, in review)
   - B. Mapping of 1983 and 1984 landslides and debris flows near Mt. Pleasant in central Utah (Lips, 1985)
   - C. Comprehensive mapping of 1983 debris flows in Utah (Brabb and others, in progress)
   - D. Evaluation of method for identifying debris-flow potential developed in 1983 - climatic conditions as predictive time indicator; partly-detached landslides as highly susceptible; material contributions from channels (Wieczorek and others, in progress)
   - E. Site studies of 1984 debris flows - East Layton (Olson, 1985); Rudd (Pierson, 1985)

V. Refined technique to prepare a debris-flow hazard zonation map for the Wasatch Front (the following steps reflect an increasing level of detail and sophistication; depending on purpose, analysis can be terminated at different stages)
   - A. Assemble historical information on flash floods, debris flows, etc. - Woolley (1946); Croft (1967) and information on surficial geologic mapping Miller (1980)

B. Examine stratigraphic evidence at natural exposures in canyon mouths, incised channels and on alluvial fans noting areal distribution, character of materials, thickness of deposits - flood or debris-flow related
C. Aerial photo and geomorphic study to identify previous debris-flow scars and source areas for future potential debris flows using as many different vintages of photography as available
D. Preliminary assessment of debris flow potential within watershed based on historical and geomorphic evidence collected in (A), (B), (C)-above
E. Determine previous debris-flow runout characteristics based upon:
   1. frequency and recurrence of paleo debris flows beyond canyon mouth
   2. extent and volume estimates of paleo debris-flow deposits beyond canyon mouth and volume of and distance to debris-flow scars in canyon
F. Determine clay-size fraction and grain-size distribution of debris-flow matrix within paleo debris flow deposits
G. Estimate volume of potential debris-flow source areas and channel contributions under present watershed conditions
H. Evaluate gradient, sinuosity and confinement of channel
I. Based on watershed characteristics make preliminary estimate of debris-flow runout distance evaluated in (E), (F), (G) and (H) above
J. Apply two-dimensional numerical modeling to simulate debris-flow routing, determine area to be affected, and velocity and thickness of flow; for example, Hamilton and others (1987)

The following handouts are provided as notes to accompany this presentation. With the exception of information from Open-File Report 83-635, the majority of cited information is from reports that are in preparation, and as such, should not yet be cited or referenced.

unit 1 & 2 debris flow deposits

distance is function of

volume, gradient, channel geometry, elevation
composition (clay %), miscellaneous (eg. change)

Roy Sidess, USU, filling of colluvial hollow

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DEBRIS FLOWS AND HYPERCONCENTRATED STREAMFLOWS

By Gerald F. Wieczorek*, M. ASCE

Examination of recent debris-flow and hyperconcentrated-streamflow events in the western United States reveals (1) the topographic, geologic, hydrologic, and vegetative conditions that affect initiation of debris flows and (2) the wide ranging climatic conditions that can trigger debris flows. Recognition of these physiographic and climatic conditions has aided development of preliminary methods for hazard evaluation. Recent developments in the application of electronic data gathering, transmitting, and processing systems shows potential for real-time hazard warning.

INTRODUCTION

During the past decade, several regions of the western United States experienced episodes of debris avalanches, mudflows, and hyperconcentrated streamflows that resulted in loss of life and extensive property damage. These sediment-water flows are distinguished from normal streamflow according to the classification system (Fig. 1) from Pierson and Costa (1984). Subsequently in this paper the term debris flow will be used to collectively refer to mudflow, and debris avalanche. Because debris flows have been inadequately understood, hazard evaluation, land use regulation, and engineering design of storm runoff systems have not taken into account their nonstandard hydraulic aspects. Little was known about physiographic conditions that favor flows, as well as climatologic factors such as rainfall intensity or the rate of snowmelt necessary for triggering flows. Recently developed methods of hazard recognition and evaluation based on available physiographic and climatic information are especially important in the establishment of real-time warning systems.

Episodes of debris flows and hyperconcentrated streamflows in California, Nevada, and Utah illustrate a wide variety of climatic triggering events and differences in physiographic conditions where these occur. This paper presents information on these events and conditions and discusses recent developments in hazard recognition, evaluation, and warning.

CASE HISTORIES

Southern California.-In the Los Angeles area, the problem of debris-flow occurrence in areas stripped by wildfires has been long recognized. Shortly after midnight on January 1, 1934, an intense downpour after more than 12 hours of rainfall brought debris flows down several canyons into the La Cañada Valley, causing significant

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property damage and loss of life. As described in Troxell and Peterson (1937, p. 82-83), "the water surface at the peak of the flood [was] .... greatly raised in the center of the cross section" and "a wall of water came down the stream channel ... with boulders riding along the top of the wave...the mixture compared to concrete with boulders." The debris-producing drainages had been burned in November of 1933, allowing sediment from erosion of small rivulets and gullies and from stream-channel deposits to be mobilized into debris flows by the intense runoff.

Newtonian Fluid Threshold

Liquefaction Threshold

Fast

Velocity

Slow

Streamflow

Normal | Hyper-concentrated

Slurry Flow

Debris Flow

Solifluction

Granular Flow

Sturtzrom

Debris Avalanche

Grain Flow

Earth Flow

Mass Creep

0% ← Sediment Concentration → 100%

Figure 1. Classification of Sediment-Water Flows (modified from Pierson and Costa, 1984).

Southern California has experienced many episodes of brush fire followed by periods of high sediment production and debris flow. Dry ravel of soil and organics during and immediately after fire carries much loose debris into channels which can be easily mobilized in flows during high runoff. Rill formation and development of rill networks in addition to the formation of a layer of water-repellent soil, a few millimeters below the soil surface, formed during fire is another major process contributing to the production of abundant debris after a fire (Wells & Brown 1981). The abundant debris, both on slopes and in channels, and the rapid concentration of runoff from denuded watersheds with water-repellent soil accentuates the debris-flow problem.

Debris flows commonly occur also in nonburned areas; however, there they are initiated principally as shallow landslides on steep slopes of colluvial soil and ravine fill. Moreover, in nonburned areas, specific meteorologic conditions, primarily antecedent rainfall and peak storm intensity, are necessary for initiating debris flows; peak storm intensity is more strongly associated with debris-flow initiation than is actual storm size (Campbell 1975). Because rainfall in southern California is predominantly orographic, intense rainfall and subsequent debris-flow activity may be generally confined to certain areas.

Northern California.-The January 3-5, 1982, storm in the San Francisco Bay region dropped as much as half the mean annual precipitation in a period of about 32 hours, causing widespread landsliding and flooding. Thousands of slides induced by the storm transformed into debris flows that swept down hillslopes or drainages, causing significant property damage and loss of life (Brown et al. 1984). Before the storm, debris flows had been recognized in the San Francisco region, but their potential had not been fully appreciated, in part because they had occurred only locally in the years since population had spread into susceptible steep terrain.

Antecedent rainfall, as well as storm intensity and duration, were significant factors in debris-flow distribution. Seasonal rainfall, as well as rainfall during the month preceding the storm, had been unusually heavy, leaving the hillside soils with high moisture content at the beginning of the storm. A threshold of storm intensity and duration for abundant debris flows was determined based on a study of storms in the region (Cannon & Ellen 1985).

Debris flows in the January 1982 storm occurred predominantly in colluvial soils located in swales. These swales concentrated ground water in the soils over bedrock resulting in high pore-water pressures and initiation of debris flows (Reneau et al. 1984). To generate high pore-water pressures in these soils, rainfall must be of moderate to high intensity and long duration.

Human modification of hillslopes and channels was directly responsible for some debris flows in the January 1982 storm. Culverts which generally would have been able to handle the flow of clear water plugged with debris, particularly trees, brush, and boulders. These blockages typically collapsed as ponded water levels rose behind the road embankments, sending surges of water and debris down the channel as debris flows or hyperconcentrated streamflows.

Basin and Range.-The arid portions of the western United States are subject to "flash floods" that range from clear-water floods to debris flows. Although there have been few witnesses to these events in the sparsely populated areas, the abundance of alluvial fans, consisting of debris-flow and stream gravel deposits in varying proportions (Blackwelder 1928), attest to a long and pervasive debris-flow history.

On September 14, 1974, an intense thunderstorm passed over Eldorado Canyon near Lake Mojave, Nevada. The duration of rainfall was short, generally less than an hour, but intensities were very high--from 3 to 6 in/h (7.6-15.2 cm/h) for 30 minutes. The intense rain eroded shallow soils, leaving rills on some of the sparsely vegetated hillsides, and the high runoff scoured unconsolidated alluvium from the larger stream channels. The initial surge was described as heavily laden with sediment and having a consistency generally equivalent to freshly mixed concrete. Descriptions characterized the first surge as a debris flow with subsequent surges of hyperconcentrated streamflow (Glancy & Harmsen 1975).

Wasatch Range.-In spring of 1983, rapid snowmelt in the Wasatch Range of northern Utah triggered numerous debris flows and hyperconcentrated streamflows that affected populated areas near the mouths of canyons north of Salt Lake City. Debris flows originated as landslides that incorporated large amounts of additional loose material from channel sides and bottoms as they surged down the canyons. Flooding was exacerbated by sediment deposited in the channels by landslides and debris flows.

Several climatic conditions in the winter of 1982 and spring of

1983 were responsible for causing these events. These conditions included (1) saturated soil mantle at the start of winter resulting from heavy, late autumn rains; (2) heavy winter snowpack; (3) low temperatures during late winter and early spring, permitting retention of the deep snow cover; and (4) sustained high temperatures once melting started. The cool weather in 1983 continued until about the middle of May when a sustained hot spell commenced, resulting in a very rapid melting of the above-normal snowpack. Subsequent high runoff resulted in flooding (Lindskov 1984) and rapid infiltration, causing temporary high ground-water levels. Such conditions triggered landslides, many of which were mobilized into debris flows. Of the many debris flows that occurred, only a few reached or extended beyond the mouths of canyons into developed areas (Wieczorek et al. 1983).

DEBRIS-FLOW HAZARD EVALUATION

The preceding examples illustrate some common physiographic settings and climatic triggering mechanisms for flows in mountainous regions of the western United States. The physiographic settings reflect the varying geologic, hydrologic, topographic, and vegetative conditions under which flows can be initiated. These examples also show the common sources of debris--landslides, rill erosion, dry ravel, channel bank collapse, and scour of stream channel deposits. Table 1 shows the general physiographic and climatic conditions for debris flows in the western United States.

To identify areas subject to debris flows and to plan and design for their occurrence it is necessary to (1) determine where they are likely to occur, (2) determine when they are likely to occur, and (3) determine where and how far they are likely to travel. Although the characteristics in Table 1 are descriptive of areas prone to debris flows, they are not criteria for evaluating susceptibility or runout distance, factors that vary widely with specific site characteristics.

Within the San Francisco Bay region a method for mapping debris-flow susceptibility was developed and subsequently evaluated against distribution of flows in the January 1982 storm within a small sample area (Smith 1986). Almost all (98%) flows originated in areas previously designated as most susceptible to debris-flow initiation. In the Wasatch Range of Utah, Pack (1985) used an analysis of geology, vegetation, slope gradient, and slope shape to classify 88% of the 1983 debris-flow sites as highly prone to failure. Whether these locally successful methods have widespread applicability is unknown.

The problem of forecasting the path and runout of debris flows has been addressed using several approaches: (1) historic or prehistoric evidence of flows, (2) empirical methods, and (3) mathematical models. Based on historic and prehistoric debris-flow deposits, Glancy and Katzer (1977) mapped the debris flow hazard level for an area south of Reno, Nevada. Their evaluation predicted the general area inundated by a hyperconcentrated streamflow in May of 1983, but failed to predict the exact boundary of the affected area because the peak flow rate of water and debris was much greater than anticipated (Glancy 1985). The difficulty of properly estimating volume and flow rate of potential debris flows or hyperconcentrated streamflows seriously affects the accuracy of evaluating routing or runout. Likewise runout and routing are affected by human construction or channel alteration.

Methods of estimating debris-flow runout have been based on empirical relationships between runout and other parameters, such as potential energy. For debris flows in Utah, Vandre (1985) proposed that runout on a 10% or flatter gradient was proportional to the elevation difference between debris-flow scarp and fan. Wieczorek and others (1983) evaluated the potential for debris-flow runout beyond a canyon mouth by calculating the volume of a landslide that mobilized and flowed to a canyon mouth and used that standard for comparison with semidetached landslides that had not yet mobilized. These various methods are site specific and cannot be extended to other regions without further analysis; therefore, their wider applicability is unclear.

Mathematical models for determining debris-flow paths require difficult-to-obtain, field-measured values. Wigmosta (1983) used fluid mechanics theory to calculate velocity, discharge of peak flow, and other flow parameters at locations along the channels of several large debris flows from the May 1980 eruption of Mount St. Helens, Washington. Jeppson (1985) used computer models to simulate debris flows from a canyon that experienced a debris flow in Utah during 1983. Chen (1985) developed one-dimensional equations for debris

TABLE 1. - Conditions for Debris Flows in Western United States

Physiographic Setting	Characteristics of Climatic-Triggering Event(s)	Principal Source(s) of Debris
	Los Angeles Ranges of Pacific Border Province*	
Loose thin soils over bedrock on sparsely vegetated steep hillsides. Following a wildfire, a very shallow water-repellent soil layer is created. Wildfire removes vegetation, reducing soil restraining effect of roots.	Antecedent rainfall is important except in burned areas. Although storms may last several days, short-term peak intensity is most important. Following a wildfire, the first several storms are the most important. Orographic rainfall can be significant.	Shallow translational landslides; following a wildfire, dry ravel, rill erosion, and gully erosion.
	California Coast Ranges of Pacific Border Province	
Moderate to thick colluvial soils in swales on steep slopes. Slopes may be thinly or thickly vegetated. Locations of ground-water concentration are important.	Antecedent rainfall is important. Both storm intensity and duration are important. Continuous moderate to high intensity lasting many hours is an important factor.	Rotational and translational landslides. Organic debris can constitute a major component of flows and cause blockages of culverts and bridges.
	Basin and Range Province	
Loose thin soil on steep hillslopes. With sparce vegetation, runoff during storms is quickly concentrated.	High-intensity, short duration rainfall during convective storms on naturally barren hillslopes or where vegetation has been removed.	Rill erosion on hillsides; stream bank collapse and scour of stream channel deposits.
	Middle Rocky Mountain Province	
Moderate to thick colluvial soils in locations of groundwater concentration on steep hillsides.	Rapid melting of heavy snowpack from sudden warm spell.	Rotational and translational landslides with significant contribution from scour of channel banks and deposits.

*Physical divisions of the United States from Fenneman (1946).

flows down a narrow valley, but points out that these equations do not apply on an alluvial fan, where debris flows can expand laterally, and for which a two-dimensional model is needed. Measurements of the rheologic properties of debris flows are relatively few, so at least for now the results from such models are largely theoretical.

HAZARD WARNING

Recognition of debris-flow triggering events and analyses to identify thresholds critical for the triggering of debris flows provide the possibility of issuing hazard warnings. The National Weather Service and the U.S. Geological Survey jointly issued a debris-flow advisory in the San Francisco Bay region in radio bulletins during the storm of January 26, 1983, based on rainfall comparisons to the January 1982 storm. Although scattered debris flows were observed following this warning, they were not so abundant as in January of 1982 because rainfall totals in the 1983 storm fell far short of forecasts and amounts in the 1982 storm.

Since 1983, an Automated Local Evaluation in Real Time (ALERT) system (Clark et al. 1983) of telemetry rain gauges has been installed in the San Francisco Bay region under coordination of the National Weather Service. This system is similar to one previously established in Ventura County, California, which provided data for flood peak analyses and allowed preventative measures to avoid a flood disaster in February of 1980 (Bartfeld & Taylor 1982). One of the ALERT stations in the San Francisco Bay region is outfitted by the U.S. Geological Survey with devices to monitor ground-water level fluctuation in shallow soils on steep slopes where debris flows are likely to be initiated (Alger, Mark & Wieczorek 1985). These data, along with rainfall measurements, are intended to provide real-time monitoring of hillside processes during storms. In the San Francisco Bay region, with the ALERT network, those responsible for the public welfare are in a much better position than ever before to issue flood and debris-flow warnings.

In Utah and other western states telemetered data on snowpack water equivalent, total precipitation, and air temperature are collected under the SNOTEL acquisition system (Crook 1983) to monitor the accumulation of the snowpack as well as the onset of rapid melting. This provides an indicator of regional hillside conditions, which is useful for hazard evaluation and warning. Following the events of 1983 along the Wasatch Front of Utah, several landslide sites were instrumented to measure temperature, precipitation, and hillside movement. In the spring of 1984 alarms triggered by landslide movement gave advance warning of debris flows (McCarter & Kaliser 1985).

SUMMARY AND CONCLUSIONS

Both on a site-specific and regional scale, advances in electronic data monitoring and transmission have made debris-flow hazard warning feasible in real time. However, judicious warnings depend upon an understanding of the debris-flow-initiation process in a particular physiographic setting, and development of historic thresholds or models upon which warnings can be reliably based.

APPENDIX 1. - REFERENCES

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completely destroyed vegetation and produced the most dramatic landscape disturbance in catchment headwaters. Sustained rainfall during this activity led to extensive, shallow slope failures and to extraordinary overland flow that developed an extensive rill network on the pumice-tephra mantle. Sediment mobilized from these rills and shallow landslides generated several pumice-rich lahars that are found interbedded with the pyroclastic valley fill and contributed to the postpumice-fall lahars on the O'Donnell River and to the pumice-bearing recessional-flow deposits observed in several channels. Truncation of rills by valley fill and the lack of an integrated drainage on that valley fill show that excessive overland flow had diminished before the caldera formed and pyroclastic flows ended. Although the climactic eruptive activity produced the most dramatic and widespread landscape disturbance and severely disrupted watershed hydrology, stratigraphic constraints on the timing of peak discharge in several eastern watersheds illustrate the delicate sensitivity of watershed hydrology to disturbance by even relatively thin, fine-grained volcanic deposits.

The timing of peak discharge with respect to the onset of the climactic phase of activity on June 15 varied in a northerly direction across watersheds and downstream within watersheds. From the Porac River to the Sacobia River, peak discharge along the mountain front occurred before the plinian pumice fall; between the Sacobia River and O'Donnell River, peak discharge largely followed the pumice fall. On the alluvial plains, peak flows generally followed the pumice fall. The timing of these lahars probably reflects localization of variable-intensity, eruption-induced rainfall, northward movement of Typhoon Yunya, and perhaps variations in the degree of disturbance of catchment headwaters by preclimactic eruptive activity. Characteristic response times of watersheds do not appear to differ significantly, and their influence on the variation in lahar timing is probably more subtle than is the influence of variations in rainfall. The interplay of these various factors affects the amount of water that moves from hillslopes to channels to fanheads, how rapidly it moves, and its ability to entrain and transport sediment.

Peak flows commonly attenuated, slowed, and diluted ıs they moved across the alluvial fans and onto the alluvial lains. Along the mountain front, peak flows were as deep s 6 m or more and had instantaneous velocities of about 6 /s. In distal reaches, peak flows commonly were less than to 3 m deep, and mean peak-flow velocities were less than m/s. The sedimentology of downstream deposits suggests at many lahars were rapidly transformed to hyperconcen-ted and normal streamflows beyond the mountain front; wever, some of the lahars remained as debris flows across alluvial fans.

The mid-June lahars damaged inhabited areas on the sely populated alluvial fans of Tarlac and Pampanga vinces primarily by triggering lateral bank erosion that undermined buildings and by aggrading mainstem channels that led to backflooding of tributary channels. Although some areas were directly buried by lahars, burial was generally of secondary importance to damage triggered by bank erosion and by induced backflooding, except along distal alluvial plains where primarily agricultural land was inundated. As devastating as these lahars were, they had far less social and economic impact than subsequent lahars triggered by the seasonal monsoon rains.

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Mansell (1971)

- pre-flooding factors
  - heavy winter snowpack
  - saturated soil @ start of winter, heavy late-autumn rain
  - low-T during late winter/early spring retention of deep snow
  - sustained high-T once melting began
  - ?
  - ?

ch handout

Colluvial-Filled Hollows, Dietrich __, 19??

Measured Ward Canyon, volumes of partly detached landslides

Debris flow potential = enough volume to reach mouth

Debris flood potential = material may not reach canyon mouth, but there may be enough water to produce a debris flood

Debris basin size ≥ volume of detached landslide

Birch Creek largest debris flow in 1983 (near Fountain Green)

Plate 1 -
Map Showing Relative Potential for Both Debris Flows and Debris Floods to Reach Canyon Mouths

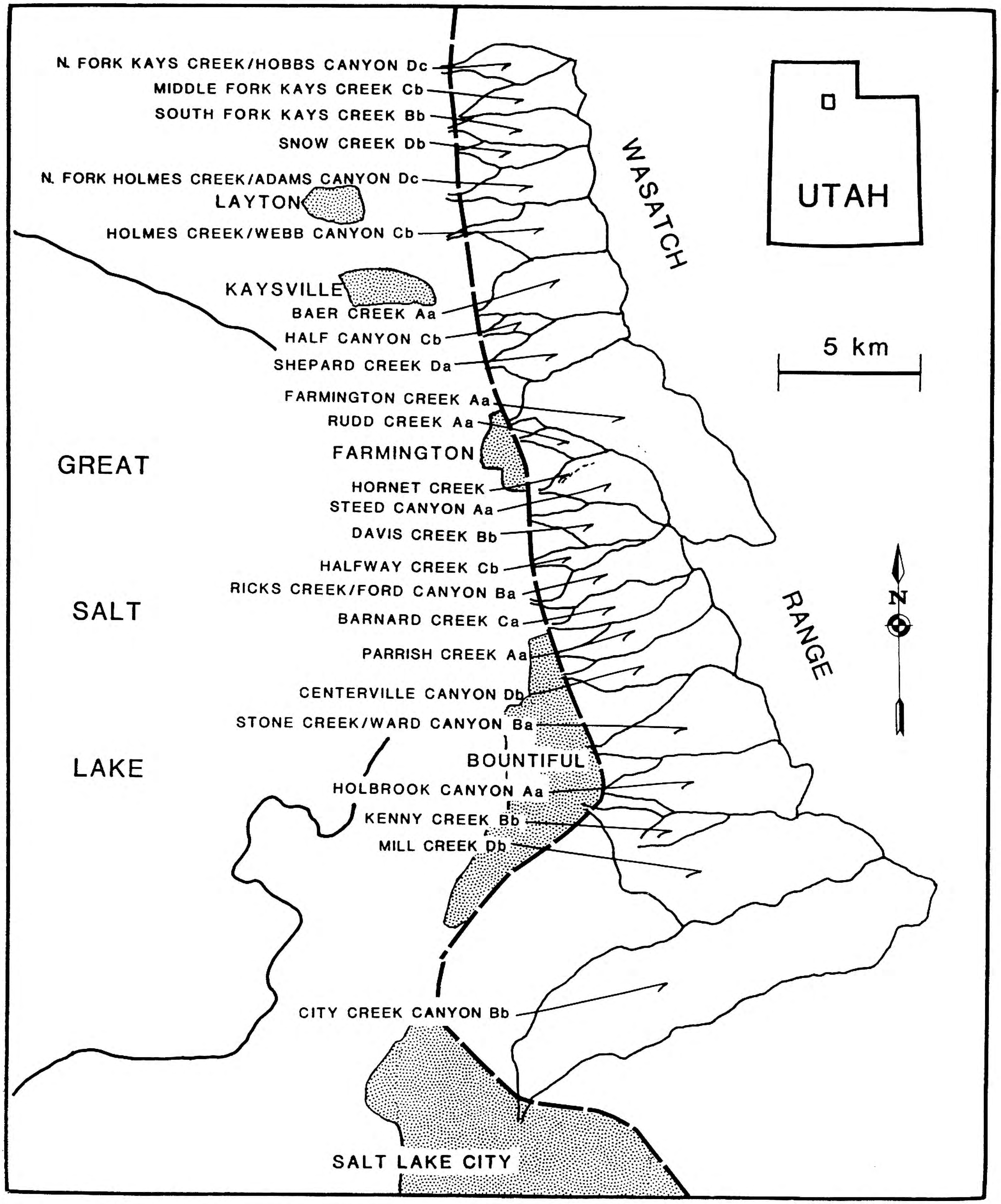
This map depicts the relative potential for debris-flow and debris-flood events to reach canyon mouths. Because the damage likely from these different processes may be different in type and areal extent, this map does not represent a risk evaluation.

Relative Potential for Debris Flow[1]	Debris-flow Criteria	Relative Potential for Debris Flood[2]	Debris-flood Criteria
Very high[3]	A, Canyons with existing partly-detached landslide of volume sufficient for debris flow to reach canyon mouth. This very high potential applies at least through the summer cloud-burst season and through the following winter and spring thaw.	Very high	a, Canyons with existing partly-detached landslides that could become mobilized as debris flows and subsequently diluted into debri floods. This very high potential applies at least through the summer cloud-burst season and through the following winter and spring thaw.
High	B, Evidence of more than one past debris flow reaching canyon mouth, indicating a recurrent long-term potential for debris flow.	High	b, At least one historic (including 1983) debris-flow or debris-flood scar or path regardless of volume or Evidence of past debris-flow or debris-flood at canyon mouth (fans mapped by Miller, 1980). This evidence suggests recurrent long-term potential for debris flood.
Moderate	C, Evidence of only one past debris flow reaching canyon mouth or Historic (including 1983) debris-flow scar or path suggesting volume sufficient for debris flow to reach canyon mouth.	Low	c, No old debris-flow scars or evidenc of past debris floods.
Low	D, No evidence for past debris flows reaching canyon mouth.		

Symbols

Small range-front canyon having rating of moderate or higher; rating shown by letter designation

Approximate location of largest partly-detached landslide in each canyon.



(Debris Flow Potential), (Debris Flood Potential)

VERY HIGH	HIGH	MODERATE	LOW
A,a	B,b	C,c	D

DEBRIS FLOW & FLOOD POTENTIAL
G.F. WIECZOREK
1987

From Open-File Report 83-635: Assumptions used in 1983 Evaluation of Debris Flow Potential

1) partly-detached landslides are probably less stable now than before movement and are probably less stable than nearby unslid materials

2) increases in ground water levels accompanying a rainstorm or rapid snowmelt could be expected to induce movement of these partly-detached landslides

compared w. volume of previous flows

3) the potential for a debris flow to reach the canyon mouth depends on 1) the volume of the partly-detached landslide that mobilizes into a debris flow and 2) the gradient of the channel

4) the total debris flow volume will consist of contributions both from a landslide at the head of the debris-flow path and from materials scoured from the channel
   --for similar initial landslide contributions, the channel contribution will be similar in canyons of similar size, shape, gradient, surficial deposits, and bedrock geology
   --most major canyons between Holbrook and Beus Canyons, are similar in size, shape and gradient and are underlain by relatively uniform schists and gneisses of the Farmington Canyon complex (Davis, 1983), a similar level of channel contribution from these canyons can be expected

5) Simultaneous failure of non-adjacent landslides is unlikely, so the largest partly-detached landslide within each canyon represents the greatest threat

6) Debris flows from partly-detached landslides in major canyons of less than a standard volume (15,500 m^3) will die out before reaching the canyon mouth but will contribute material as debris flood. A smaller standard (3,600 m^3) was assumed for smaller canyons.

notes: 3) assumption that landslide material is continuously being depleted as it moves downslope

Table 1 - Evaluation of Potential for Debris Flow and Debris Flood From Canyons

Drainage (South to North)	Historic & Prehistoric Documentation of Debris Flows and Debris floods reaching canyon mouth	Volume (m^3) of Largest Single Debris Flow 1983	Largest Estimated Volume (m^3) of Single Partly-Detached Landslide	Average Main-Channel Gradient	Evaluation of Potential	
					Debris Flow	Debris Flood
City Creek	1854, 1864[5], 1874[5], 1879[5]	Minimal	---	-	B	b
Mill Creek	alluvial fan[1]	Minimal	---	-	D	b
Kenney Creek	historic, multiple prehistoric[2]	Minimal	---	-	B	b
Holbrook Canyon	None	22,000±4,000	42,000±5,000	.120	A	a
Standard Stone Creek/ Ward Canyon	prehistoric[3], 1983[3]	15,500±1,500	2,000±500	.126	B	a
Centerville Canyon	alluvial fan[1]	2,000±200	---	.140	D	b
Parrish Canyon	1930[5], 1930[5]	1,000±200	50,000±10,000	.177	A	a
Barnard Canyon	1930[5]	6,400±1,000	10,000±2,000	.195	C	a
Ricks Creek/ Ford Canyon	1901[5], 1923[5], 1929[3], 1930[5], 1934[5]	1,040±200	4,000±500	.203	B	a
Davis Creek	1878[5], 1901[5], 1903, 1923[5], 1929[3], 1930[5]	Minimal	---	.305	B	b
Steed Canyon	prehistoric[3], 1901[5] 1923[5], 1930[5]	10,000±2,000	25,000±5,000	.341	A	a
Rudd Canyon	prehistoric[3], 1983[3,7]	64,000[7]	70,000-100,000	.314	A	a

Farmington Canyon	1878[5], 1923[5], 1926[5], 1936, 1947[4]	17,000±3,000	40,000±5,000	.127	A	a
Shepard Creek	alluvial fan[1]	5,000±1,000	2,000±200	.175	D	a
Baer Creek	prehistoric[3], 1912[4], 1923[4], 1927[4], 1945[4], 1947[4]	2,400±400	20,000±5,000	.166	A	a
Holmes Creek/ Webb Canyon	alluvial fan[1], 1917[5]	Minimal	---	.209	C	b
S. Fork Kays Creek	1912[4], 1923[2], 1927[2], 1930[4], 1945[2], 1947[2]	Minimal	---	.203	B	b
M. Fork Kays Creek	prehistoric[1], 1947[2]	Minimal	---	-	C	b
Waterfall Canyon	1923[4]	Minimal	---	-	C	b
Ogden Canyon	1888[5], 1923[4,5], 1980[6]	Minimal	---	-	C	c
Coldwater Canyon	prehistoric[1], 1983[3,8]	12,000±2,000	---	.205	B	b
Willard Canyon	prehistoric[1], 1912[5], 1923[4], 1936[5]	8,000± 1,000	10,000±2,000	.195	A	a
Facer Canyon	multiple prehistoric[3], alluvial fan[1]	3,000±500	30,000±5,000	.307	A	a
Threemile Creek/ Perry Canyon	1923[4,5], alluvial fan[1]	Minimal	---	-	C	b

Sources of information:

[1]Miller (1980)
[2]Winkelaar, U.S. Forest Service, (oral commun., 1983)
[3]determined during this study
[4]Croft (1981)
[5]Woolley (1946)
[6]Thom Heller, U.S. Forest Service (oral commun., 1983) - both 1923 and 1980 events reported in tributaries to Ogden Canyon
[7]Kaliser, Utah Geologic and Mineral Survey (oral commun., 1983)
[8]Pierson, U.S. Geological Survey (oral commun., 1983)

Correlation of 1983 partly detached landslides with 1984 debris flows in Topographic Hollows along Wasatch Front between Salt Lake City and Willard

		+	-
partly detached landslides	+	11	16
	-	13	491

Within Major and Half Canyons:
Topographic Hollows with 1984 Debris Flows and No Partly-Detached Landslides

Probabilities - $\frac{13}{13 + 491} = 0.025$

Odds - $\frac{13}{491} = 0.0265$

Topographic Hollows with 1984 Debris Flows and Partly-Detached Landslides

Probabilities - $\frac{11}{11 + 16} = 0.407$

Odds - $\frac{11}{16} = 0.6975$

$$\text{Odds ratio} = \frac{0.6875}{0.0265} = 25.97$$

Null Hypothesis: Debris flows occurred in 1984 in the same proportion in topographic hollows with and without partly-detached landslides.

$$X^2 = [(\text{observed-expected})^2/\text{expected}]$$
$$X^2 = 86.5$$

From X^2 - Tables with P = 0.01 $\cdot$ $X^2 = 6.64$. Our observed value is much larger than this, therefore we have strong evidence that the distribution of 1984 debris flows in topographic hollows is different with and without partly-detached landslides.

Adding all minor canyons to this analysis:

		+	-
partly detached landslides	+	11	16
	-	22	567

Topographic Hollows with 1984 Debris Flows and No Partly-Detached Landslides

Probabilities - $\frac{22}{22 + 567} = 0.037$

Odds - $\frac{22}{557} = 0.0388$

Topographic Hollows with 1984 Debris Flows and Partly-Detached Landslides

Probabilities - $\frac{11}{11 + 16} = 0.407$

Odds - $\frac{11}{16} = 0.6875$

$$\text{Odds Ratio} = \frac{0.6875}{.0388} = 17.72$$

$$X^2 = 69.7$$

Table 3. Analysis of materials from the Birch Creek debris flow

Sample #	Distance from beginning of debris flow (m)[1]	GRAVEL (> 2000) ($x10^{-3}$mm)	SAND (2000-62) ($x10^{-3}$mm)	SILT (62-4) ($x10^{-3}$mm)	CLAY (<4) ($x10^{-3}$mm)	D50 ($x10^{-3}$mm)	Trask $(D_{75}/D_{25})^{1/2}$	Field Notes
BC-1		1	39	32	28	33	7.6	Bedrock at main scarp
BC-13	1021 m	21[2]	46	19	14	200	6.5	1983 debris-flow deposit
BC-18	1555 m	9	61	19	11	200	3.5	1983 debris-flow deposit
BC-16	1612 m	4	57	24	15	130	5.0	paleo debris flow
BC-17	1612 m	13	49	26	12	140	5.9	paleo debris flow
BC-21	1861 m	4	54	28	14	120	4.8	1983 debris-flow deposit
BC-2	2724 m	3	54	26	17	101	4.8	1983 debris-flow deposit
BC-3	3337 m	2	56	26	16	102	4.8	1983 debris-flow deposit
BC-4[2]	3711 m	1	94	3	2	280	1.4	1983 hyper-concentrated-flood deposit
BC-5[2]	3711 m	20[3]	58	13	9	320	3.5	1983 debris-flow deposit
BC-6[2]	3711 m	8	79	7	6	270	1.8	1983 hyper-concentrated-flood deposit

Table 4. Largest boulders found in the boulder front snouts at the Birch Creek debris flow.

Boulder front snout number	Largest boulder diameter (m)	Boulder front snout number	Largest boulder diameter (m)
1	2.0	15	1.2
2	2.3	16	1.3
3	3.0	17	0.6
4	2.1	18	0.5
5	2.0	19	0.8
6	4.0	20	1.0
7	1.0	21	0.5
8	1.5	22	0.3
9	1.7	23	0.3
10	1.0	24	1.0
11	3.8	25	0.7
12	1.7	26	0.8
13	1.0	27	0.9
14	1.0	28	0.8

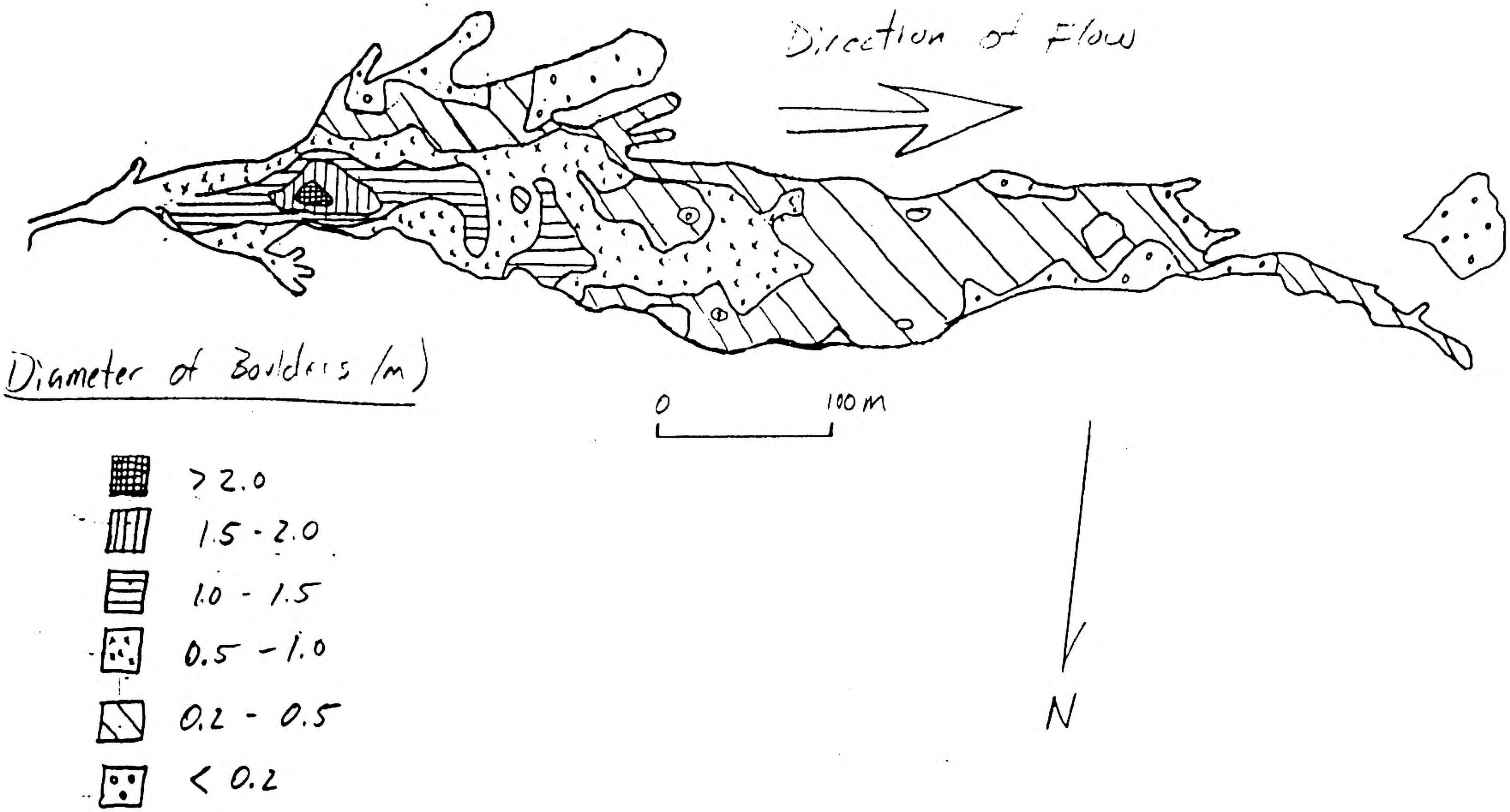

Direction of Flow
Diameter of Boulders (m)
0
100m
> 2.0
1.5 - 2.0
1.0 - 1.5
0.5 - 1.0
0.2 - 0.5
< 0.2
N

Figure 9.

Table 5. Identification of deposits at Birch Creek debris flow where flow crosses Utah State Highway 117, samples BC-4 through BC-12, Table 3

Observable Features	Debris Flow	Hyperconcentrated Flood
Bedding	Massive	Finely bedded
Sorting	Unsorted	Well sorted
Dominant particle size	Clay-cobble	Sand
Color	Gray	Light brown to tan
Organics	Abundant	Absent/Rare

Grain Size Analysis	Range	Mean ± S.D		Range	Mean ± S.D	
Combined % silt and clay	22-77	51	21	5-30	14	8.6
D_{50} (m)	39-320	137	111	105-280	226	66
Trask (D_{75}/D_{25})	1.6-5.3	3.4	1.3	1.4-1.8	1.7	0.17

arboraceous debris. These deposits are similar in morphology to recent (1983) hyperconcentrated-flood deposits observed at this site, and therefore are identified as paleo hyperconcentrated-flood deposits. The third type of material was organic-rich peaty soils, very dark in color and with a noticeable odor of rotting organic matter. These peaty soils probably resulted from a soil horizon rich in organic material that developed on the paleo debris-flow or hyperconcentrated flood deposits.

Using Carbon-14 dating techniques on the organic layer immediately below the lowest identifiable debris-flow deposit (at pt. 12 on Plate 1), we established the maximum age for the lowest debris flow at 4,210 ± 60 years B.P. The organic layer immediately above the uppermost debris flow (excluding 1983) was dated as 2,100 ± 60 years B.P. which establishes the minimum age of the upper flow. Exposed in this channel are at least 17 to 20 paleo debris flows. Using the maximum and minimum ages, the recurrence rate for prehistoric debris flows to reach this location is at least 100 to 120 years.

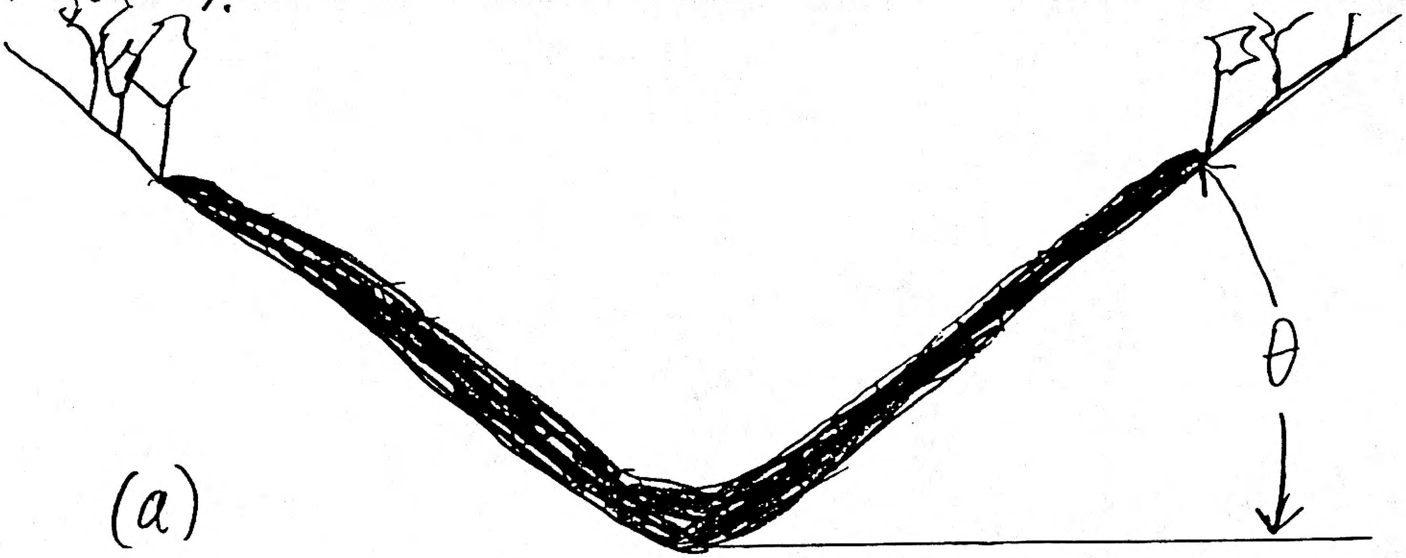
Below the steep section (pt. 14, Plate 1) the channel incision continued onto the alluvial fan, exposing additional stratigraphy. Using a similar

sampling technique for a point lower on the alluvial fan (pt. 15, Plate 1) the upper and lowermost debris-flow deposits were dated at 2110 ± 40 years B.P. and 4470 ± 70 years B.P., respectively. At this location there were only 8 to 10 prehistoric debris flows identifed, and therefore the recurrence rate for prehistoric debris flows is at least 245 to 317 years. This longer recurrance rate at a point further removed from the canyon mouth is consistant with theory that the further a given point is beyond the channel mouth (and therefore from the source area), the less frequently debris flows will reach that point.

CROOKED CREEK

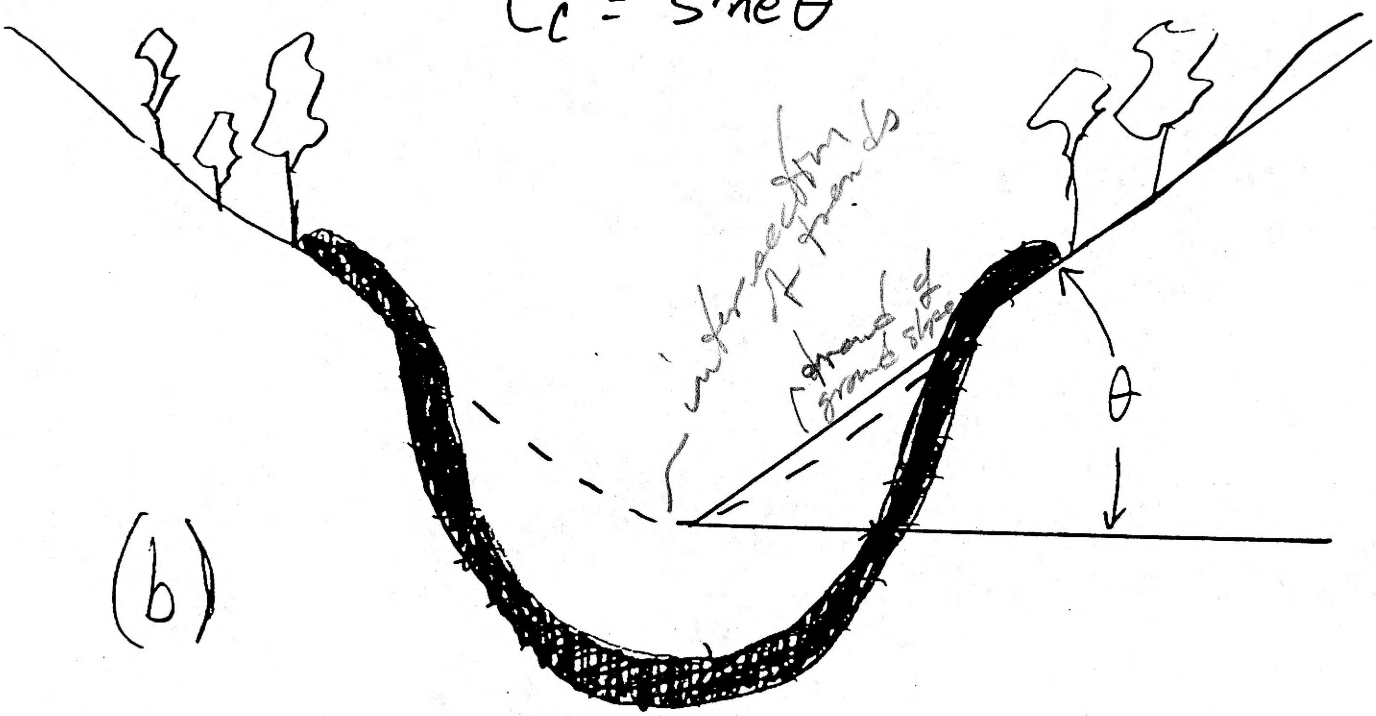
Setting

The Crooked Creek debris flow is approximately 2 km southwest of the town . . . section of Sanpete Valley (fig. 1).



(a)

$C_c = \text{sine}\,\theta$



(b)

$C_c = \text{Sine}\,\theta$

C_c = coefficient of confinement

Table 14. Data used for regression equations

Site	Distance (m)	Volume (m^3)	Coefficient of Confinement	Percent Clay	Elevation Change (m)
Birch Creek	5681	167,000	0.06	14	305
Crooked Creek	2390	8,500	0.25	19	280
Lower Gooseberry Reservoir-I	1447	17,250	0.08	15	110
Lower Gooseberry Reservoir-II	657	2,950	0.17	23	97
Little Clear Creek	946	1,800	0.17	10	134
South Fork of North Creek	4760	45,000	0.24	31	268
Santaquin	765	13,500	0.12	38	61
Ward Canyon	5893	15,500	0.28	2	293

Table 15. Debris-flow Runout Model uses and limitations

Model is appropriate for the following uses:	Model is inadequate and not recommended for the following uses:
1. Evaluating runout distance of a debris flow resulting from a landslide	1. Evaluating debris flow runout distance from a drainage basin without specific landslides identified
2. Estimating areas that may be impacted by debris flows	2. Evaluating debris flow runout distance from a flow initiating in a channel
	3. Specific site planning or zoning to reduce risks

Takei (1982)

Scale of Debris Flows in Japan (caused disasters in 1972 1977)

[number in each column shows frequency
histogram shows percentage against total (total 551)
25 % per 1 line (column of total), 05 % per 1 line(individual column)]

volume of debris m^3	drainage area km^2		0.032	0.056	0.10	0.178	0.316	0.562	1.00	1.78	3.16	5.62	1.00	17.8	31.6	56.2	
	class	class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		total 551	15	13	13	95	115	74	56	75	37	25	14	11	5	2	1
$\times 10^2$ 3.16	1	8	1	1	1	2	2	0	1								
5.62	2	15	1	2	0	5	2	1	2	1							
$\times 10^3$ 1.00	3	18	3	1	3	6	4	0	1	0							
1.78	4	43	4	1	1	7	14	8	4	3	1						
3.16	5	61	2	3	2	16	14	8	4	10	2						
5.62	6	66	4	3	2	8	22	12	8	3	3	1					
10^4 1.00	7	76		1	2	19	22	12	7	6	6	1					
1.78	8	87		1	2	18	14	10	14	15	5	6	1	1			
3.16	9	74				10	13	11	6	15	9	3	3	2	1	1	
5.62	10	45				2	3	8	3	13	8	2	2	3	0	1	
$\times 10^5$ 1.00	11	21				2	2	1	1	6	1	7	1	0	0		
1.78	12	25					1	3	3	3	2	4	5	3	1		
3.16	13	7					1	0	1	0	0	1	1	1	2		
5.62	14	1										1					
$\times 10^6$ 1.00	15	1							1								
1.78	16	2												1			1
	17	1													1		

Regression Equation

$$V = 13.600 \cdot A^{0.61}$$

Hamilton and others, in press 5

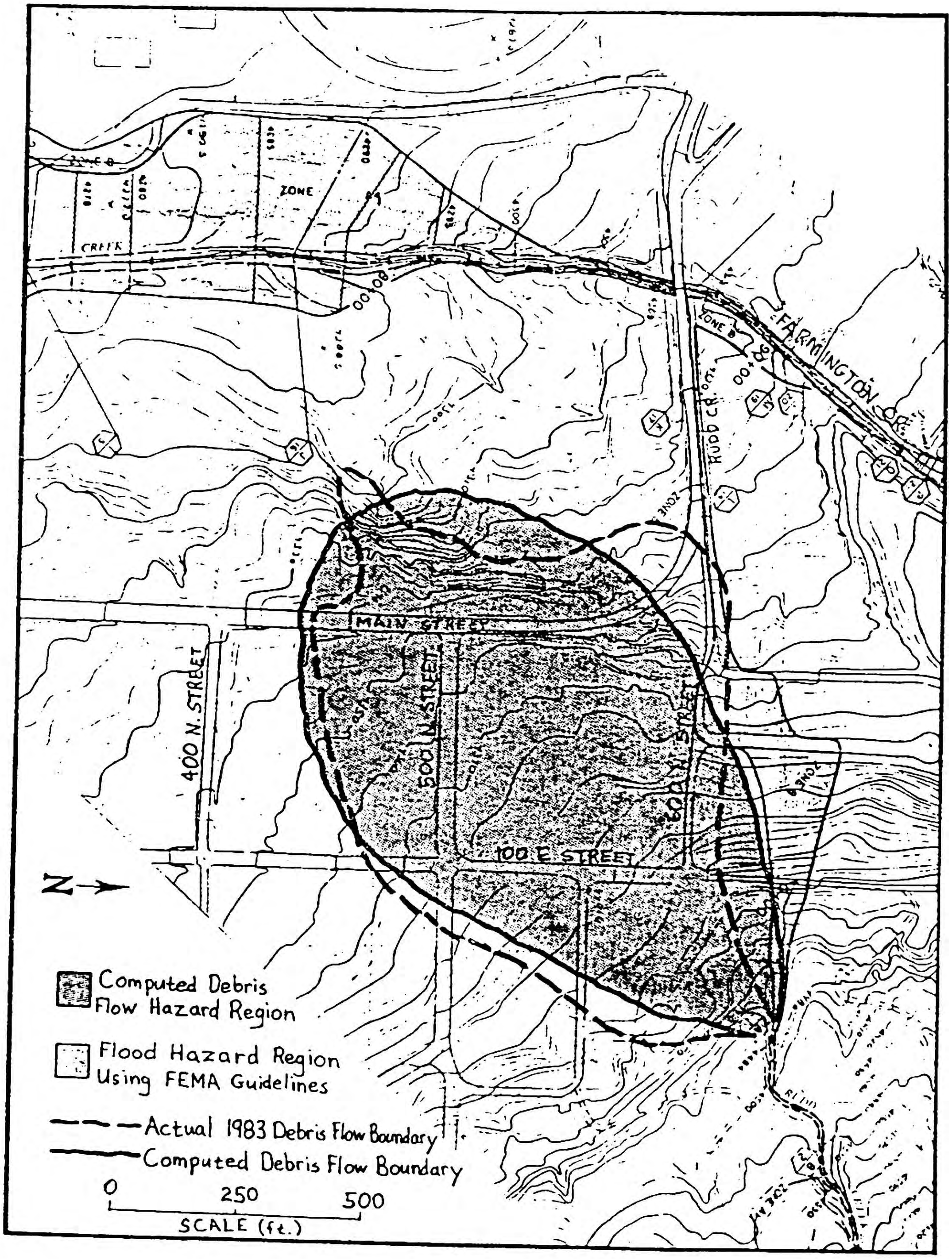


Figure 6 Computed outline of Rudd Creek debris flow compared to actual outline of the May, 1983 Farmington, Utah

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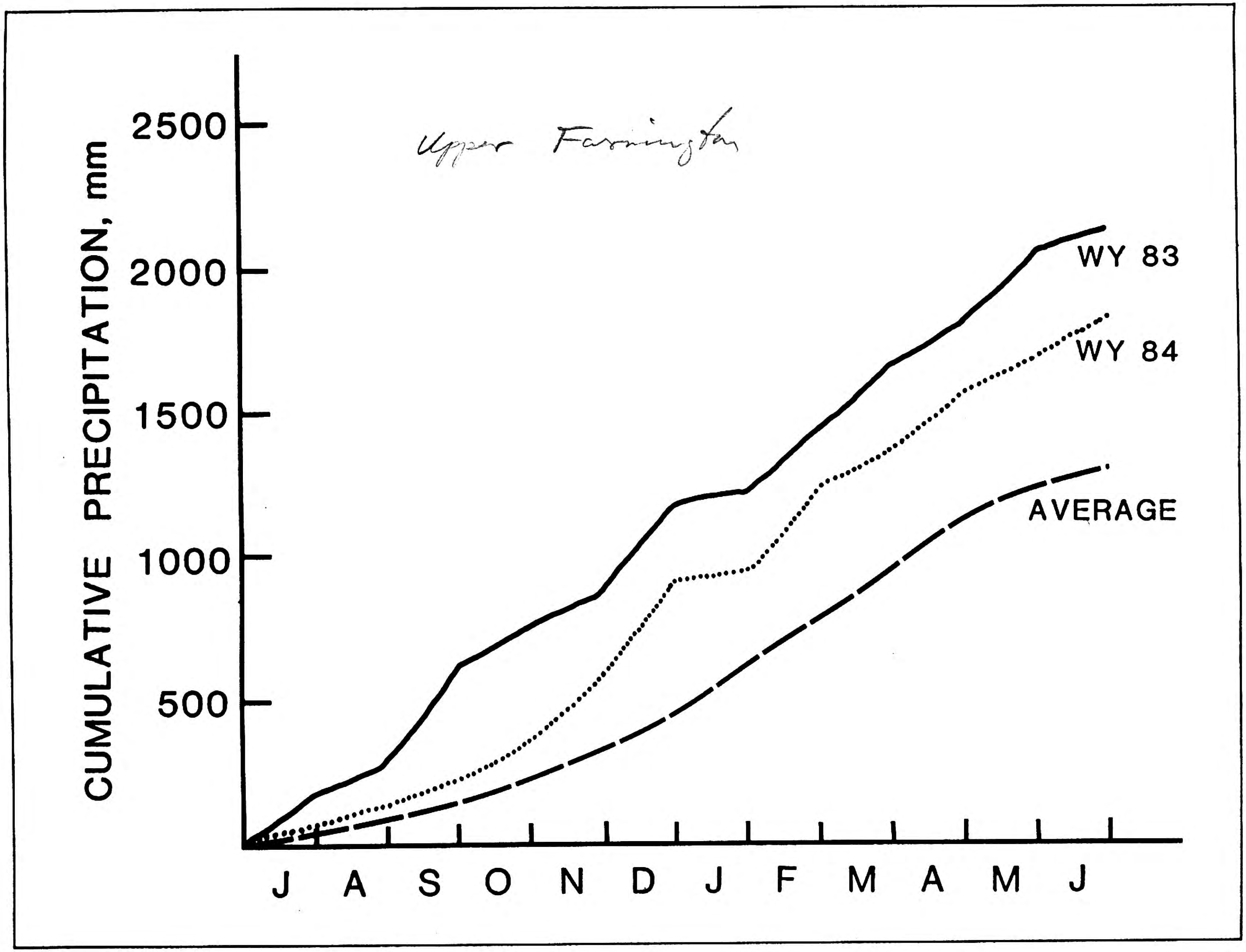
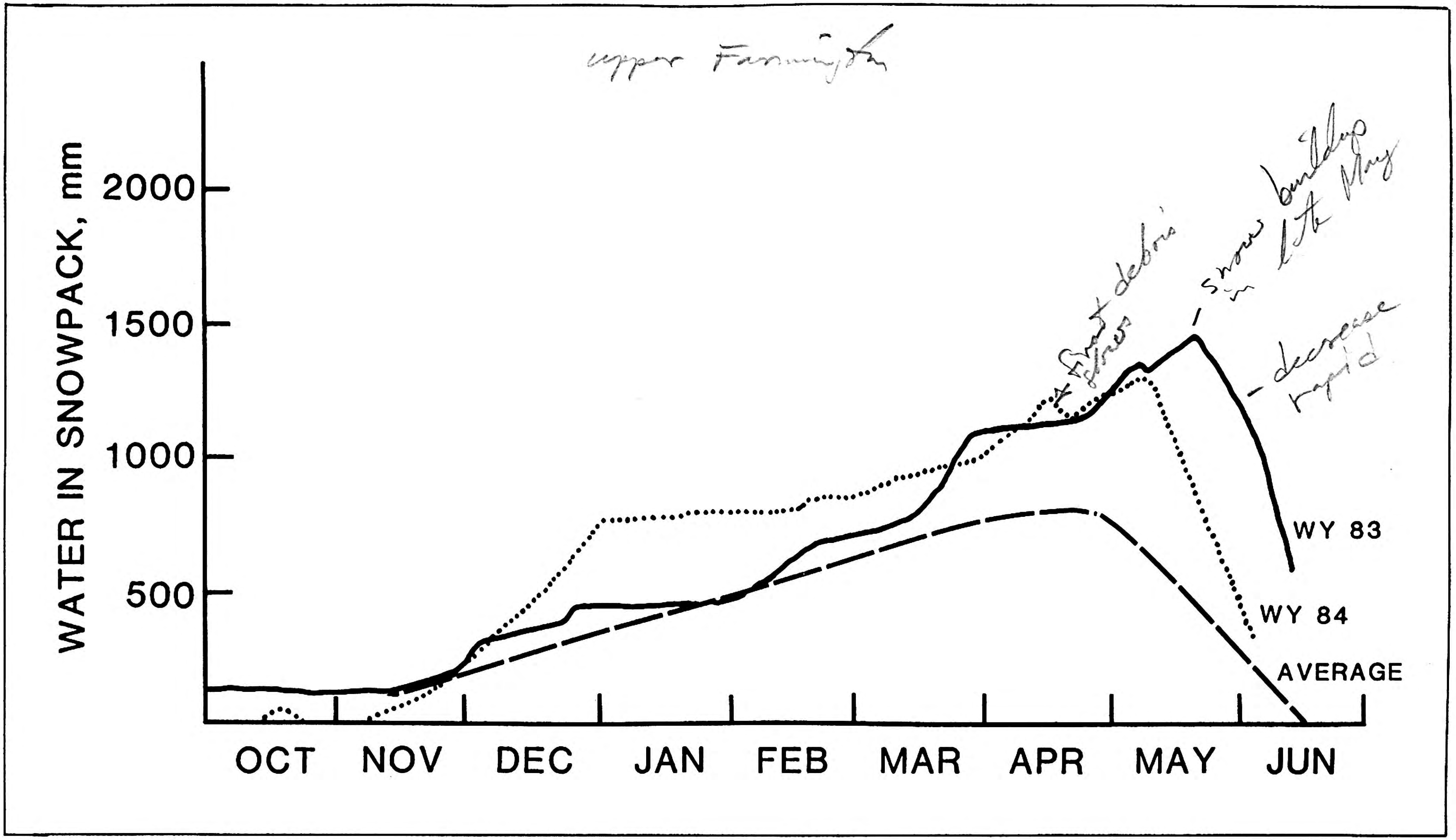
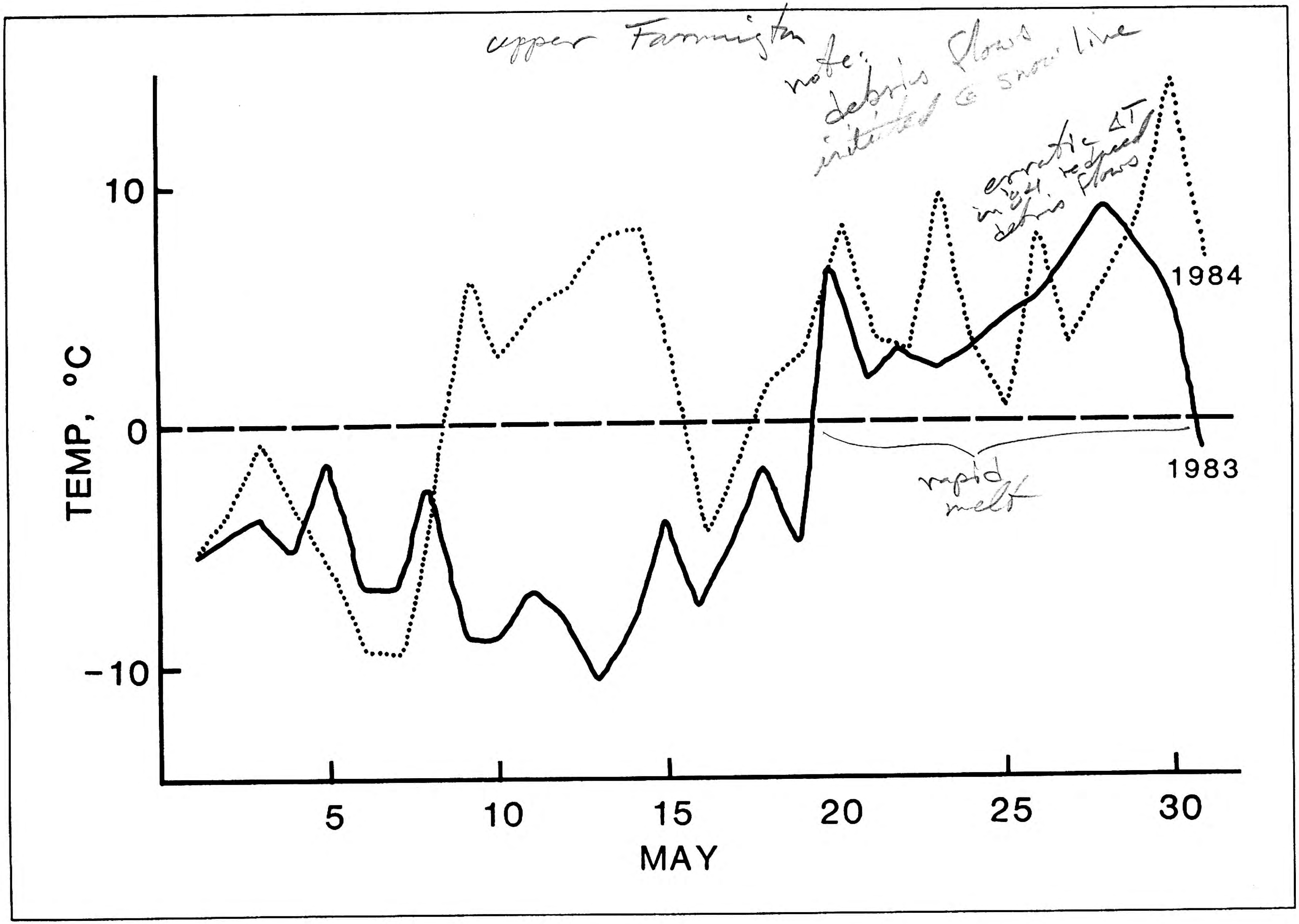

Upper Farmington
CUMULATIVE PRECIPITATION, mm
2500
2000
1500
1000
500
WY 83
WY 84
AVERAGE
J A S O N D J F M A M J


upper Farmington
WATER IN SNOWPACK, mm
2000
1500
1000
500
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
WY 83
WY 84
AVERAGE
+ Frost debris flows
snow buildup in late May
decrease rapid


upper Farmington
note: debris flows initiated @ snow line
erratic ΔT in '84 reduced debris flows
rapid melt
TEMP, °C
10
0
-10
5
10
15
20
25
30
MAY
1984
1983

Marsell (1971) - Conditions contributing to flooding that contributed to spring snowmelt:

(1) heavy winter snowpack

(2) saturated soil mantle at start of winter resulting from heavy, late-autumn rains

(3) low temperatures during late winter and early spring; permitting retentaion of deep snow cover

(4) sustained high temperatures once melting started

(5) additionally ppt., esp. warm rain, which increased rate of melting

(6) streams within a drainage basin reaching peak flow simultaneously

From Open-File Report 83-635: Studies needed for careful evaluation of potential should address the following questions:

1) Relations between rainfall (or snowmelt), ground-water levels, and landslide movement. Such relations would permit prediction of timing of debris flows. Real-time prediction and warnings could then be made based on telemetered rainfall, water-level, or ground-movement information.
2) Stability of the partly-detached landslides. Are these masses in fact significantly less stable than nearby hillslopes, and how long will they remain so? These questions should be approached through detailed site-specific studies including stability analyses of the landslides.
3) The process of transformation from landslide to debris flow. Understanding developed through such study could help evaluate the potential for debris flow of the partly-detached landslides.
4) Incorporation of channel materials by debris flow. Possible variations in materials available for incorporation is one of the major uncertainties of our analysis.
5) The transition from debris flow to debris flood. Understanding of this transition would permit more accurate prediction of the nature of flow from canyon mouths.
6) Factors that control debris-flow runout. Understanding of runout would help in prediction of areas likely to be affected beyond canyon mouths.
7) Recurrence of debris floods and debris flows at canyon mouths. Systematic field investigation and dating of deposits would help define the expectable frequency of events from each canyon.

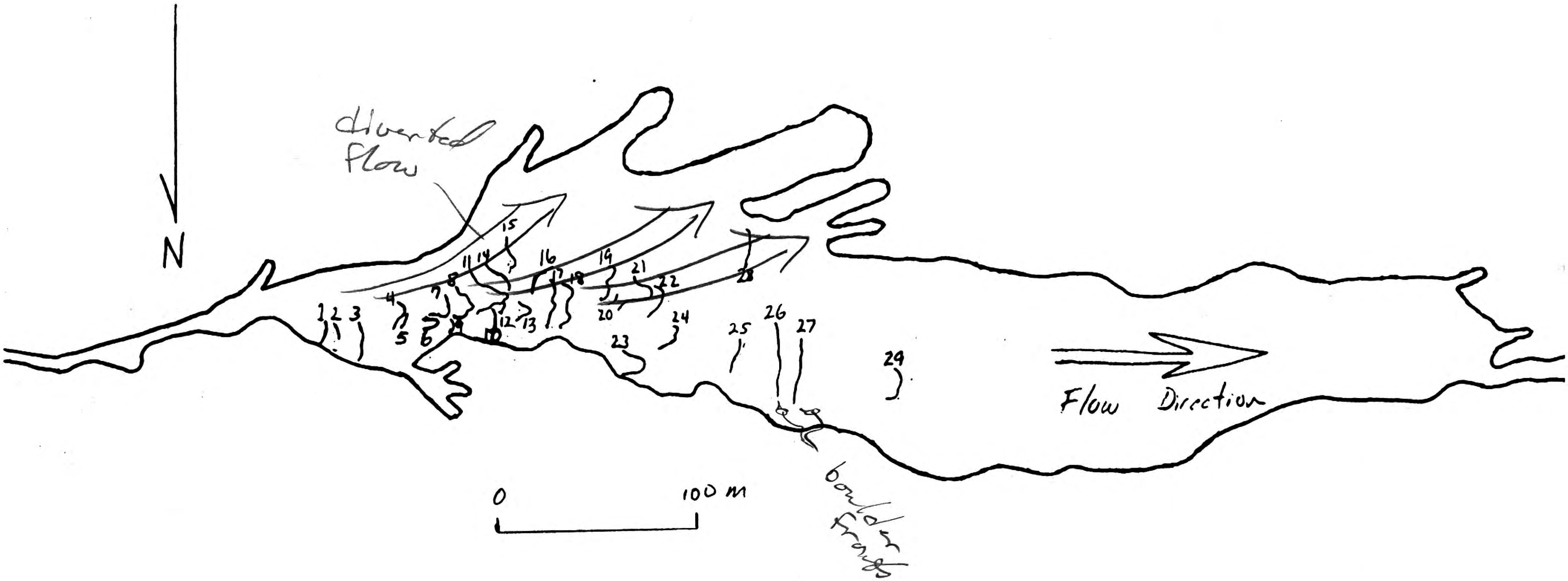
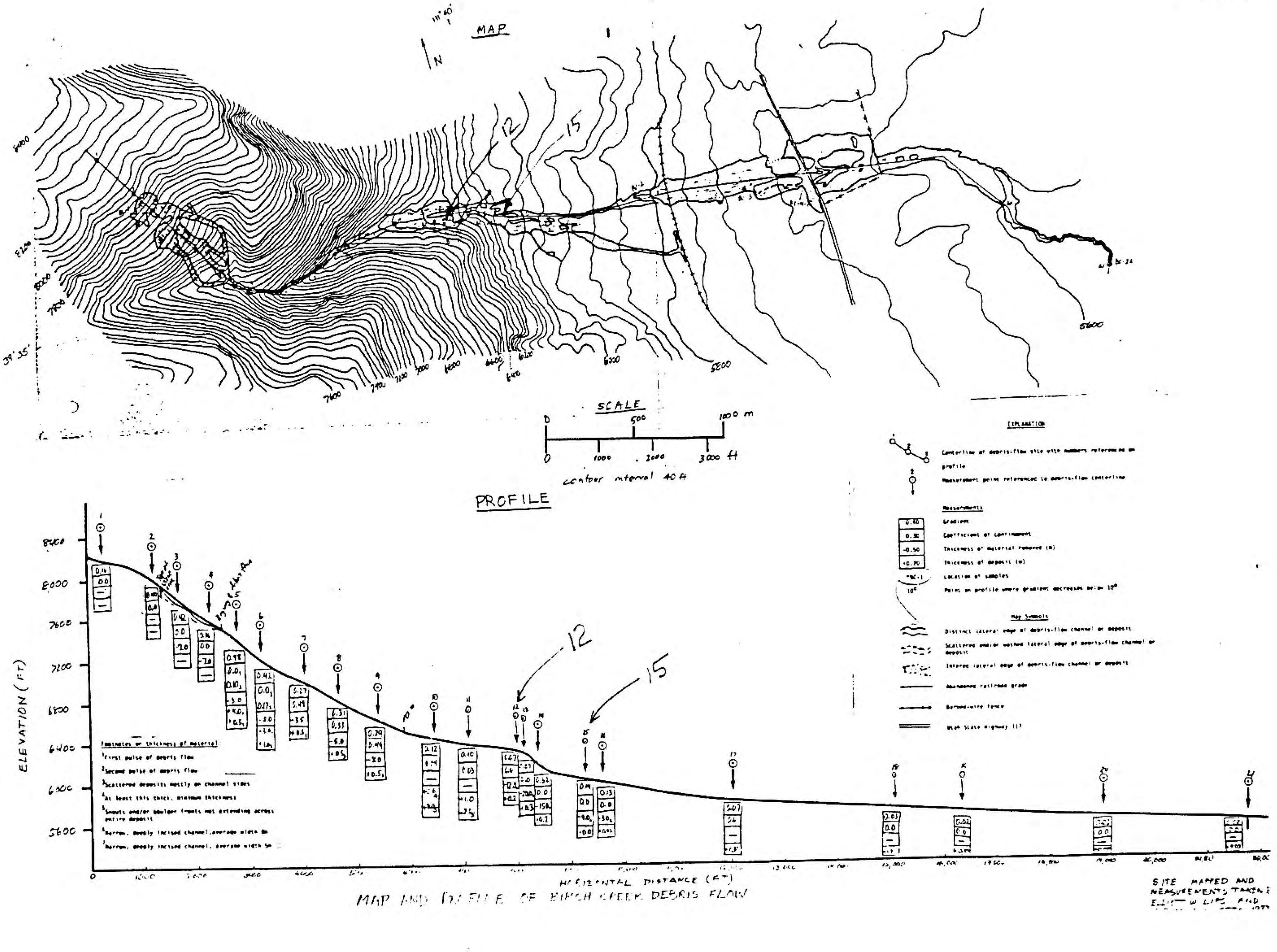

diverted flow
N
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
Flow Direction
0
100 m
boulder fronts

Figure 20

PLATE 1



MAP AND PROFILE OF BIRCH CREEK DEBRIS FLOW