GEOLOGIC CONSEQUENCES OF THE 1983 WET YEAR IN UTAH

by

Bruce N. Kaliser and James E. Slosson, Ph D

UTAH GEOLOGICAL AND MINERAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
Miscellaneous Publication 88-3 1988

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GEOLOGIC CONSEQUENCES OF THE 1983 WET YEAR IN UTAH

by

Bruce N. Kaliser[1] *and James E. Slosson*[2]*, Ph D*

1988

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The UTAH GEOLOGICAL AND MINERAL SURVEY disseminates information concerning Utah's geology to promote the understanding, enjoyment, utilization, and respect of Utah's geologic resources and hazards.

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GEOLOGIC CONSEQUENCES OF THE 1983 WET YEAR IN UTAH

by

Bruce N. Kaliser[1] and James E. Slosson[2], Ph D

PREFACE

In 1983 Bruce N. Kaliser was chief of the Hazards Section of the Utah Geological and Mineral Survey (UGMS). He personally investigated many of the geologic events occurring in Utah as a result of the period of unusually heavy precipitation that began in September, 1982 and continued through 1983. He also directed other UGMS personnel in the investigation of these events and compiled data from numerous other sources. When Mr. Kaliser resigned from the UGMS in 1987, the UGMS contracted with him and Dr. James E. Slosson to complete a report on these events. Dr. Slosson, formerly California State Geologist and a member of the National Research Council Committee on Ground Failure Hazards, had worked on several of Utah's 1983 landslides, often in conjunction with Mr. Kaliser, before collaborating on this project. This report, based in a large part on a manuscript prepared by Mr. Kaliser while at the UGMS, is the product of that contract.

It is hoped that this record of the events of 1983 will provide valuable information for understanding the processes involved and lead to reduction of losses from future similar events.

Dr. Slosson would like to acknowledge the following individuals for their help in fulfilling his contribution to this paper: Gay W. Havens, Robert L. Hill, Nancy J. Slosson, Thomas L. and Lynn A. Slosson, and Jenny Lind.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GEOLOGIC CONSEQUENCES
OF THE 1983 WET YEAR IN UTAH

by

Bruce N. Kaliser[1] and James E. Slosson[2], Ph.D.

ABSTRACT

Geologic consequences of the abnormally wet year of 1983 were unprecedented in number, magnitude, and geographic distribution in the 136-year history of Utah. That year was preceded by an extraordinarily wet 1982 so that antecedent moisture levels were very high. Monthly precipitation in September, 1982 set records at many measuring stations in the state. Accumulated snowpack and the moisture contained therein, combined with the abnormally late timing and high rate of melt in May and June, were critical parameters in the creation of sustained peak flows of mountain streams and in the triggering of over 1,000 landslides. Resultant total damages for 1983 have been assessed at approximately $650,000,000, more than half of the total can be attributed to the Thistle landslide in Spanish Fork Canyon.

Slope movements ranged in scale from world-class massive landslides (reactivated ancient landslides) in the Wasatch Plateau to relatively minor 500± cubic yard shallow failures which resulted in debris flows and debris floods. Creep of two large landslides on the Wasatch Front have been documented - one in bedrock and the other on a massive, complex, ancient slide.

Most important, for the first time in Utah it has been documented that debris flows are the consequence of slope failures. Some flows, after initiation, incorporated significant additional volumes of material from slopes, swales and channels down gradient. At least three debris flows reached alluvial fan environments beyond the mouths of canyons; several others traveled as far as canyon mouths before transformation to damaging debris floods.

Ground-water elevations, both for shallow, unconfined aquifers on valley floors and in perched horizons in benchland and mountainous terrain, were at historically high levels. Piezometric levels for confined aquifers were well above normal. Base levels of canyon streams, indicated by minimum daily flows, also reflect the filling and pressurizing of ground-water reservoirs. Adverse impacts on all sectors of the economy in Utah have been phenomenal. Landsliding has aggravated erosion and will continue to affect sediment transport well into the future. Rising water tables have affected agricultural yields, aggravated frost-heave problems, possibly influenced ground response from a magnitude 4.25 earthquake in the Salt Lake Valley, created new wet lands, and increased inflow-infiltration overloading of sewage treatment plants. The foregoing are some of the adverse geologic impacts witnessed in 1983. Great Salt Lake and Utah Lake have risen at unprecedented rates.

The wet year of 1983 has focused considerable attention on the susceptibility of Utah's urban areas to geologic hazards. The inadequate use of knowledge that currently exists in the United States for answering critical questions pertaining to landslides, debris flows and debris floods questions has also been made evident as the non-earth science community wrestles with the hard decisions of hazard mitigation related to slope failures. The knowledge to recognize and mitigate has been available for more than three decades but unfortunately little use has been made of this knowledge.

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INTRODUCTION

The advent of the 1983 water year on October 1, 1982 brought indications that geologic events caused by or related to availability of water were occurring to a greater than normal degree as a result of the record amounts of precipitation (figure 1). The year was noteworthy not only from a hydrological but also clearly from a geological point of view.

The effects of the wet cycle include not only flooding and rising lake levels but also:

- rise in the shallow unconfined water tables
- rises in piezometric levels of confined aquifers
- earth movement (landslides and debris flows) caused by water-induced soil and rock slides on mostly moderate to steep slopes
- damage to property

Included in the damage were lifelines such as highways, railroads, power, gas, and water lines, as well as residential structures, agricultural areas, parks, and industry (especially the salt-extractive industries around Great Salt Lake). Damage was also noted to wildlife and fish resources in Utah.

Landslides of almost every type and in great proliferation occurred, particularly along the Wasatch Front in northern and central Utah. Data indicate that never before in the state's 136 years of recorded history had so many landslides occurred. The water-caused and/or related geologic activity generally followed the snow line to even higher elevations through the winter and spring of the year. The outstanding event of the year was the Thistle Landslide, initiated on April 10. A peak of activity was reached in late May as debris slides broke off steep Wasatch Mountain slopes (figure 2) and created debris flows and debris floods. Later, in June and July, another peak of activity was reached in the Wasatch Plateau (figure 2), not only with debris flows but also with reactivated, massive, complex landslides, several of which were over one mile in length.

Abnormal wet conditions continued through the spring of 1983 resulting in a 9-month water-year precipitation/snow melt of 150 to 300 percent of normal in central and southern Utah. In addition, the fall and spring periods were cooler than normal and the winter was warmer.

The increase in moisture in the mountains is illustrated in figure 3 showing the curves for nine drainage basins in the state. It is apparent that, for April, the snow water content equalled or exceeded the maximum previously recorded for these four basins; by May, all nine basins exceeded previous maxima. This peaking in May was a full 1.5 months later than normal. Only in southeastern Utah was precipitation in May not considerably above average (figure 4). On May 19th, 20 inches were added to the snow accumulation at Alta, bringing it to 805 inches. The equivalent of 40 to 60 inches of water existed at elevations of about 8,000 feet. Across the state, snow/water percentages ranged from 250 to 8,000 percent of average (figure 5).

Conditions suitable for debris slides/flows caused by snowmelt occurred in late May. Temperatures rose into the 80s and 90s between May 27th and May 31st and these near-record high temperatures accelerated the rapid runoff from the snowpack. Figure 6a shows the accumulation of snow water content for a station at 8,400 feet elevation in northern Utah. Note that for a period of nine days in May the rate of snowmelt averaged 1.33 inches per day. Figure 6b shows that 24 inches melted over a period of 15 days (averaging 1.6 inches per day) at a station of approximate elevation 8,000 feet along the Wasatch Front. The record from a third station at an elevation of 7,500 feet on the Wasatch Front is illustrated in figure 6c. The gradient for this station is even steeper, averaging 3 inches per day for 6 days. Thunderstorms followed this melt period with heavy, but brief, precipitation.

Several scientific hypotheses have been offered for this wet cycle. One hypothesis which involves the effects of solar heating and particulate matter (nuclei) in the air resulting from eruptions of Mount St. Helens and the Mexican volcano, El Chichon, together with an exacerbated El Niño ocean warming off the west coast of South America, has been suggested as the hypothesis best supported by available data. Whatever the cause, the hydrograph of Great Salt Lake (figure 7) suggests that Utah's climatic and hydrologic regime may follow a cyclical pattern --possibly, in part, related in time and place with El Niño.

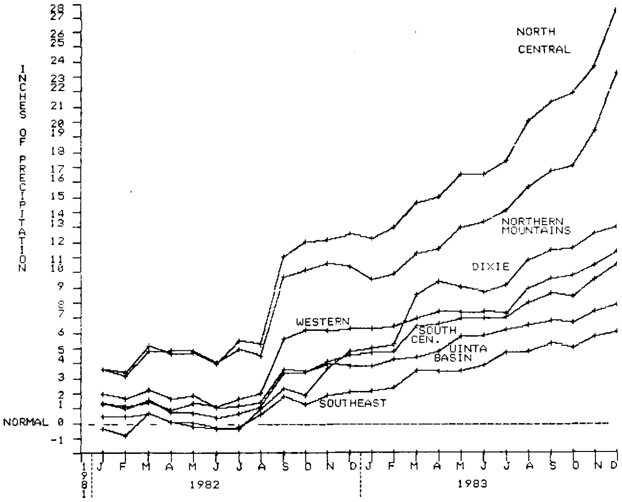


Figure 1.
October 1981 to December 1983 precipitation for the six climatologic divisions of Utah; cumulative departure from normal.

Extraordinary precipitation in the water year 1984 continued well above normal. During December, for example, snowfall at Farmington was 448% of normal and 364% above the previous year. Stream flows for City Creek in Salt Lake City showed levels during November, December, and January which were approximately 90% of those the previous year and well above average. Stream discharges in Salt Lake County during December 1983 were 99.7% of that of December 1982. During late April and early May, snowpack continued accumulating moisture in a manner remarkably similar to that of 1983. In May, rapid onset of high temperatures again brought on phenomenal snowmelt. Landsliding and debris flows were again triggered en masse and another emergency response mode was required. Unfortunately, the recurrence of landsliding and debris flows began before documentation of the phenomenon attributed to 1983 had been completed. For this reason, it has become difficult in some cases to sort out whether an event occurred in 1983 or 1984. However, it is very apparent that the more adverse geologic events occur during very significant wet cycles. The writers are fully cognizant that slope movements and other wet-cycle phenomena were prolific in 1984, perhaps to an extent still unappreciated by many. Inasmuch as only the events of 1983 are treated in this paper, the reader, upon finding omissions, may wish to re-examine the timing of the events in question. Also, it is noted that prior to the onslaught of activity in 1983, the scientific and engineering community was not as well prepared for a response, let alone the documentation of events. Therefore, as a generalization, the events of 1984 received more adequate scientific attention and may have been better documented.

Scope

Twenty-four of the twenty-nine counties within Utah are included in the scope of this paper (figure 8). The remaining five counties have been treated by Davis (1984). Some wet-year effects did occur in the five counties, but the major consequences were exhibited in the twenty-four counties discussed herein.

Nearly all of the effects of the wet year could be classed as "geologic consequences." For this reason, the full gamut of effects are examined in this paper. Emphasis, however, has been placed upon slope movements, including all types of landslides, debris flows, and debris floods. Ground-water effects are also given priority. The rise of lake levels is a geologic consequence of note but investigation of many of the ramifications, such as those that are geochemical and meteorological in nature, have been left to those workers who possess greater expertise in those subjects. Ephemeral lakes

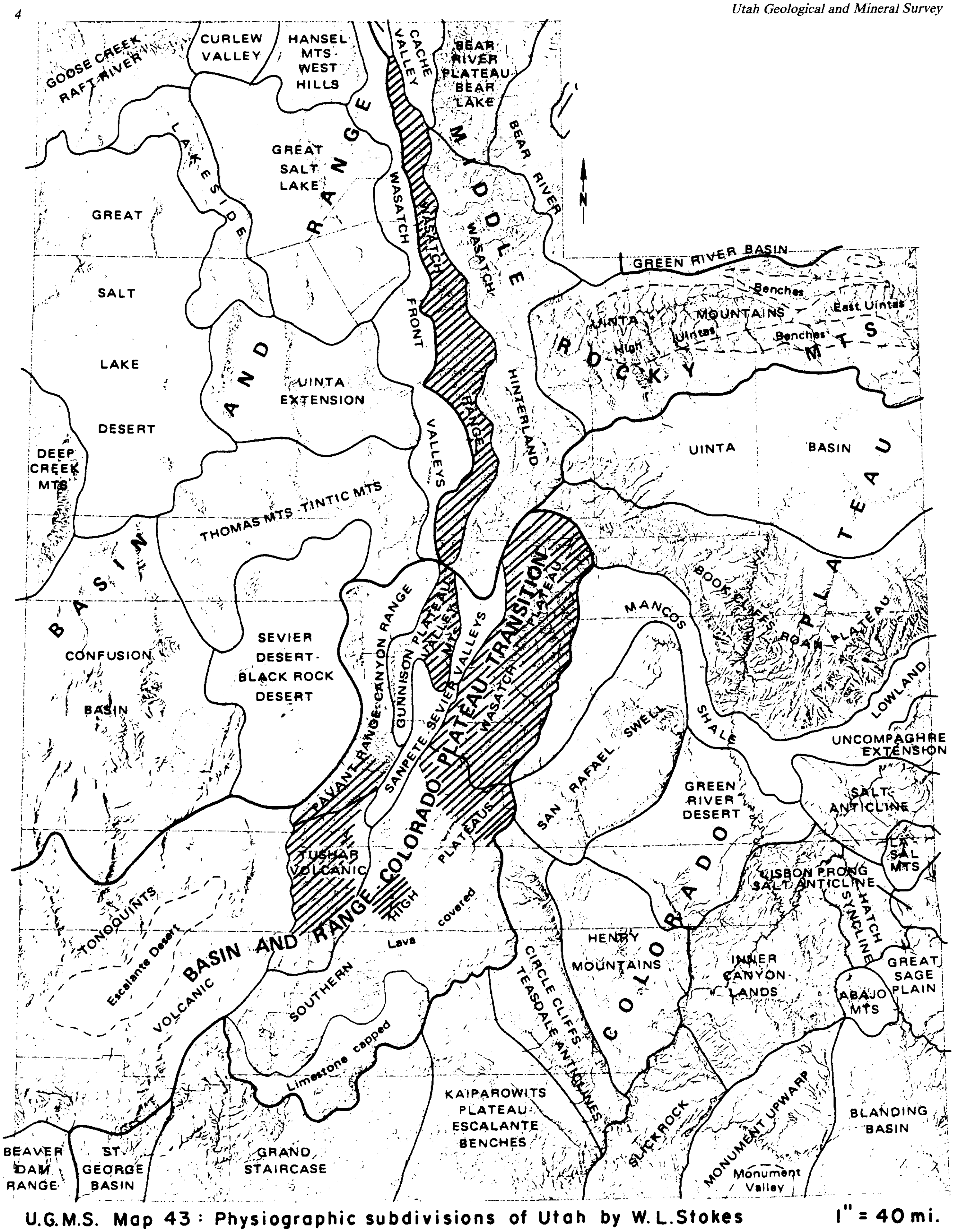


Figure 2.

Areas in Utah where slope movements were concentrated in 1983.

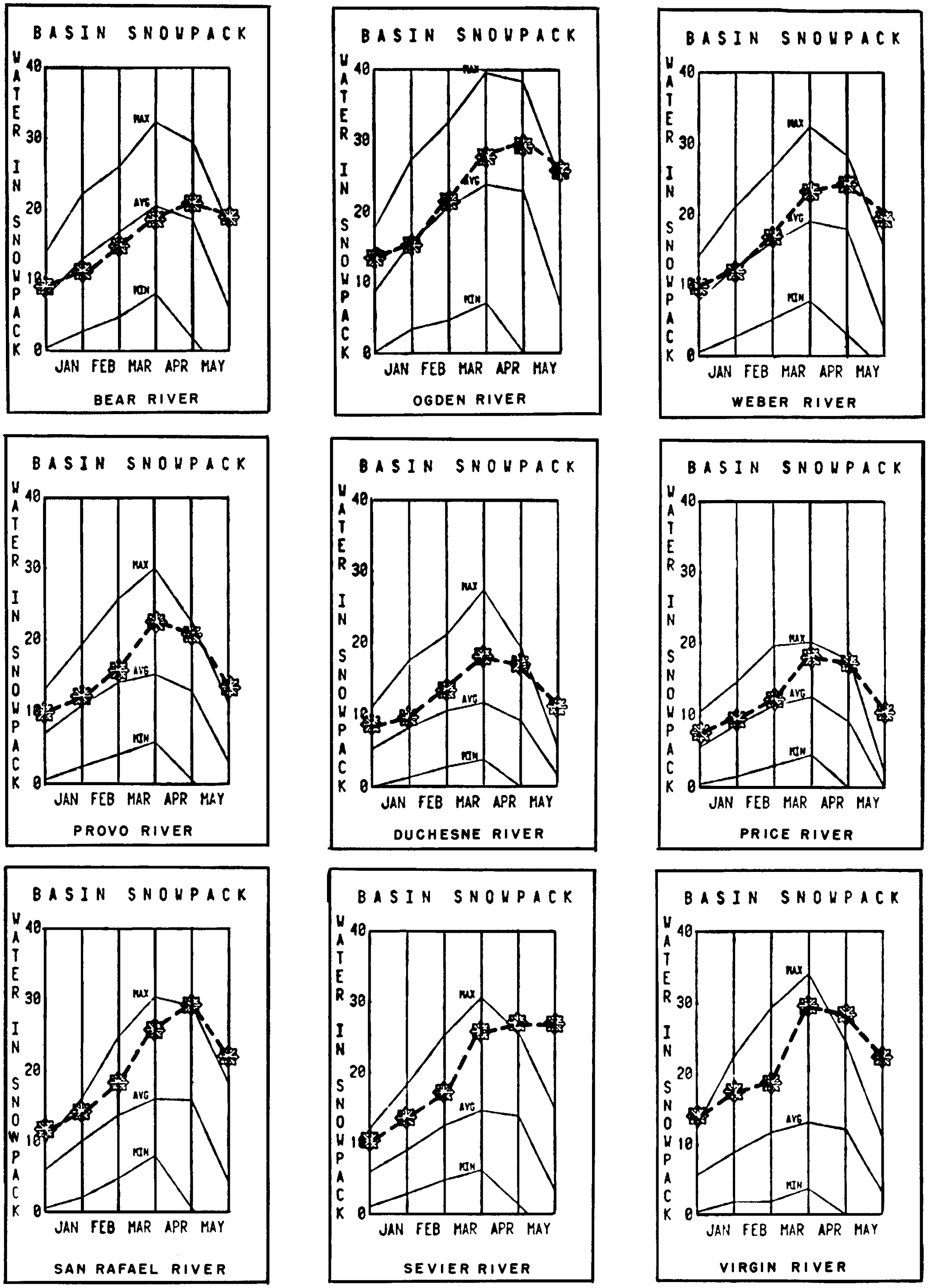
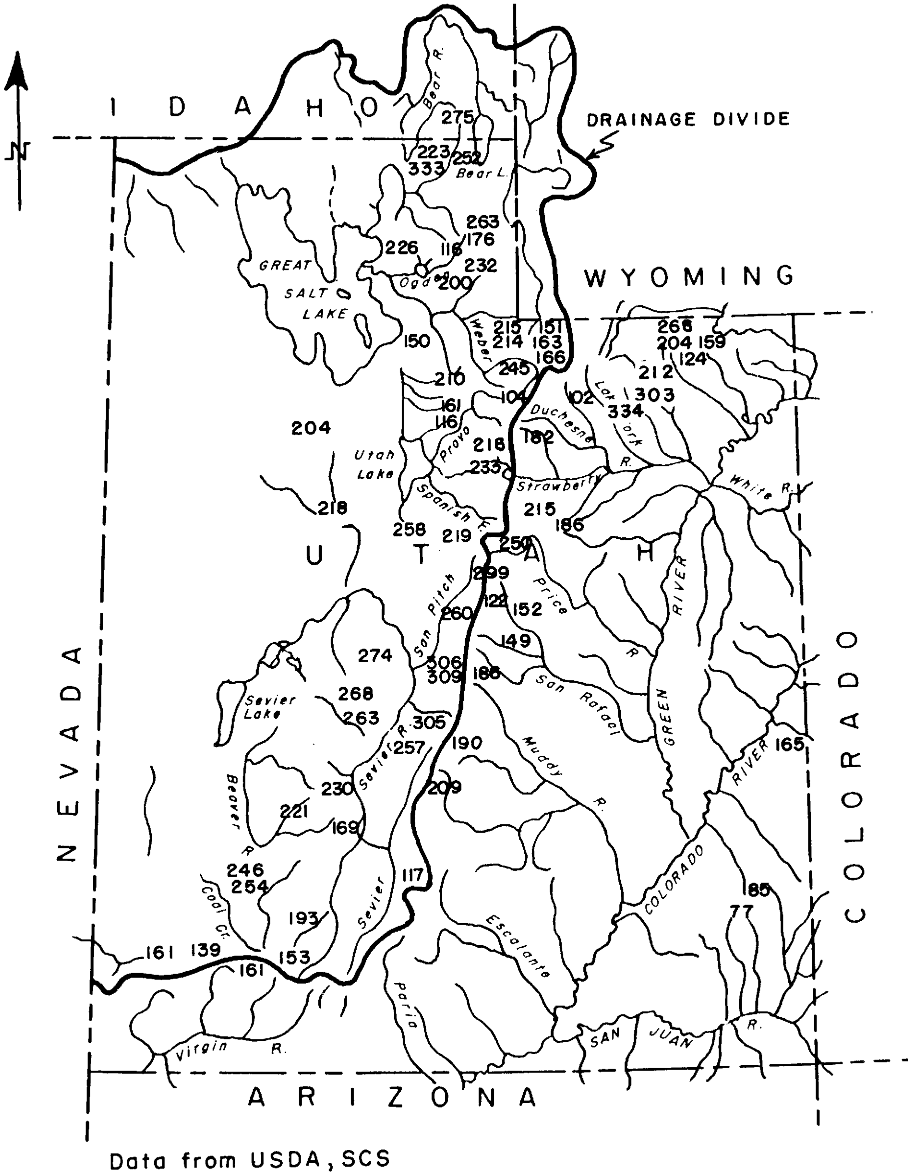
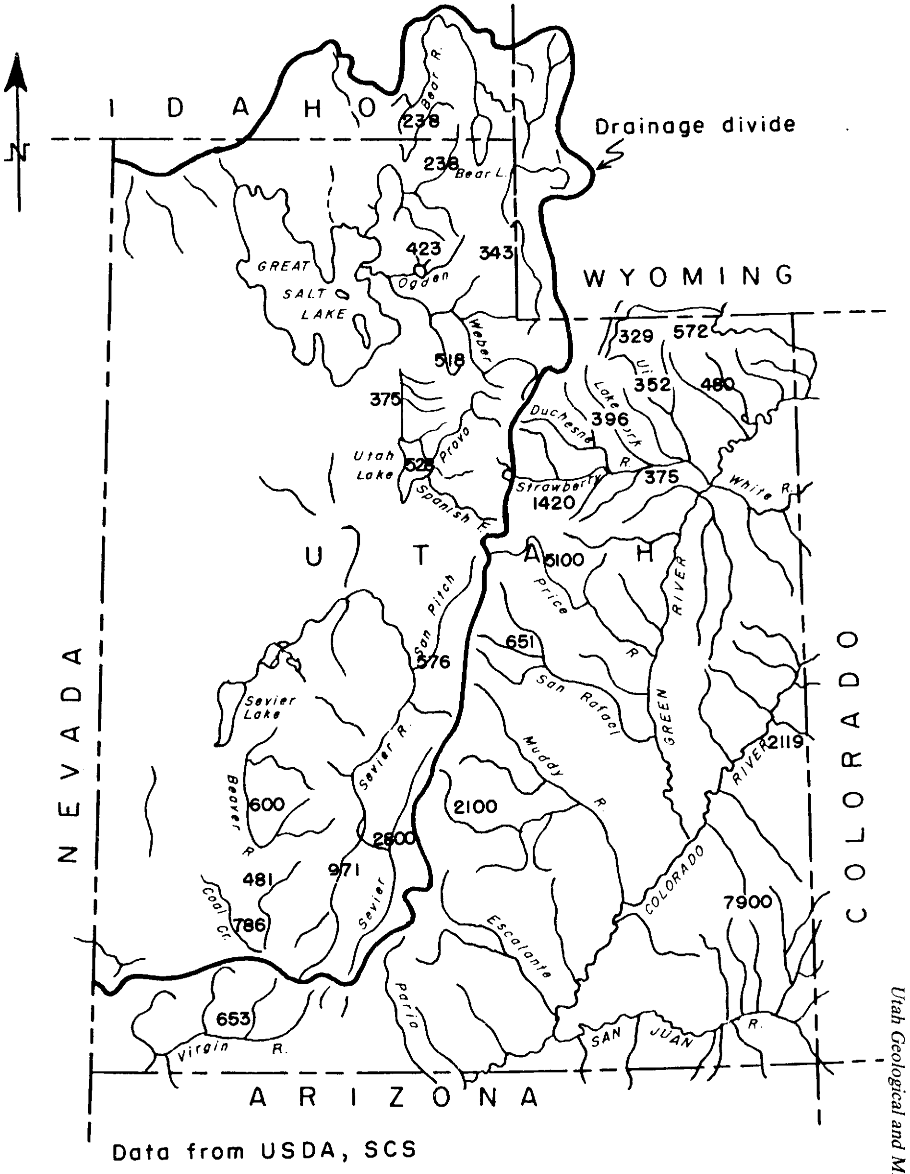


Figure 3. *1983 Winter-spring snowpack for Utah drainage basins.*



Data from USDA, SCS

Figure 4.
Percent of average precipitation for May, 1983 (using 30 year average, 1951-1980).



Data from USDA, SCS

Figure 5.
Water content in snow pack; percent of average for last week in May, 1983 (using 15 year average).

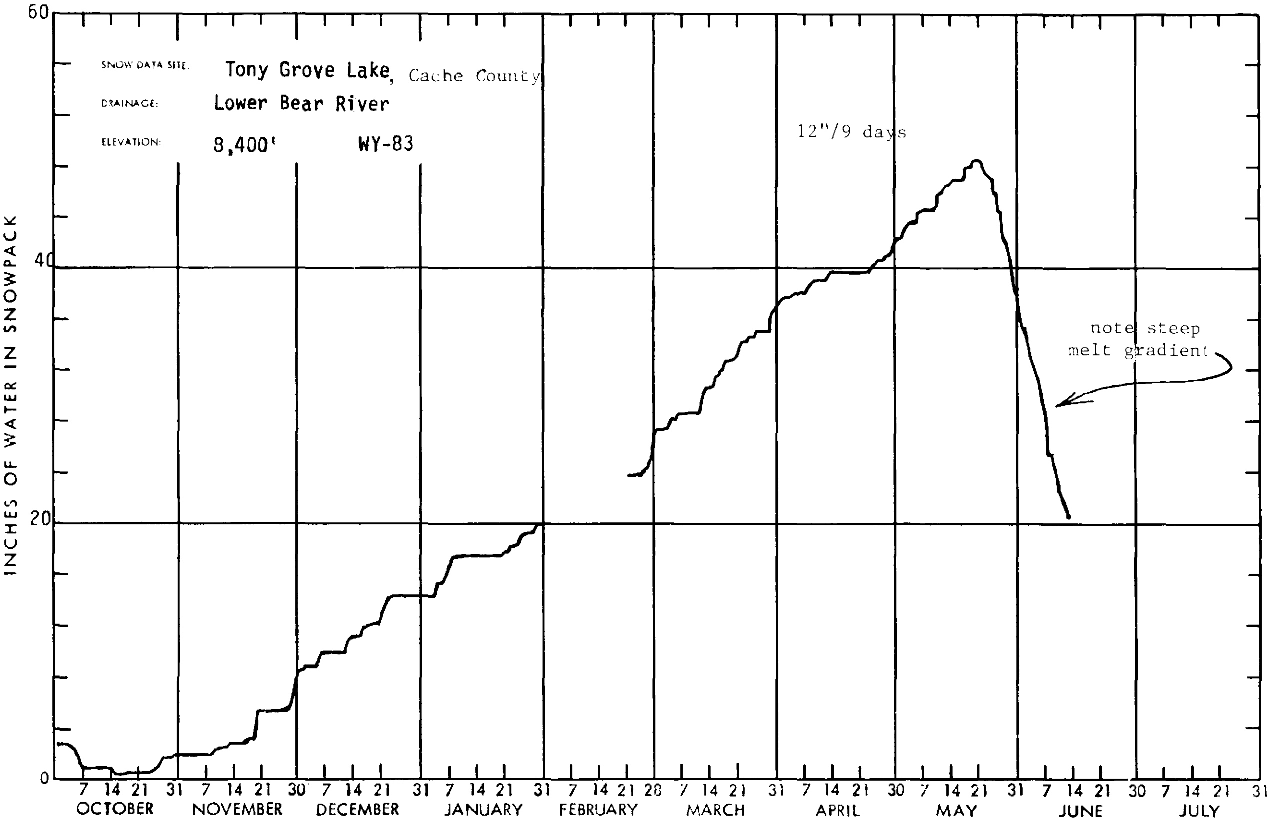


Figure 6a.
Daily snow pack moisture measurements for 8400 feet elevation Wasatch Front station.

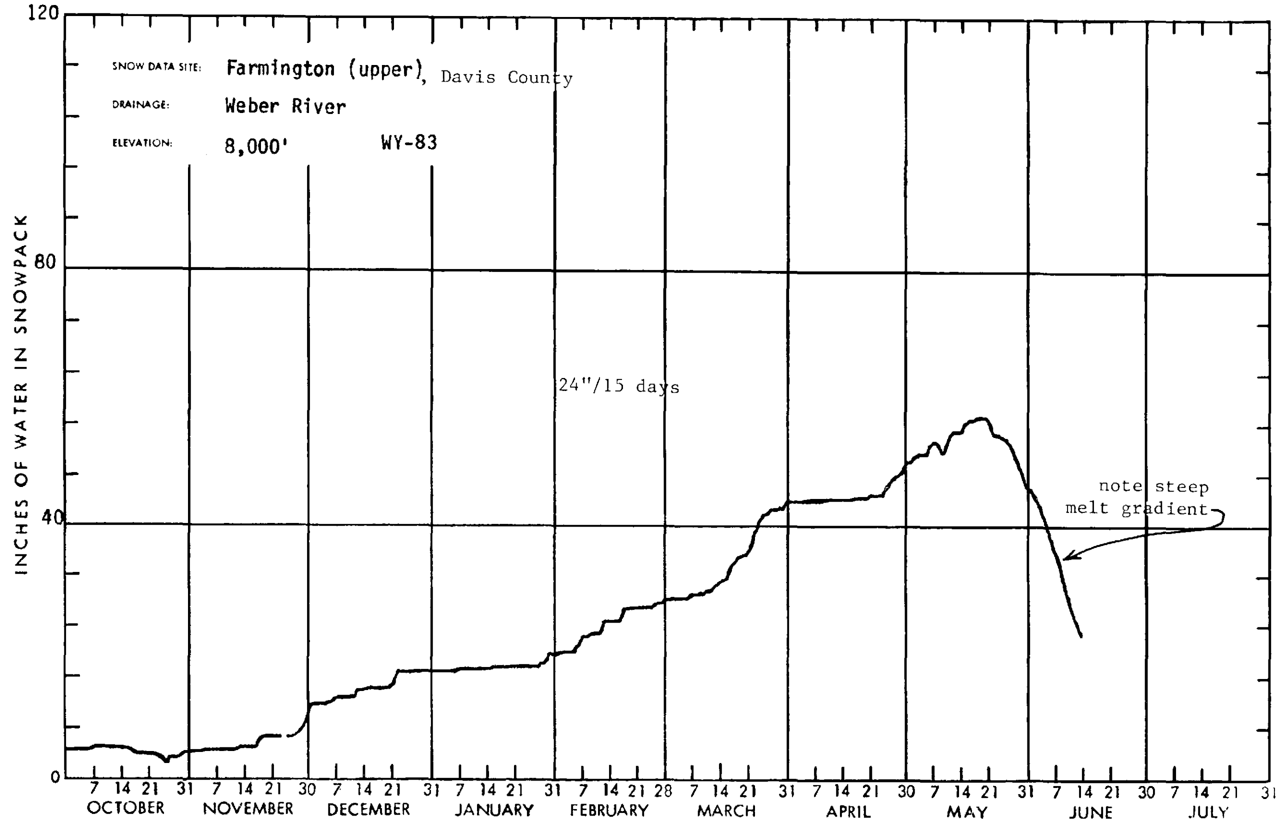


Figure 6b.
Daily snow pack moisture measurements for 8000 feet elevation Wasatch Front station.

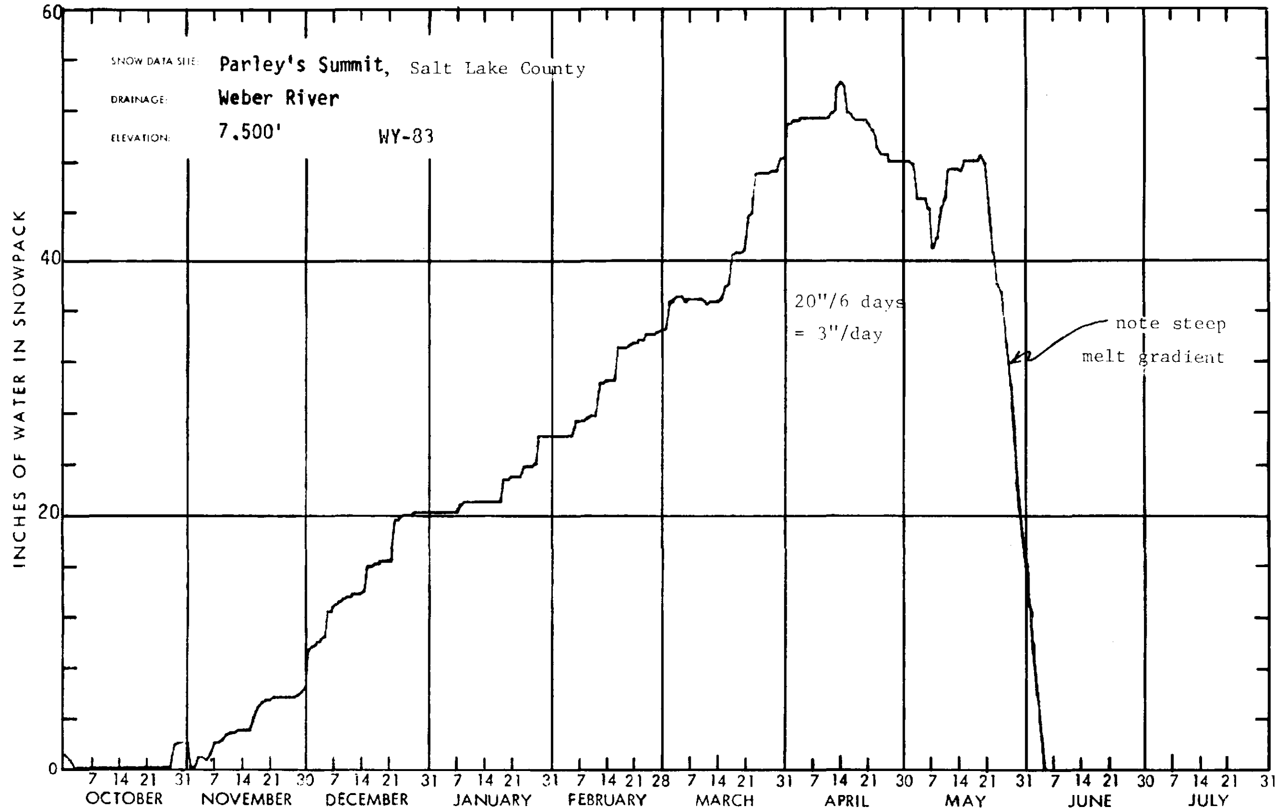


Figure 6c.
Daily snow pack moisture measurements for 7500 feet elevation Wasatch Front station.

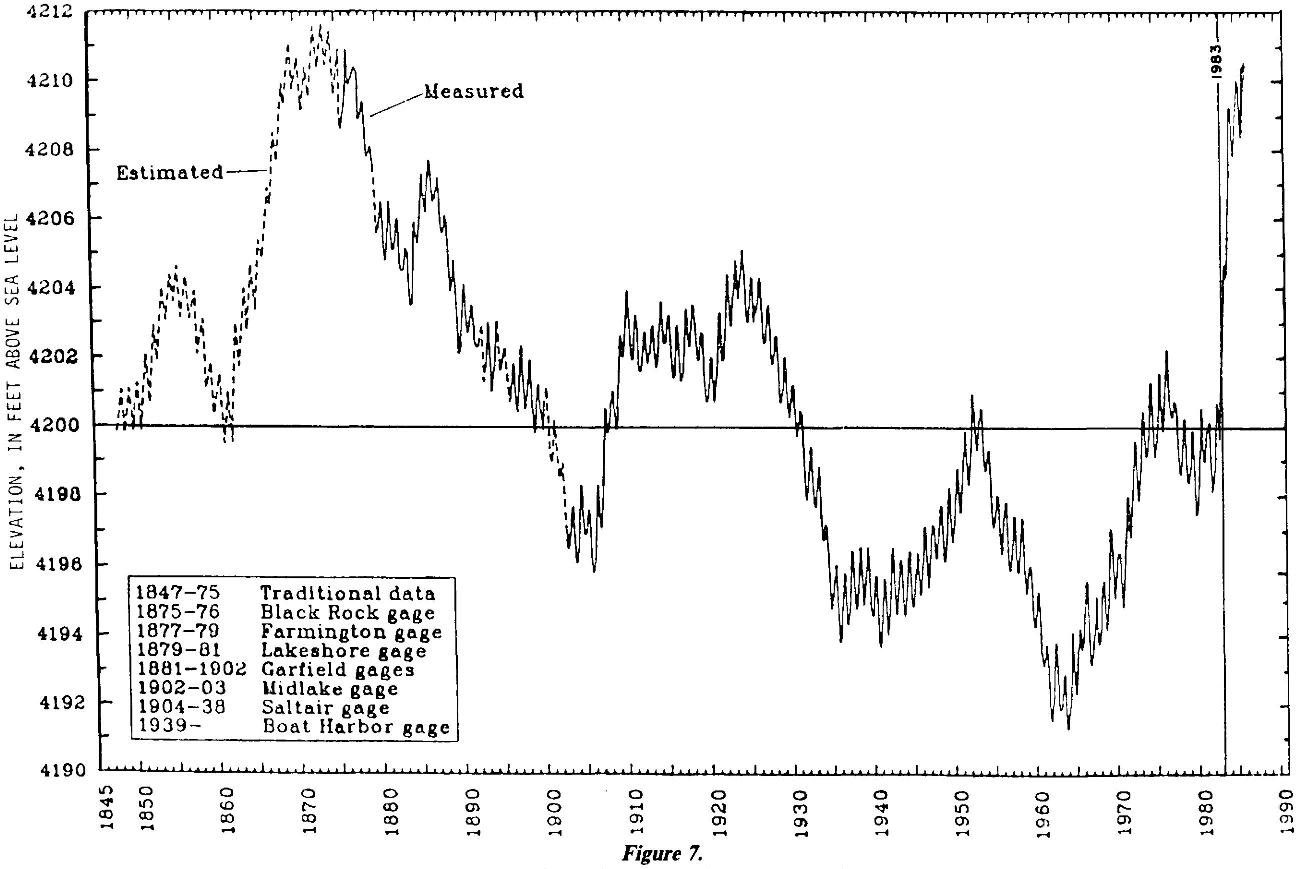


Figure 7.
Fluctuations of the level of Great Salt Lake.

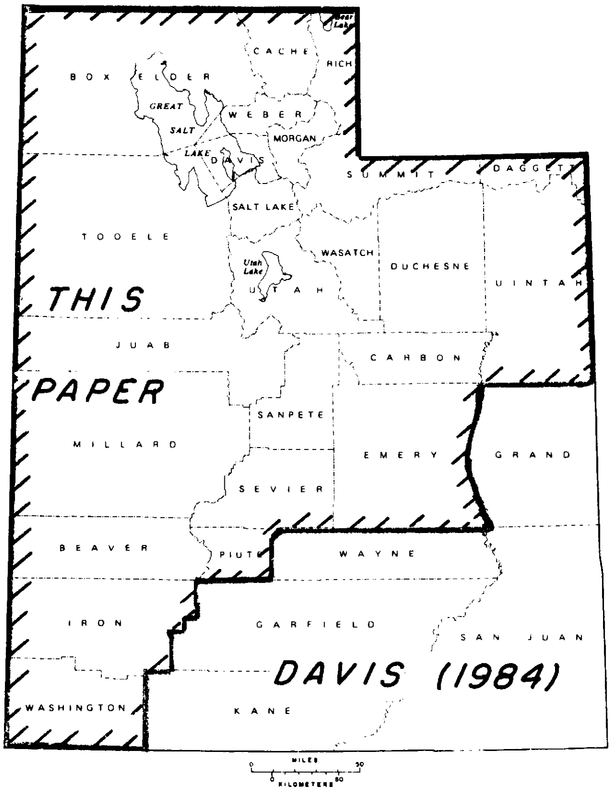


Figure 8. *The 24 county area of Utah covered in this paper.*

in playas in the Great Basin are on federal lands and in rather remote locations. Consequently, data and knowledge of their growth and characteristics are rather meager.

This paper is a compilation effort with only very limited field reconnaissance performed in its support. It is reliant upon the observations and recordings of very many individuals and agencies with a multitude of backgrounds. It should be kept in mind that the disclosures of conditions are likely to be inverse to the distance from paved roads and/or paths covered by aerial over-flights.

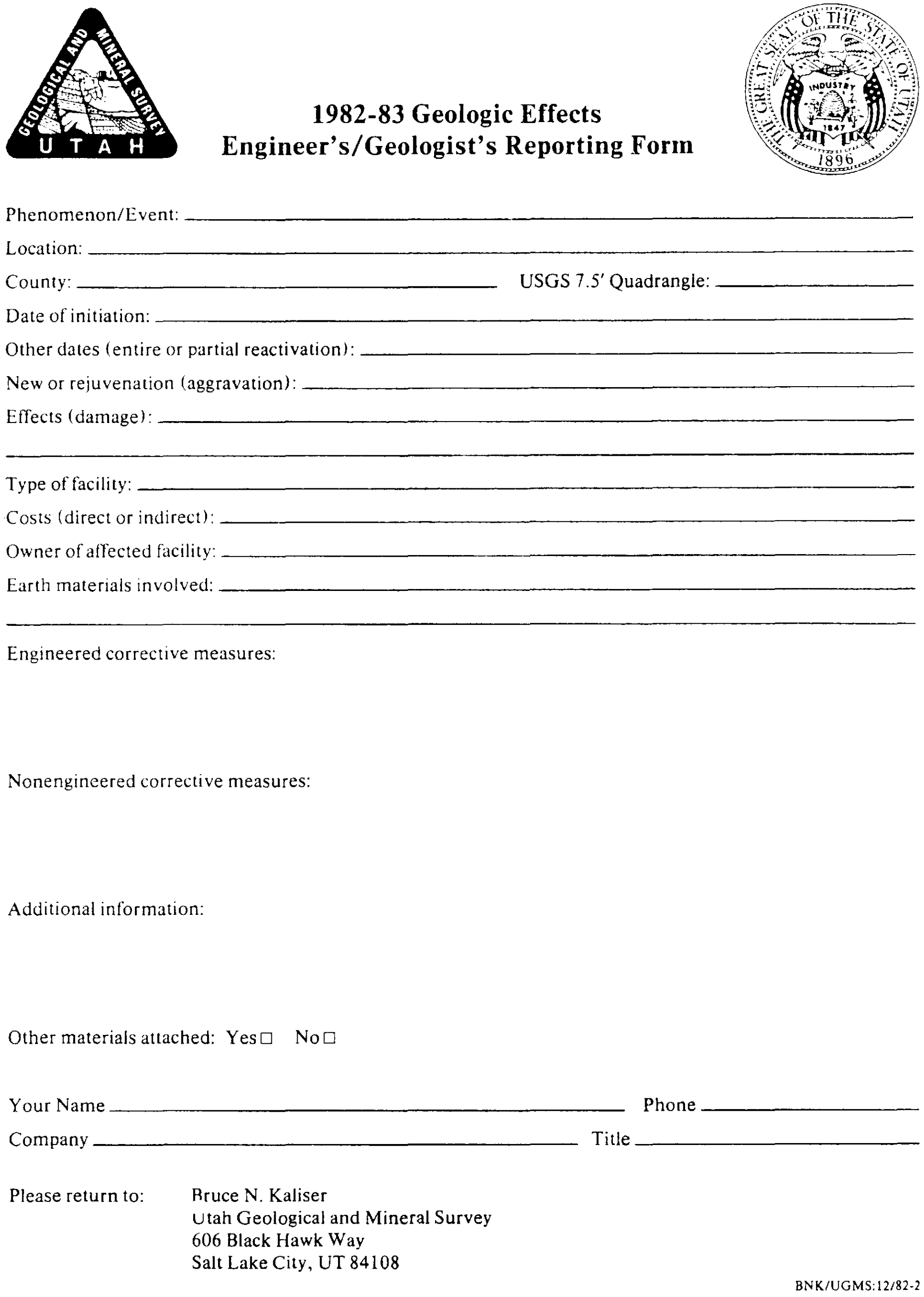
Ground-water levels were also extraordinarily high in mountain, benchland, and valley physiographic provinces. The elevation of water tables to shallow depths aggravated many municipal and rural public works problems by causing deterioration of pavements and by shallow subsurface infiltration into sewer lines.

The record high stream flows caused a massive amount of erosive activity, both in natural channels and beyond, when the channels could no longer confine the flows. Sediment was produced over large areas and, in turn, was deposited in massive volumes over diverse environments. The costs of controlling and repairing the damage were the highest in the history of the state. The fact that the excess moisture regime had not subsided with the end of the water year indicated that the geologic consequences of this cycle were not yet over.

The impact on the state was such that no sector of its economy was left untouched. Total damages statewide have been tabulated at $627,000,000 in a study for the U.S. Army Corps of Engineers (Stephens, 1984). Twenty-two counties in Utah were identified in a Presidential disaster declaration, including twelve political subdivisions. The authors believe that the actual damages may have exceeded $650,000,000. For the first time in U.S. history, a landslide was included in a Presidential disaster declaration - the Thistle landslide. Costs incurred as a result of the Thistle landslide alone were minimally estimated at $337,000,000 (Stephens, 1984).

Procedures

In order to collect the information documented in this paper, two questionnaires were distributed to federal and state government land agencies, geotechnical engineering firms, and water users throughout the state. The one form (figure 9) went to professionals such as civil, hydrologic and soils engineers in public service and private practice; and the other form (figure 10) was distributed to irrigation and canal companies in the belief that their systems were most vulnerable to geologic hazards; the infrastructure of water facilities in Utah is by far the most widespread, geographically, of any lifeline. Of approximately one thousand mailed forms, about one hundred damage reports and one hundred fifty no-damage



1982-83 Geologic Effects Engineer's/Geologist's Reporting Form

Phenomenon/Event:
Location:
County: USGS 7.5′ Quadrangle:
Date of initiation:
Other dates (entire or partial reactivation):
New or rejuvenation (aggravation):
Effects (damage):

Type of facility:
Costs (direct or indirect):
Owner of affected facility:
Earth materials involved:

Engineered corrective measures:

Nonengineered corrective measures:

Additional information:

Other materials attached: Yes☐ No☐

Your Name Phone
Company Title

Please return to: Bruce N. Kaliser
Utah Geological and Mineral Survey
606 Black Hawk Way
Salt Lake City, UT 84108

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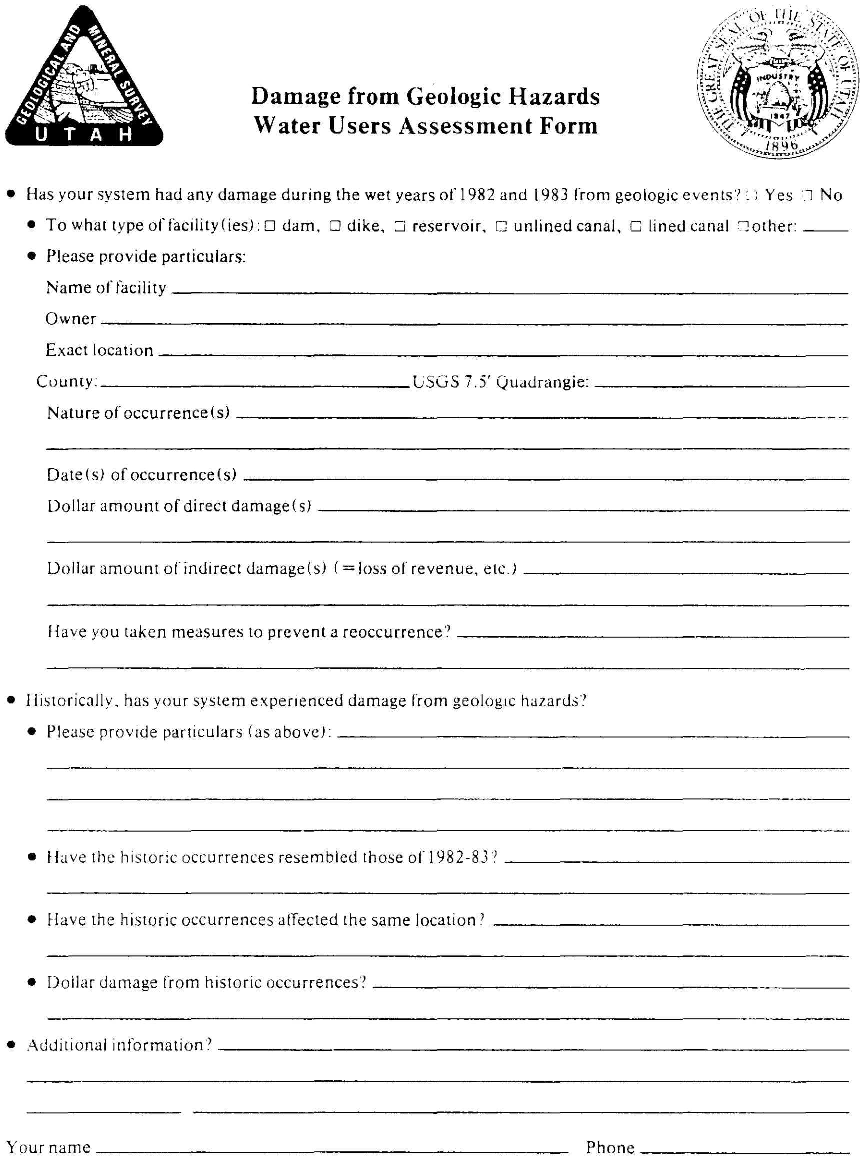
Figure 9. *Reporting form for geologic effects.*



Damage from Geologic Hazards Water Users Assessment Form

- Has your system had any damage during the wet years of 1982 and 1983 from geologic events? ☐ Yes ☐ No
  - To what type of facility(ies): ☐ dam, ☐ dike, ☐ reservoir, ☐ unlined canal, ☐ lined canal ☐other:
  - Please provide particulars:

Name of facility
Owner
Exact location
County: USGS 7.5′ Quadrangle:
Nature of occurrence(s)

Date(s) of occurrence(s)
Dollar amount of direct damage(s)

Dollar amount of indirect damage(s) (=loss of revenue, etc.)

Have you taken measures to prevent a reoccurrence?

- Historically, has your system experienced damage from geologic hazards?
  - Please provide particulars (as above):
  - Have the historic occurrences resembled those of 1982-83?
  - Have the historic occurrences affected the same location?
  - Dollar damage from historic occurrences?
- Additional information?

Your name Phone

Figure 10. *Reporting form for damage.*

reports were returned, resulting in about a 25% response. Information was also collected from thirty-eight sewer districts for analysis of infiltration due to rise of shallow groundwater levels.

Files of a large number of other agencies were perused for any relevant data. These agencies included, but were not limited to: State Office of Comprehensive Emergency Service, Department of Transportation, Department of Public Safety, Office of Dam Safety, U.S. Forest Service, U.S. Agricultural Stabilization and Conservation Service, U.S. Geological Survey, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and the State Division of Environmental Health. Trips were made to the various counties to acquire information from local field offices of federal and state agencies, county offices, city offices, and individuals.

No geologic field work was undertaken specifically for this compilation. However, during the course of the spring and summer of 1983, one of the authors of this report was heavily involved in emergency operations and recovery efforts, particularly in northern and central Utah, and also provided field assistance to state and local government entities with respect to particular geologic events and hazards so that personal knowledge of much that happened is included in this compilation. The primary author devised the procedure for undertaking this documentation effort, supervised the compilation work and prepared this report. William B. Case, Utah Geological and Mineral Survey geologist, undertook the sewage district infiltration analysis which will appear as a related publication. Cathy Nanz extracted data from agencies' files and acquired information from visits to county offices during the months of February through June, 1983. Genevieve Atwood, State Geologist, and Don Mabey, Deputy Director, have given continuous encouragement towards this paper.

Wet Periods

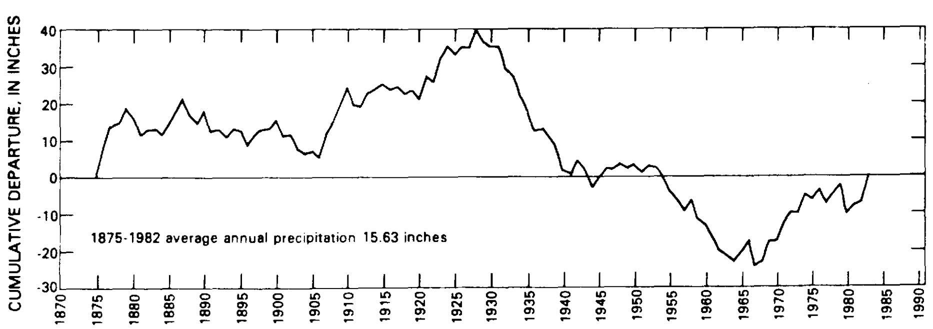
It has not been generally recognized that the period prior to 1983 was also extraordinarily high in moisture content (figure 1). The 1982 water year (October 1, 1981 through September 30, 1982), in fact, was the wettest year of record in the Salt Lake Valley. Total precipitation at the Salt Lake Airport was 25.15 inches, 167% of normal. This exceeded the second wettest year, 1973, by 2.89 inches.

From the beginning of the 1982 water year (October 1981) through the spring of 1983 (21-month period), four high monthly precipitation records were established at the Salt Lake Airport: October 1981; July 1982; September 1982; and March 1983. The September 1982 record was most extraordinary, setting an all-time high monthly precipitation of 8 to 10 inches of rain at valley elevations and more at higher elevations. Snowpack, too, was a record with 700 inches accumulated at Alta station in Salt Lake County for the period November 1981 through April 1982.

The effects of the 1982 precipitation can be especially appreciated when the cumulative departure curve is viewed for a greater than 100-year period for Salt Lake City (figure 11). Twenty-eight years of negative curve existed immediately prior to 1982.

A good indication of the effects of the excessive rainfall and snowmelt on the water availability is afforded by comparing the minimum daily stream flows (i.e., base flows) of mountain drainages. Table 1 does this for six Salt Lake County streams and examines the top six years of record for the period 1921 through 1983. The next highest year of minimum daily flow was only 78% of the 1983 figure. Second highest was only 49%.

Julander and Hawkins (1985) used a frequency analysis and determined that return periods for average stream flows in Davis



from Arnow, 1984

Figure 11. Cumulative departure from average annual precipitation at Salt Lake City, 1875-1982.

County for the months of October, November, and December of 1982 ranged between 60 and 2,000 years for various drainages. It also can be assumed from this data that ground-water reservoirs and water tables were high early in the 1983 water year.

Table 1

Comparison of total flows of six Salt Lake County streams for top six years of record (1921 through 1983).*

Year	Minimum Daily Flow (cfs)	% of 1983	Maximum Daily Flow (cfs)	Avg. Daily Flow (cfs)	Yearly Flow (cfs)
1983	109.6		2219	420	153,275
1921	85.6	78	1817	326	118,885
1982	53.7	49	1326	318	116,213
1975	68.6	63	1639	303	110,554
1952	53.0	48	1378	302	110,342
1922	66.0	60	1549	293	107,039

**City Creek, Emigration, Parleys, Big Cottonwood, Little Canyon, Mill Creek*
Data from Salt Lake City Public Utilities Department

GROUND-WATER (PIEZOMETRIC) LEVEL CHANGES THROUGHOUT UTAH

Geologic consequences of the wet year are manifested most significantly in the increase that occurred in piezometric levels and unconfined water tables over much of the state. This effect, more than any other, contributed to the mass movements experienced so commonly throughout diverse geologic terrain in 1983.

Data for ground-water level changes for geographic areas and/or political subdivisions throughout the state are provided in table 2. There are three columns provided so that one can trace the change in the water table in a given community over a three-year period, from left to right. A plus (+) preceding the number indicates that the water table has risen; a minus (-) indicates that it has fallen. All values are in feet. A plus (+) following the number denotes that the actual value exceeds the number by an additional fraction of a foot; for example, +2+ means that the water table has risen more than 2 feet during the period of time (1, 2 or 3 years) indicated by the heading of the column (3/81-3/82, 3/81-3/83, or 3/81-3/84). Data are derived from observation wells maintained by the U.S. Geological Survey.

Table 2 shows that, with few exceptions, the ground-water levels have increased in communities throughout the state in both 1982 and 1983. The values, in parentheses in the second and third columns, express the changes for the last twelve months in the period of the column heading. These figures enable one to track the magnitude of the changes for the twelve-month period more easily over the 3-year period.

TABLE 2: Ground water level changes, in feet, for 12, 24, & 36 month periods*

	3/81-3/82	3/81-3/83		3/81-3/84	
Cache County:					
Clarkston	+2	+2**	(0)**	0	(-2)**
Newton	0	+3	(3)	+4	(1)
Mendon	0	+1	(1)	+2	(1)
Wellsville	0	+2	(1)	+3	(1)
Richmond	+5	+7	(+2)	+8	(1)
Smithfield	-2	0	(-2)	+1	(1)
Logan	-2	+3	(-5)	+5	(2)
Hyrum	0	+5	(5)	+5	(0)
Paradise	-1	-2	(-1)	-1	(1)
Box Elder County:					
Willard	-2	+5	(-7)	+7	(2)
Snowville	+2	+3	(1)	+8	(5)
Weber County:					
Plain City	-2	+1	(3)	0	(-1)
Hooper	-3	-2	(1)	0	(2)
North Ogden	-6	-2	(4)	+0	(11)
Ogden	-3	-1	(2)	+3	(4)
Roy	-6	-5	(1)	+1	(6)
Davis County:					
Sunset	-10	-11	(-1)	0	(11)
Clearfield	-9	-11	(-2)	-1	(10)
Syracuse	-3	-2	(1)	+1	(3)
Layton	-5	-4	(1)	+1	(5)
Farmington	-3	-3	(0)	+5	(8)
Centerville	+1	+1	(0)	+7	(6)
Bountiful	-1	+1	(2)	+7	(6)
Beaver County:					
Milford	-1	-2	(-1)	+5	(7)
Minersville	-1	-1	(0)	+4	(5)
Iron County:					
Paragonah	-1	-1	(0)	+13	(14)
Parowan	-1	0	(1)	+22	(22)
Enoch	0	-2	(-2)	0	(2)
Cedar City	-1	+4	(5)	+15	(19)
Hamilton Fort	-3	+2	(5)	+7	(9)
Kanarraville	-4	-3	(1)	0	(3)
Beryl Junction	-5	-5	(0)	-4	(1)
Utah County:					
American Fork					
Water Table Aquifer:	0	+1	(1)	+3	(2)
Shallow Artesian Pleistocene:	-2	+3	(5)	+5	(2)
Deep Artesian Pleistocene:	-7	+8	(15)	+16	(8)
Tertiary Artesian:	-6	+6	(12)	+14	(8)
Spanish Fork					
Water Table Aquifer:	N.D.	N.D.		N.D.	
Shallow Artesian Pleistocene:	N.D.	+3		+6	(3)
Deep Artesian Pleistocene:	-1	+5	(6)	+12	(7)
Tertiary Artesian:	-1	+7	(8)	+14	(7)
Quaternary or Tertiary Artesian:	+5	+11			
Utah County:					
Lehi					
Water Table Aquifer:	-2	-1	(1)	-1	(0)
Shallow Artesian Pleistocene:	-2	+3	(5)	+4	(1)
Deep Artesian Pleistocene:	-3	+5	(8)	+10	(5)
Tertiary Artesian:	-6	+6		+11	
Quaternary or Tertiary Artesian:	+6	+11			
Orem					
Water Table Aquifer:	N.D.	+2		0	
Deep Pleistocene:	-3	+4		+6	
Payson					
Water Table Aquifer:	0	+4		+7	
Deep Pleistocene:	N.D.	N.D.		+13	
Santaquin					
Water Table Aquifer:	-8	+6		+15	
Deep Pleistocene:	N.D.	N.D.		N.D.	
Goshen					
Water Table Aquifer:	-2	-1		+2	
Deep Pleistocene:	N.D.	N.D.		N.D.	
Alpine					
Shallow Artesian Pleistocene:	N.D.	N.D.		N.D.	
Deep Artesian Pleistocene:	-7	+15		+30	
Pleasant Grove					
Shallow Artesian Pleistocene:	-3	+2		+2	
Deep Artesian Pleistocene:	-5	+8		+11	
Provo					
Shallow Artesian Pleistocene:	-3	+1		+1	
Deep Artesian Pleistocene:	-2	+4		+4	
Salem					
Shallow Artesian Pleistocene:	+1	+6		+10	
Deep Artesian Pleistocene:	-2	+12		+25	
Cedar Fort	-6	-4	(2)	+8	(12)
Fairfield	-3	-1	(21)	+7	(8)
Washington County:					
Enterprise	-6	+4	(10)	0	(-4)
Tooele County:					
Lake Point	-1	+1	(2)	+6	(5)
Erda	-2	0	(2)	+7	(7)
Tooele	-2	-5	(-3)	+8	(5)
Grantsville	-1	+3	(4)	+8	(5)
Millard County:					
Leamington	+2	+2	(0)	+6	(4)
Delta	0	+2	(2)	+4	(2)
Holden	-4	-6	(-2)	+14	(20)
Meadow	-5	-2	(3)	+14	(16)
Kanosh					

Salt Lake County: (February, not March)	3/81-3/82	3/81-3/83		3/81-3/84	
Salt Lake City	0	+2	(2)	+4	(2)
Murray	+1	+6	(5)	+8	(2)
Sandy	-1	+1	(2)	+4	(3)
Draper	-2	0	(2)	+4	(4)
Herriman	-1	0	(1)	+8	(8)
Kearns	-4	-1	(3)	+1	(2)
Magna	-1	0	(1)	+2	(2)
Sanpete County:					
Fairview	-1	0	(1)	0	(0)
Spring City	-3	0	(3)	+5	(5)
Manti	-5	-3	(2)	-1	(2)
Moroni	+1	+3	(2)	+2	(-1)
Fountain Green	+1	+2	(1)	+2	(0)
Juab County:					
Mona	-2	+2	(4)	+10	(8)
Nephi	-7	0	(7)	+12	(12)
Levan	-7	-3	(4)	+25	(28)

*Data acquired from U.S. Geological Survey files of shallow observation wells (unless otherwise indicated in subheading).

**Values in parentheses represent changes over only the last twelve months of two- or three-year period.

In Cache County, the rate of ground-water-level change slowed between March 1983 and March 1984, but the upward trend continued. In Weber, Davis, Beaver, Iron, Tooele, Millard, Juab, and western Utah Counties, however, not only did the upward trend continue but it did so at an accelerated rate. Data has been provided for several aquifers in Utah County's urban corridor. It is interesting to note that in Lehi, in eastern Utah County, each confined aquifer demonstrated a diminishing upward change from March 1983 to March 1984 versus March 1982 to March 1983. The same was true in American Fork with the exception of the shallow, unconfined aquifer.

LANDSLIDING

Landsliding is the phenomenon of 1983 that gained much notoriety. Steep slopes in the Wasatch Mountains and the Wasatch Plateau have always been prone to landsliding, but slope failures of all types occurred in 1983 on a scale unprecedented in the recorded history of Utah.

Historic Perspective

A search of archival materials in various depositories throughout the state has yielded relatively little information, on the whole, with respect to landslide events since settlement of Utah in 1847. In addition to a literature search, a number of individuals have been interviewed, particularly to determine whether or not slope failures have occurred historically where 1983 events occurred. Lack of data related to previous landslide activity during earlier wet years most likely is because of indifference and/or failure to record data rather than the absence of failures. Observations of pre-1983 landslides is suggestive of youthful appearance, probably related to landslide activity associated with very wet years that occurred during the past 135+ years.

Since 1966, the senior author has investigated landslides in Utah. In a normal year, landslide investigations have numbered less than ten. The senior author believes that it is likely that the year with the greatest number of landslides prior to 1983 may likely have been 1952; however, there is very little documentation of 1952 events. Slope failures have generally evoked little attention and little interest in Utah prior to 1983. There are a number of reasons for this. Landslides that occurred in inaccessible or relatively remote locations were not reported. Lifeline corridors such as for water, gas, oil, and electric transmission, which now cross vast stretches of terrain, were far less common in prior years. All-terrain vehicles and availability of reconnaissance aircraft for getting into and flying over roadless country were nonexistent or rare, and during wet periods individuals likely stayed away from difficult terrain. If a landslide had little gross effect upon a community, it is likely that it went unreported. And finally, geologists, particularly engineering and environmental geologists, were few in number and none were specifically dispatched to investigate landslide events until 1966. Between 1964 and 1981, twenty-five occurrences of earth and rock movement were generally reported in the Utah Geological and Mineral Survey Quarterly Review (table 3).

TABLE 3: Events reported between 1964 and 1981 in the Utah Geological and Mineral Survey Quarterly Review (1964-1975) and Survey Notes (1976-1981)

May 24, 1967:	Empire Canyon, Park City, Summit County, rock slump. Damage to road, 7,000-volt power lines, telephone line, and mine assay office, garage and car.
May 12, 1968:	Echo Canyon, Summit County, rock slump. Damage to 16 transcontinental telephone lines and Interstate 80.
July 10, 1968:	Pole Canyon (Echo Canyon tributary), Summit County, flow. Damage to Interstate 80. Cloudburst triggered.
February, 1969:	Reporting of weathered rock sliding on north side of Pine View Reservoir, Weber County.
May 12, 1969:	Empire Canyon, Park City, Summit County, rock slide. Damming of Empire Creek, creation of a 30-foot deep reservoir, inundation of power station.
May, 1969:	Bench south of Weber Canyon, Davis County, mudflow from fill failure. Damage to Weber Basin Civilian Conservation Corps Center.
June 6, 1969:	Uintah, Weber County, landslide. Damage to home.
April, 1970:	Mountain Green, Morgan County, slumps. Damage to home.
August 21, 1971:	Minersville, Beaver County, debris flow. Damage largely prevented by debris basin; some damage to school, streets, fences, irrigation system, stock grounds and homes.
March 1972:	Ogden, Weber County, Valley Drive, reactivation of slumps.
August, 1972:	Near Coalville, Summit County, rock slide. Damage to Interstate 80.
December, 1972:	Near Coalville, Summit County, fill embankment slide. Damage to Interstate 80.
May, 1974:	Manti, Sanpete County, landslide rejuvenation and debris flows. Damage to city aqueduct, irrigation system.
October 4, 1974:	Riverdale, Weber County landslide. Damage to home and several vehicles.
May, 1975:	Further Manti landslide rejuvenation. Threatened to block Manti Creek.
April 8, 1977:	Salt Lake City Avenue, slump in cut zone. Damage to new foundation for school.
August 13, 1978:	Willard, Box Elder County, debris flow. Damage to Highway 89, Ogden-Brigham City Canal, and three homes.
April 16, 1979:	Smelter Creek, Uintah County Damage to road, irrigation system.
April, 1979:	Deer Creek Reservoir vicinity, Wasatch County, slumps. Damage to railroad embankment.
April, 1979:	Provo, Utah County, slumps. Damage to residential lots.
August 18, 1979:	Ogden, Weber County, debris flood. Damge to Pineview Canal and homes.
April, 1980:	Carbon County, slump. Damage to U.S. Highway 6.

July 6, 1980:	Ogden, Weber County, landslide and earth flow. Damage to seven cars on apartment house parking lot and cemetary lots.
May 17 & 19, 1981:	Uintah, Weber County, landslide and earthflow. Damage to railroad grade, train (and homes through river diversion).
May & June, 1981:	Memory Grove, Salt Lake City, fill failures. Damage to park and residential lot.

Landslides in the 1983 wet cycle have occurred both at localities where there have been historic earth movements and at new localities. It is quite interesting to note that, at many locations where landslides have occurred in recent years, there has not been 1983 movement. It will not be possible to establish whether or not there has been historic activity at many locations of 1983 events. However, it is possible that creep, or slow down-slope deformation, may have occurred episodically in the past or that smaller instantaneous slope failures may have occurred, say in 1952, and were not reported.

Slope Movement Nomenclature

The classification of slope movements devised by Varnes (1978) has been used in this paper. This scheme gives primary consideration to the type of movement and secondary consideration to the type of material involved.

Slope failures may involve only soil*, only in-place bedrock, or a combination of both. When comprised of soil, the landslide may consist entirely of old landslide deposits or entirely of newly displaced soil deposits. The incorporated soil deposits may consist of clay, silt, sand, gravel, cobbles, boulders, and organic matter in any proportion. Rate of movement may be very fast or, conversely, hardly perceptible -- whether in soil or rock materials. The rate may change slowly or rapidly over short or long durations of time. A landslide can also consist largely or entirely of old or new man-placed fill material. Failure can involve a distinct earth mass moving coherently or less well-defined masses, and the depth to the failure surface or failure zone may be uniform or irregular.

Debris flows (mudflows, debris avalanches) are in the "family" of slope movements, but not the "genus." An understanding of debris flows and debris floods is critical to a comprehension of the consequences of the 1983 wet year.

A **debris flow** is a dense mixture of rock fragments, gravel, sand, mud, organic matter, and water. It possesses a combination of density and strength and it supports inclusions (boulders) of higher density than water both during transport and when the mass comes to rest. This ability arises from the fact that non- Newtonian fluid motion prevails. There is both velocity- dependent strength (i.e., matrix viscosity) and velocity-independent strength (i.e., shearing resistance of the mass).

A **debris flood** does not have static shearing resistance; therefore, transport of inclusions is possible only because of the strength provided by the motion of the fluid. When the fluid velocity goes to zero, the strength also goes to zero and the supporting capability of the mass is lost. Inclusions of higher density than the fluid (water) subsequently sink according to Stokes Law at rates that are dependent on the viscosity of the fluid.

A **mudflow**, according to Varnes (1978), is a rapidly moving, wet earth flow containing >50% particles smaller than 2mm; a **debris flow** is the same but with >50% consisting of particles coarser than 2mm in size. It is important to recognize that both "debris flow" and "mudflow" have been commonly used by some in the literature in a generic sense to refer to flowing slurries without regard for proportional content of particles coarser than coarse sand size (2mm).

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*engineering soil, i.e., any unconsolidated earth material, with or without organics.

TYPE OF PHENOMENON		EVENT OR MECHANISM	LOCATION	USAGE IN THIS PAPER	USAGE ELSEWHERE			
Floods		Clear water floods	Floodplains & drainage channels incl. distributary channels on fans	Clear water flood				
		Mud floods, debris-laden flood, super charged floods	Drainage channels & alluvial fans with runout occ. as far as valley floors	Debris flood	Mudflow			
Slope Movements		Wet, non-cohesive flows		Debris flow, Mudflow		Mudslide	Soil slip-debris flow	Debris aval-anche *
		Wet, cohesive flows	Slopes (hillside, mountainous benchland, river bluffs)	Earth flow				
	Landsides	Wet slides (may partly or wholly change state to flows)		Debris slide, Earth slide/slump				
		Dry slides; commonly insufficient moisture to generate flows		Debris slump, Rock slump, Rock slide				
		Falls		Rock fall, Earth fall				

* Commonly dry to moist; also termed "Rock avalanche", "Rock fragment flow"

Table 4. *Summary of slope movements.*

Types of Slope Movements

Topples and lateral spreads (Varnes, 1978) are unknown amongst the 1983 events.

Falls occurred to a minor extent. Mobilization of soil material on very steep slopes, normally highway cuts, detached boulders in a colluvial soil matrix. The boulders are then able to free fall, normally short distances. This phenomenon was uncommon, but because it deposited boulders on roads, it was conspicuous and hazardous. To the writer's knowledge, only rock falls occurred, not debris or earth falls.

Slides, involving shear displacement, were of both the rotational and translational character. With the preponderance of shallow debris slides on steep mountainsides, translational movements were by far the more abundant in frequency of occurrence. When examined in detail, many of the debris slides actually involved a combination of translational and rotational modes of failure (figures 12a&b). The governing factor in these instances appears to be the location of the perched ground-water zone or a zone of excess pore-water pressure with respect to the other subsurface conditions, such as weathering profile, A and B soil horizon type, thickness, inclination, bedrock structure, foliation, weathered zone transition, and shear strength of the materials in absolute and relative terms. Ground-surface morphology and slope angle likely also play a role. Very soon after failure of shallow debris slides, evidence is obscured, and it is not easy to identify the failure mechanism(s).

Bedrock slides appear to have been relatively scarce events. Again, however, close inspection can reveal that a slide consists almost entirely of bedrock with only a thin veneer of soil material carried along. The bedrock may have such an oxidized appearance that from any distance it resembles soil. Soil may have washed down over the exposed rock in a subsequent rain or snowmelt event, thus masking the bedrock character of the slide.

Transition from bedrock to debris slides on steep mountainside terrain was not uncommon. This transition is the result of the existence of adversely oriented zones within weathering profiles, particularly of adversely oriented zones within weathering profiles developed on the Farmington Canyon Complex metamorphics. The Farmington Canyon Complex is commonly considerably weathered so that a coarse, granular residual or colluvial soil remains. In some cases, however, the rock is somewhat intact with either fracture zones, joint sets and/or weathered veins and veinletes permitting detachment along such surfaces of weakness. Where bedrock is more integrally resistant there is an irregular surface left exposed after sliding. Where bedrock is less resistant, relatively good translational or rotational surfaces may be left.

The term debris slide is applied in this paper to slides usually involving only a thin prism of relatively coarse, granular soil with pure rotational movement (common), to combinations of translational and rotational movement (relatively common), and those with pure translational movement (very common).

Earth slides, predominantly of the earth slump type, also were somewhat frequent in occurrence, particularly at low elevations

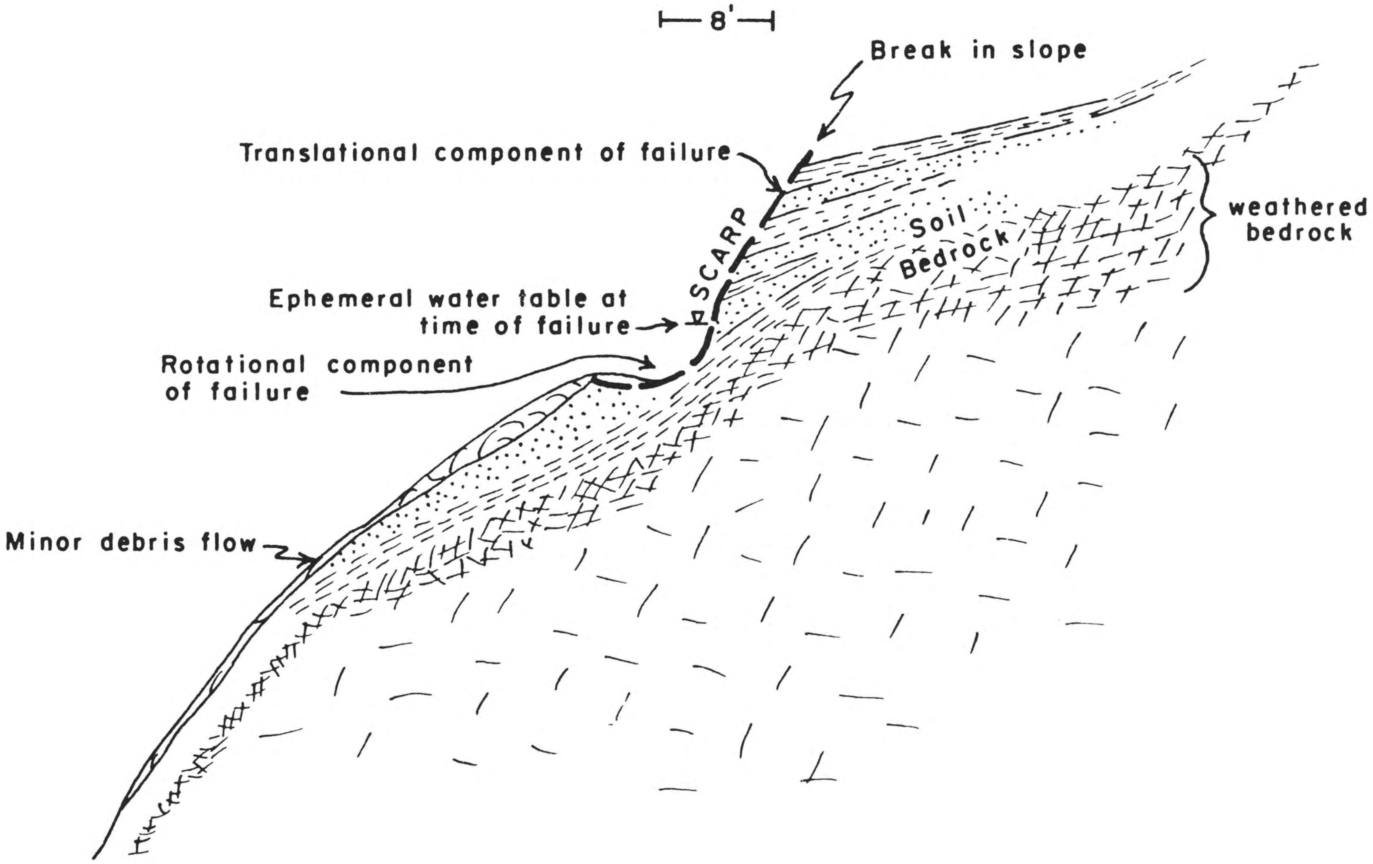


Figure 12.
a. Schematic diagram of typical mountainland debris slide.
b. Photograph of debris slides on Wasatch Plateau.

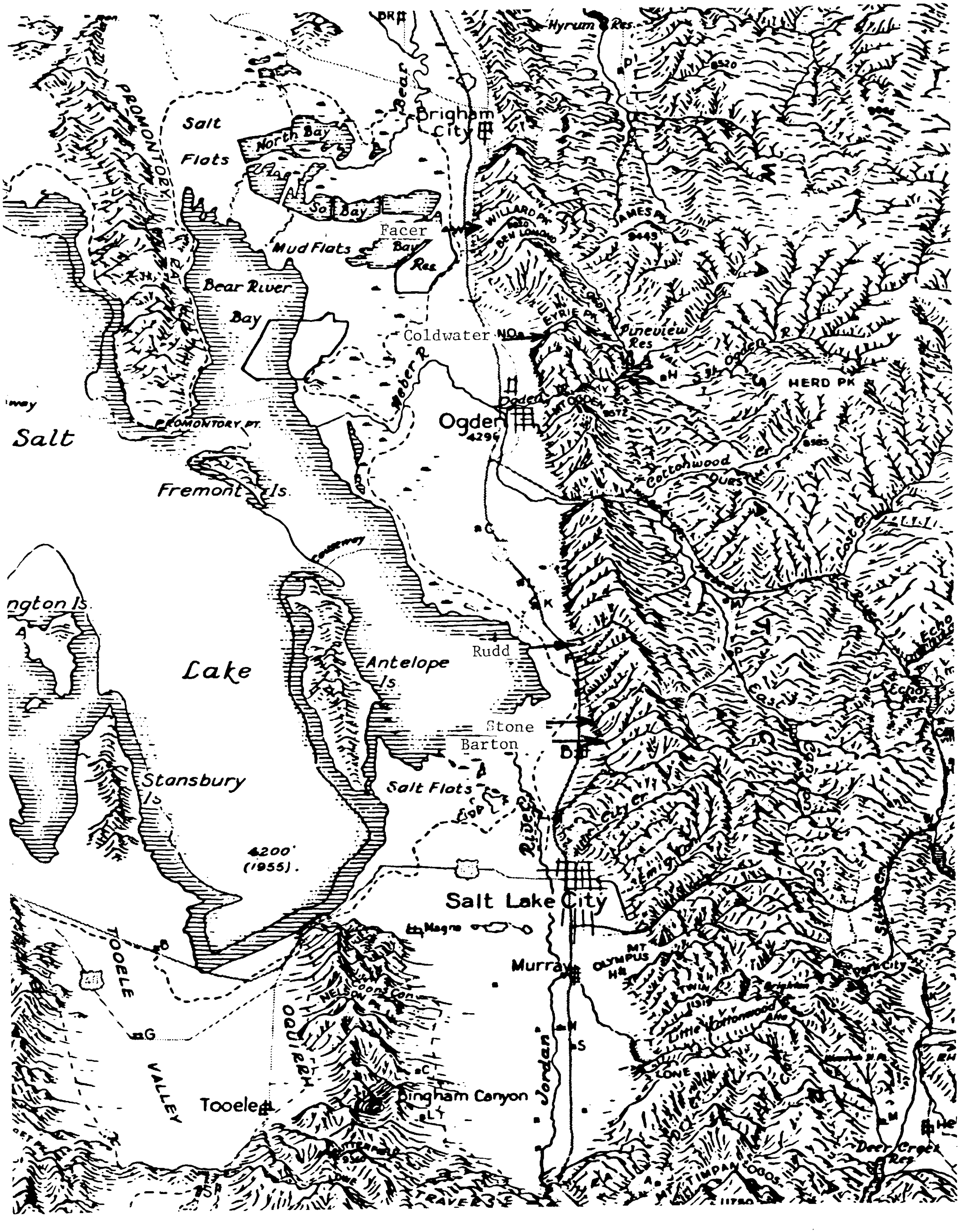


Figure 12c. *1983 Destructive debris flows and debris floods.*

(below 5,000 feet) along the Wasatch Front and at all elevations in the Wasatch Plateau. Earth block slides resulting from pure translational movement were quite rare. Rock slides were very few. The largest rock slide event in 1983 may have been the Twin Lakes landslide in Twelvemile Canyon, Sanpete County.

Flows, as already alluded to, were the most common type of movement. Rock flows, however, were unknown. Most common were debris flows primarily from saturation of debris slides rather than from accretion of transported sediments. It is very important to recognize this distinction because, in early decades (1920s, 1930s, and 1940s), the Wasatch Front and Davis County, in particular, gained notoriety for a succession of debris flows reportedly caused by the latter phenomenon.

Relatively rare were flows deprived of sufficient coarse material to classify them as true mud flows. Only in a few instances did flows consist of well-sorted sands, and these were observed only where Lake Bonneville (Quaternary) sand forms a veneer over bedrock on steep canyon walls or cuts.

Complex movements involving a combination of flow, slide, and fall were common. Recognized as the most common situation in 1983 was the debris slide-debris flow. Well over fifty percent of movements were of this type of complex movement. Second in importance in 1983 was the slump-earth flow. The rotational slumps involve either debris or earth-size material and the resulting flow. There is every transition in the flows from only slight movement beyond the daylighted rupture surface ("foot line") to a lengthy run out beyond the rupture toe.

Table 4 summarizes the types of slope movements that occurred in Utah in 1983 as well as the flow/flood type of sediment and debris transport. It may help to refer to this table for clarification of terms.

Debris Slide-Debris Flows

The greatest number of 1983 slides were those which caused debris flows and debris floods (also called hyperconcentrated stream flows). Over 1,000 of this type of slide occurred in 1983, most of which were where slides had not previously occurred. This type of slide is generally a debris slide and is both small and shallow. The failure zone can be more or less parallel to the sloping ground surface (i.e., translational) or it may penetrate to greater depths under portions of the slide (i.e., have a rotational component). Frequently, such slides, particularly if large, may have both translational and rotational components; in other words, even these small landslides may be complex (figures 12a, b). These slides are normally caused by some critical threshold of pore water pressure being exceeded in the slope material with a resulting sudden failure. Upon failure, the pore water pressures are at least somewhat relieved for a time, preventing further movement. The failed material is largely or entirely soil that has accumulated upon the underlying rock. This veneer is frequently colluvial soil and/or residual soil.

A minority of the slides involve thicker wedges of soil material which have their origin in ancient landslide deposits, glacial materials, alluvium, or fill. The Rudd Creek debris flow, which occurred on May 30, 1983 in Farmington, Davis County (figure 12c), had as its source a soil wedge which exists in the main channel of the drainage. This wedge of sediment had a very gentle slope upstream and a steep slope downstream, facing westward. The gentle upstream slope provided an extraordinary opportunity for snow to accumulate, melt, and, in turn, seep into the ground at the same time as runoff down the channel and over the wedge surface was also infiltrating into the ground. Thus, pore water pressures were able to build up rapidly in such a local environment.

Experience with the large number of debris slides of 1983 has shown that the local topographic, vegetative, and geologic environment become crucial considerations in the following ways:

1. Steepness of slope
2. Thickness of soil material over bedrock
3. Thickness of zone of weathered rock
4. Structural planes of weakness (i.e., schistosity and fracturing) of rock
5. Buried profile of rock
6. Geometry of soil mass over bedrock
7. Change in ground surface slope above and below slide and laterally to either side
8. Relationship of surface recharge zone to slide area and below
9. Subsurface hydrologic factors
10. Nature and distribution of ground surface vegetation
11. Recent changes in vegetative cover
12. Modification of slide vicinity by man, such as removal of toe or vegetation by road or fire-break construction
13. Texture of the residual soil derived from parent rock
14. Organic soil profile near surface
15. Profile of the buried rock
16. Surface drainage
17. Relief or elevation differential
18. Microclimatologic influences (orographic, albedo, etc.)
19. Wildlife influences (trails, burrows, etc.)
20. Geometry of slope
21. Presence of soil horizons with higher clay content
22. Piping susceptibility of soil horizons
23. Moisture content of earth materials

Areal Distribution of Landslides

Slope movements in Utah occurred from near the Idaho state line on the north to approximately Arizona on the south. In western Utah, few occurred in mountains of the Basin and Range. In the Basin and Range-Colorado Plateau transition zone (figure 2), slides were frequent in the Tushar Mountains, the northern part of the Gunnison Plateau, the northern portion of the Southern High Plateaus (south of the Wasatch Plateau), and on the Sevier Plateau (figure 13).

Intensive landslide activity occurred in the Wasatch Plateau, in the transition zone, and in the westernmost subprovince of the Middle Rocky Mountains, the Wasatch Range. The Thistle landslide bordered on the eastern extremity of the Wasatch Range. From available data, landslide activity appears to have dropped off considerably to the east in the Wasatch hinterland, Bear River Plateau, and Uinta Mountains. On the Colorado Plateau, most slides occurred in the western portion of the Book Cliffs-Roan Plateau, but some slides occurred in the La Sal Mountains (Davis, 1984).

A comprehensive inventory of slope movements, unfortunately, will never be possible because there is far less than full aerial photographic coverage before and after the 1983 snowmelt period. Inventories done to date consist of partial coverage of Davis County by Pack (1985) and limited coverage (consisting of five drainages) of the western Wasatch Plateau by Lips (1985). In the latter case, most of the slides are not differentiated as to year of occurrence, 1983 vs 1984.

Obviously, those drainages with a direct impact on communities or those having major recreational or resource values were the ones which received attention. By the time the crisis period was over, the window of opportunity to log the events was also nearly over. A wet 1984 coming on top of 1983, as it did, made it impractical for most agencies to

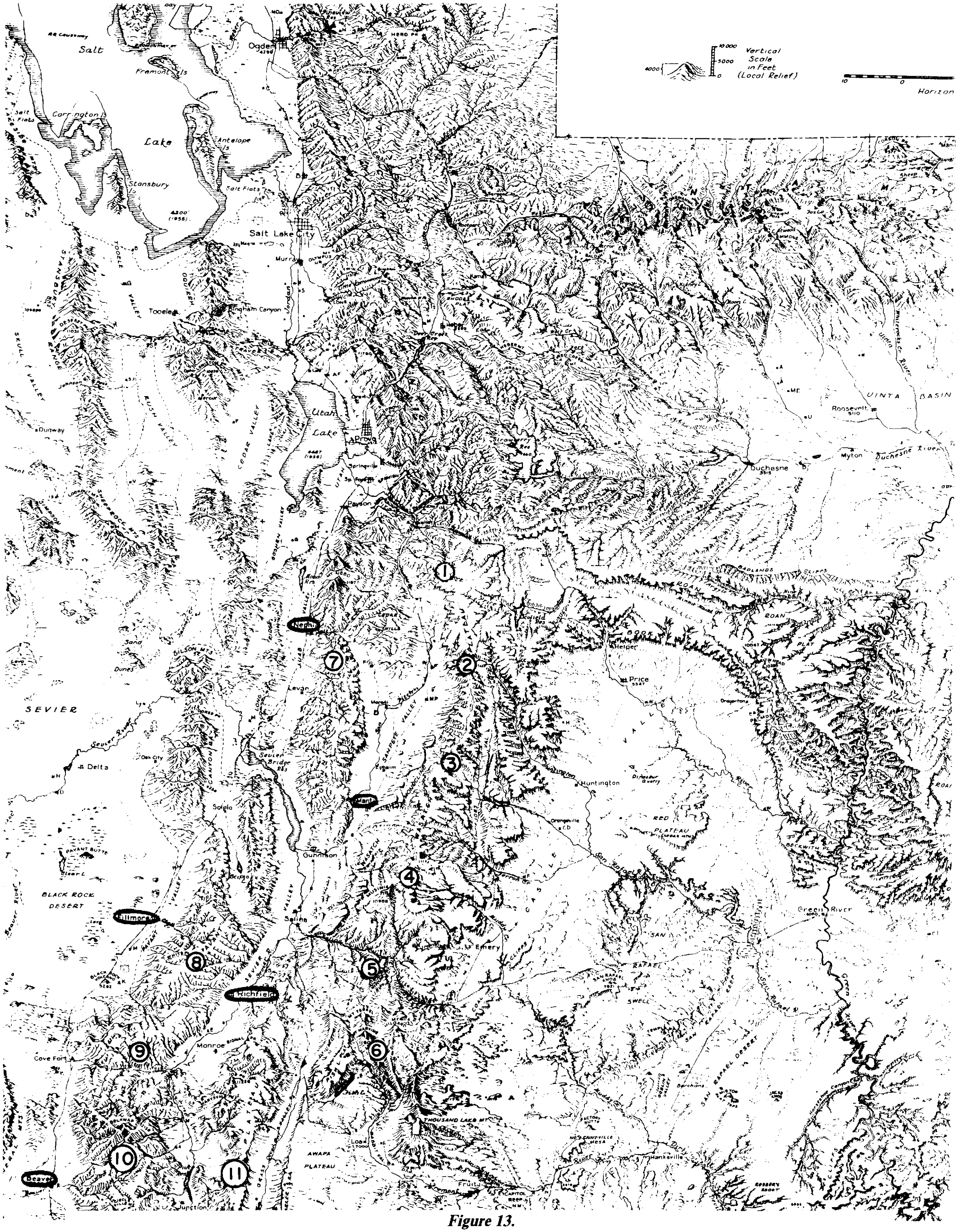


Figure 13.
Location map for map Figures 13-1 through 13-11; numbers are positioned at map center of each Figure.

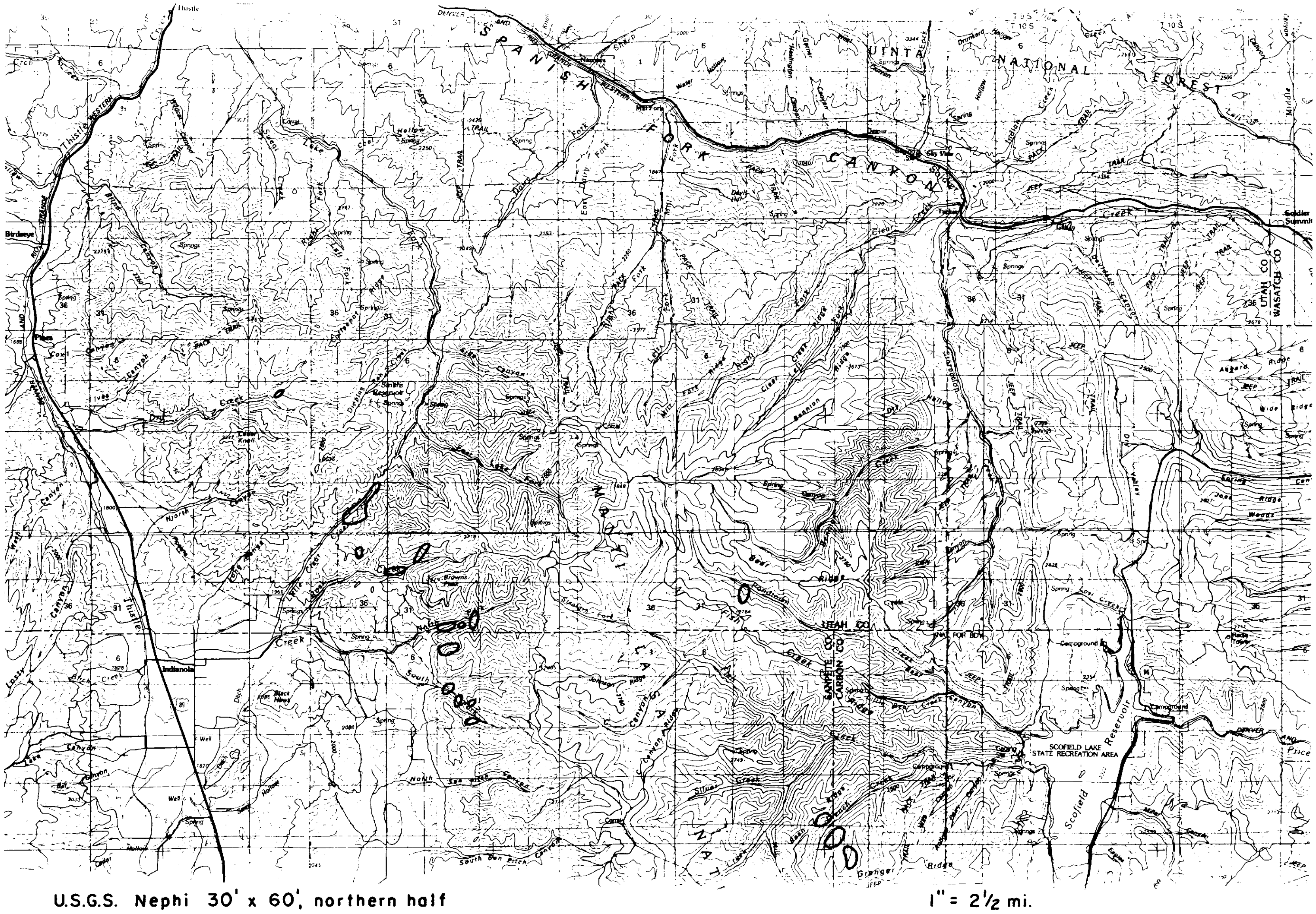


Figure 13-1.
Slope movement areas in the northern Wasatch Plateau.

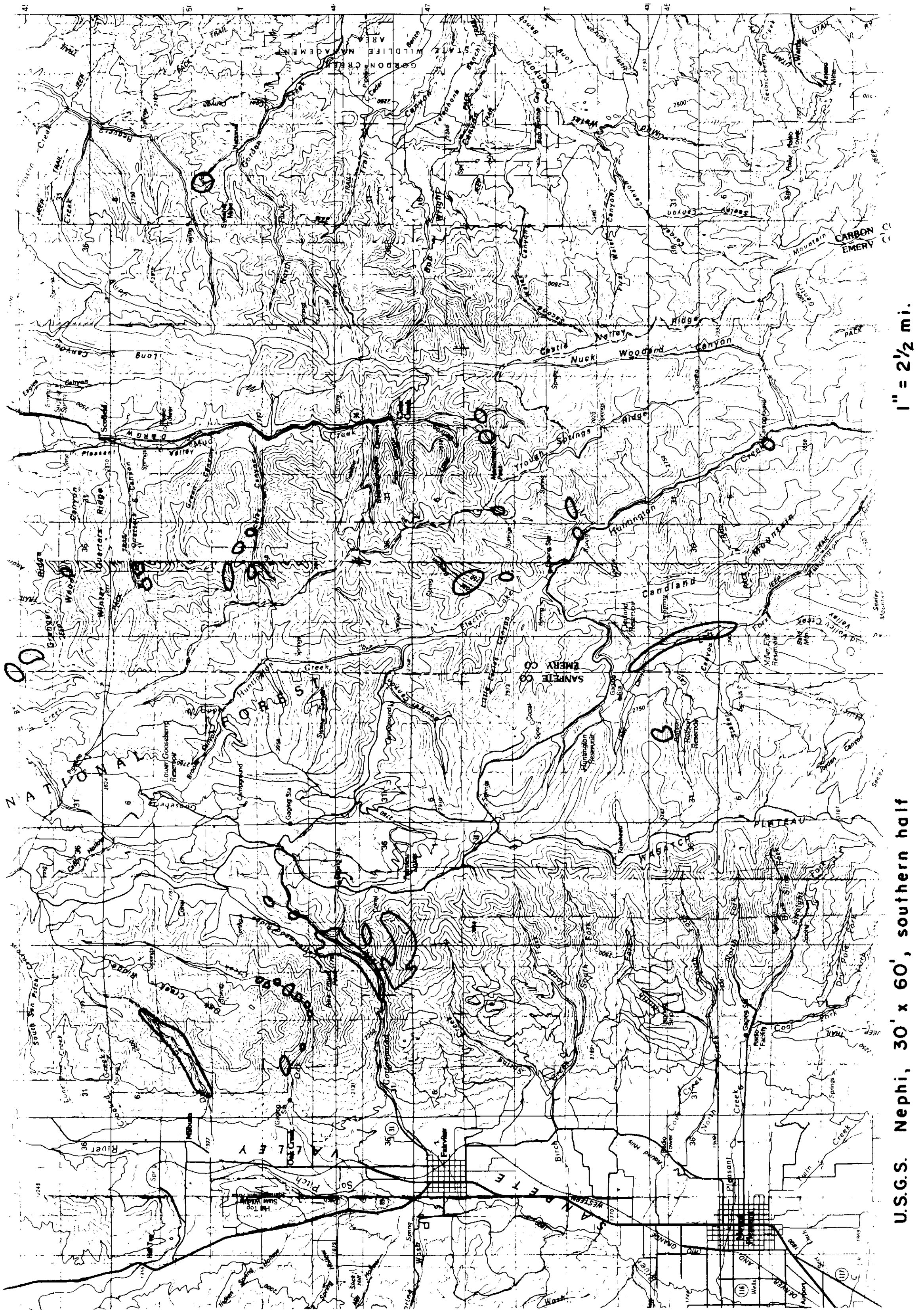


Figure 13-2.
Slope movement areas in the northern Wasatch Plateau.

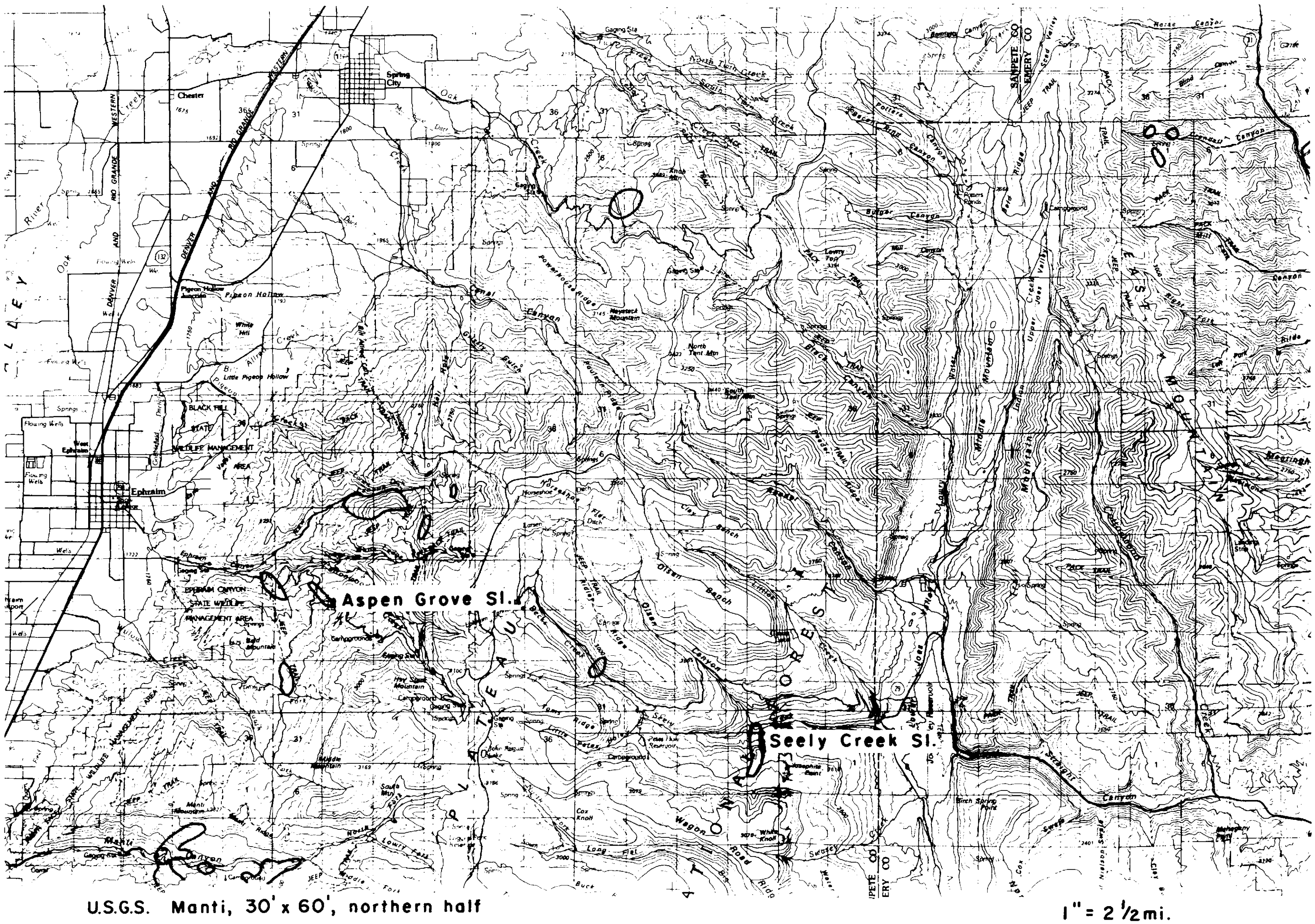


Figure 13-3.
Slope movement areas in the central Wasatch Plateau.

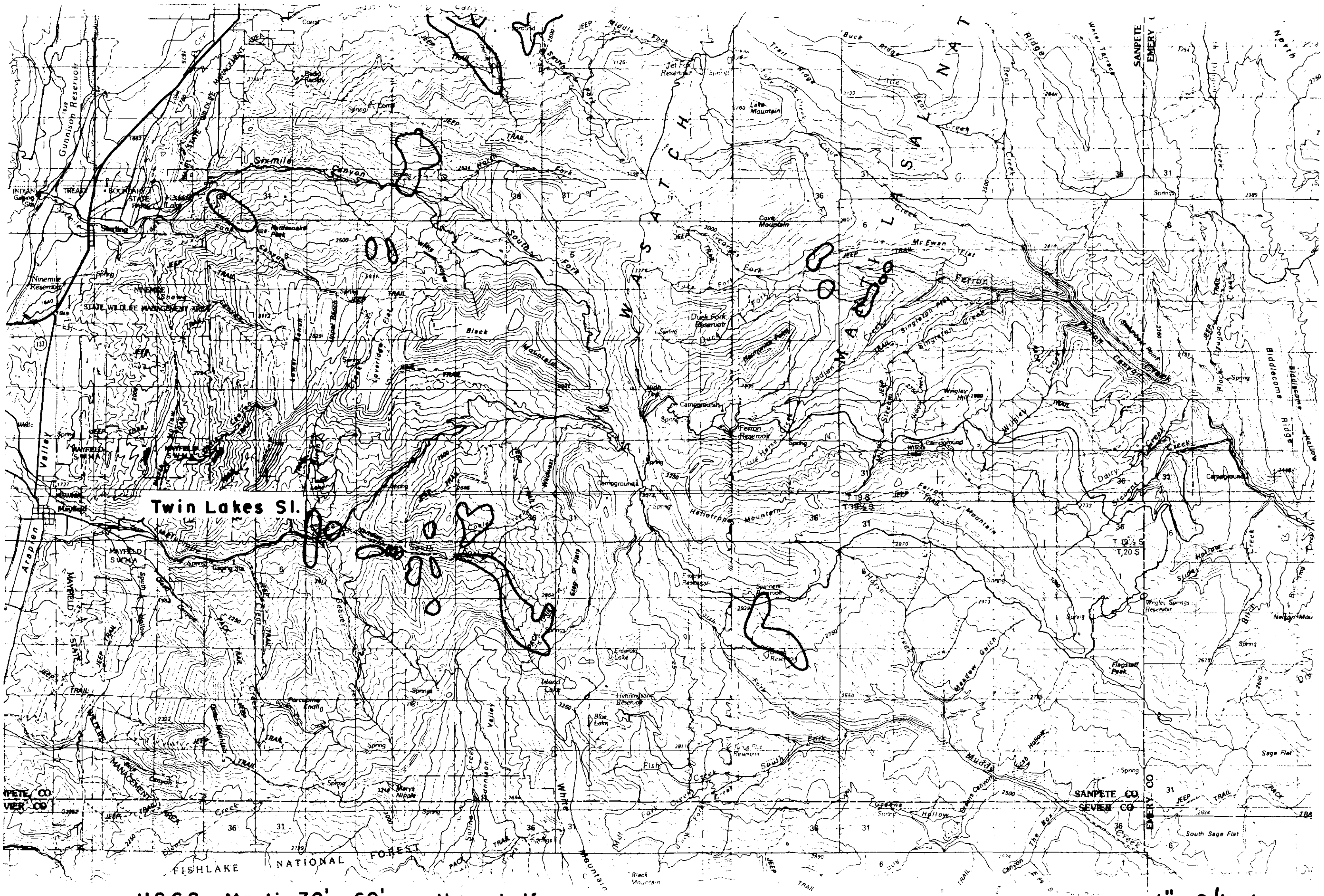


Figure 13-4. Slope movement areas in the southern Wasatch Plateau.

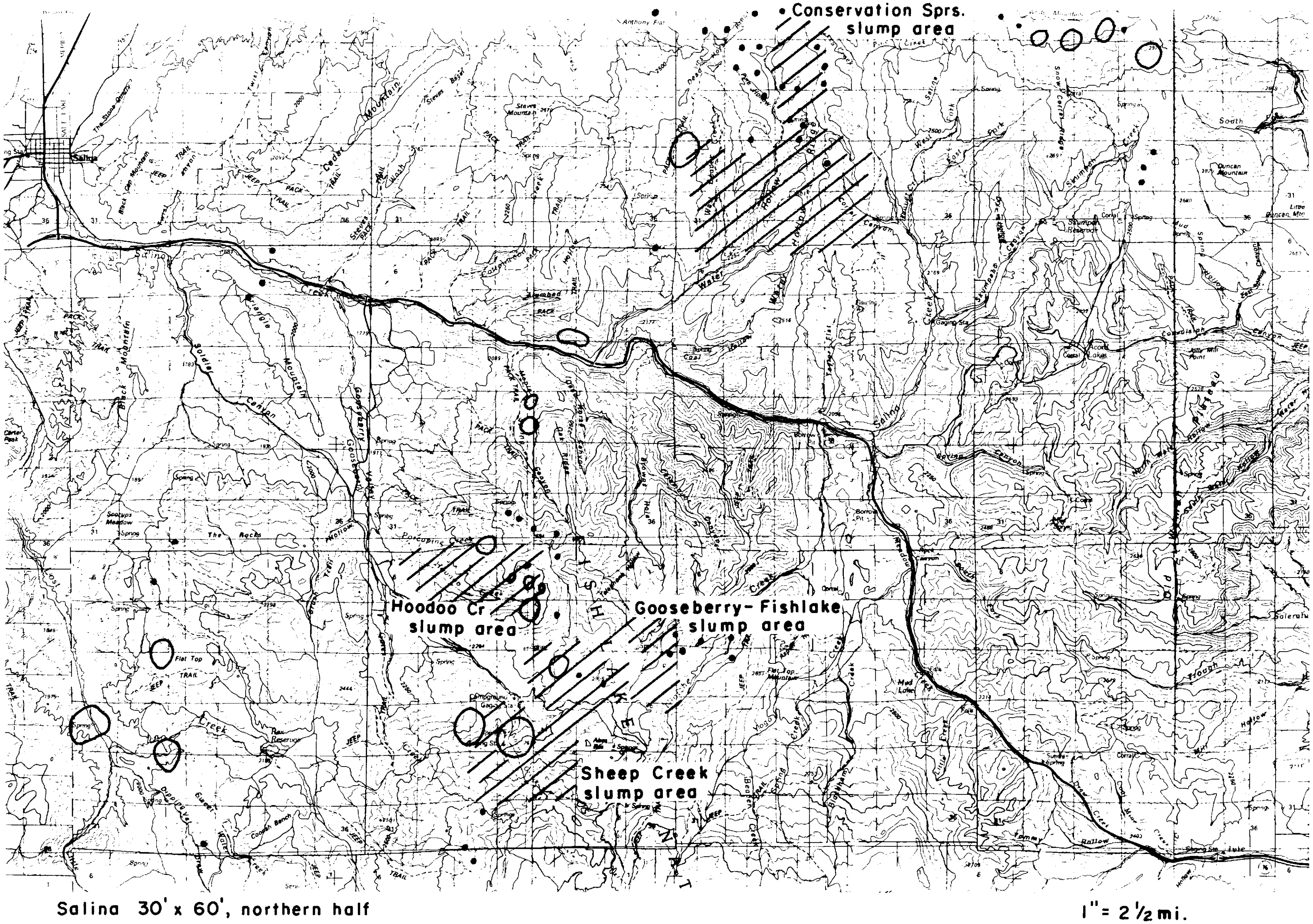


Figure 13-5.
Slope movement areas in the southern Wasatch Plateau.

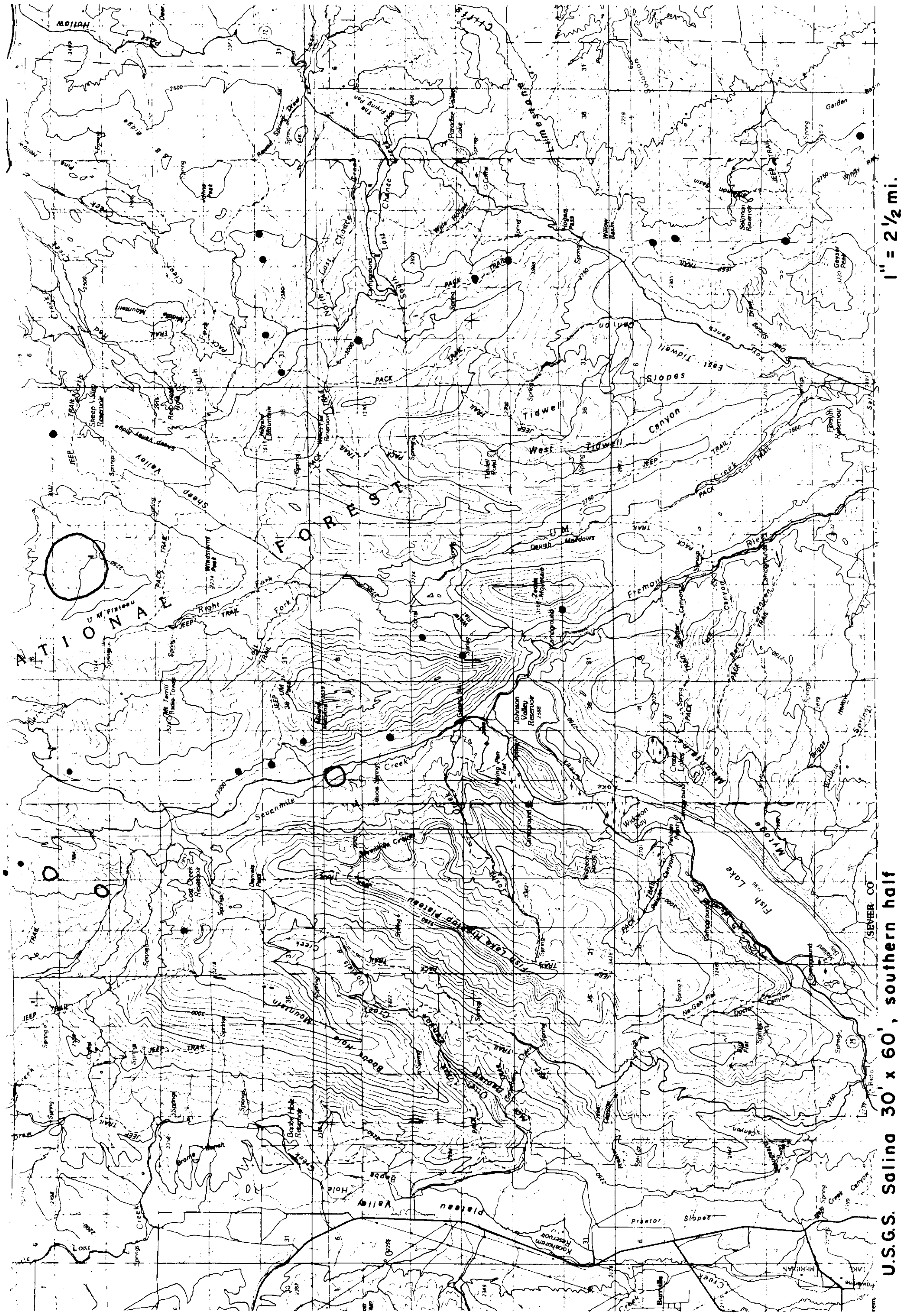
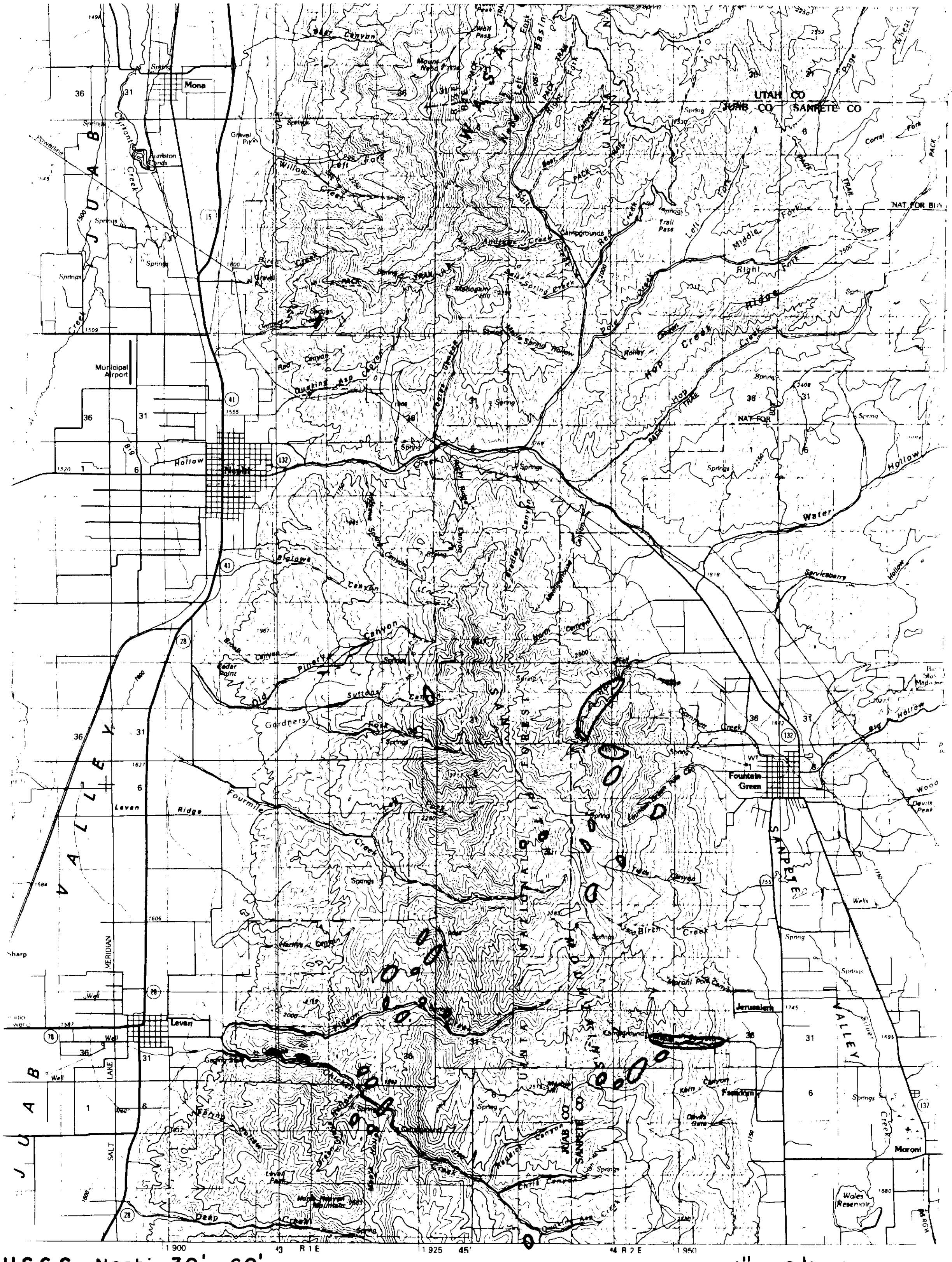


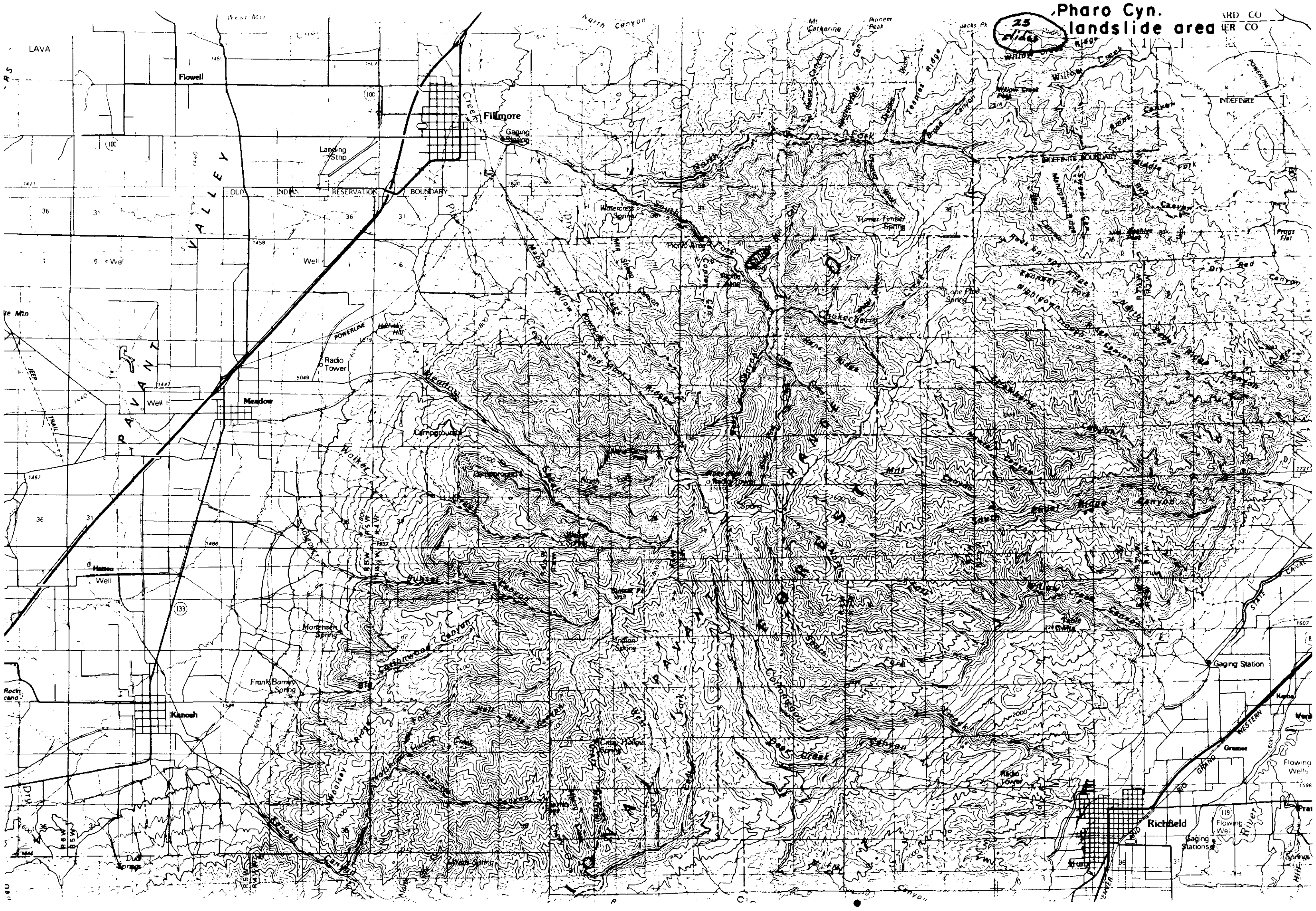
Figure 13-6.
Slope movement areas in the Fish Lake Mountains.



U.S.G.S. Nephi 30'x 60'

1" = 2 ½ mi.

Figure 13-7.
Slope movement areas in the northern San Pitch Mountains.



U.S.G.S. Richfield 30'x 60', northern half

1" = 2½ mi

Figure 13-8.
Slope movement areas in the Pavant Range.

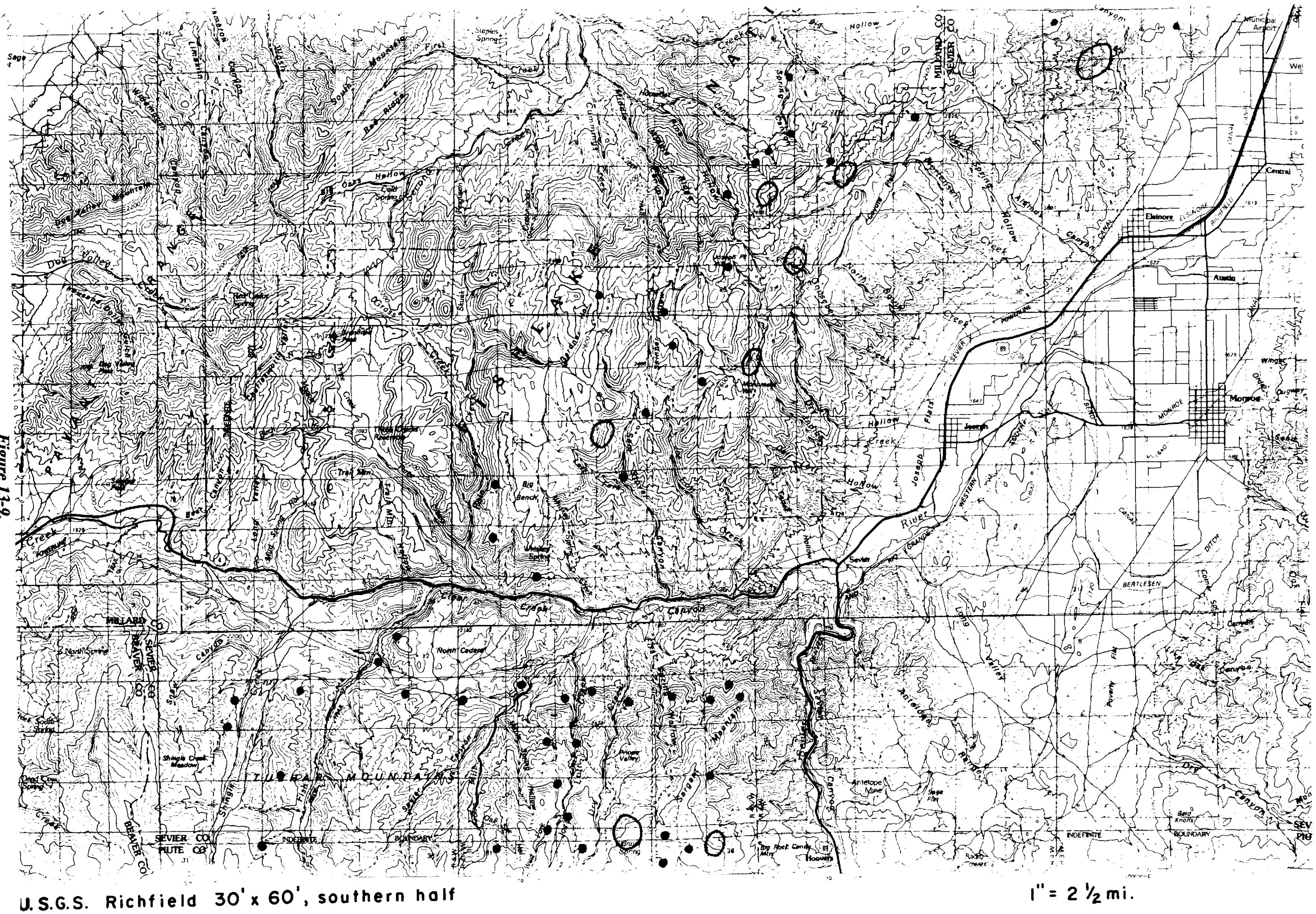


Figure 13-9.
Slope movement areas in the northern Tushar Mountains and southern Pavant Range.

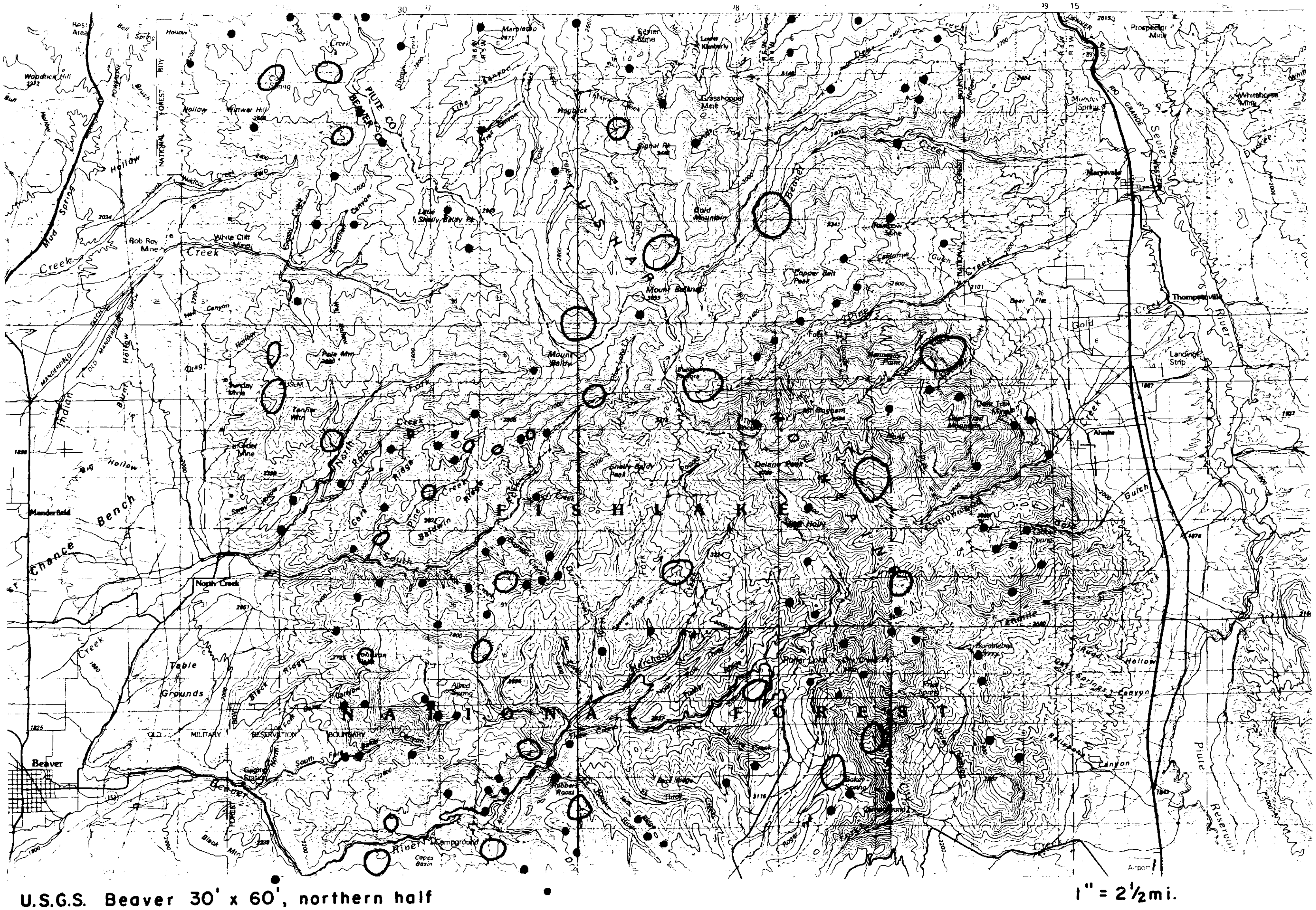


Figure 13-10. Slope movement areas in the Tushar Mountains.

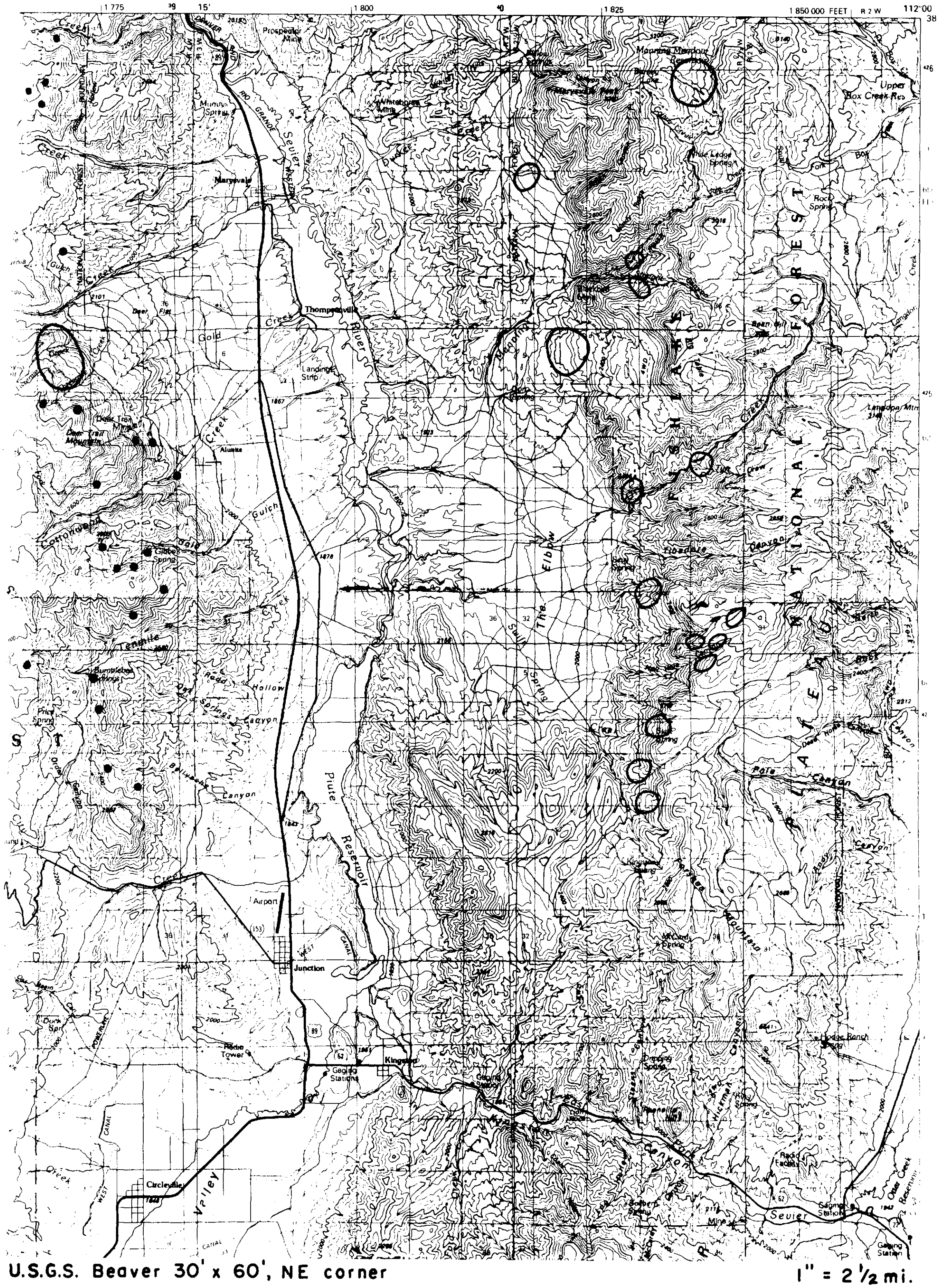


Figure 13-11.
Slope movement areas on the Sevier Plateau.

provide an intense effort at documenting 1983 events. Undoubtedly, much of the higher elevation country that experienced slope movements in 1983 is still largely or entirely uninventoried. Some efforts are currently underway, particularly by the U. S. Geological Survey, to distinguish 1983 events, but it is extremely likely that, at the conclusion of the wet cycle, all of the events may have been grouped together in the same time period. Less than complete geographic coverage is likely to be provided in an inventory process.

Sequence of new slope movements

Benchland along the Wasatch Front in northern Utah experienced a few failures in October of 1982 with the start of the 1983 water year. Two occurred along the old bluff of the Ogden River at a locality where historical movements had not previously been recorded. Bonneville-age deltaic sediments with a cover of colluvium were involved, together with some old fill placed on the slope mostly to fill a ravine years earlier. The slides in Layton also involved Bonneville sediments, mostly sands and silts and, in addition to saturation, were at least partially due to improper grading practices performed in the development of residential subdivisions.

On February 14, the Provo 1500 East slump-earth flow occurred. This failure involved an older slide which had not experienced movement in historic times. The February 14 slide also appears to have been, in part, destabilized by a high cut that had been excavated across the toe of the landslide. This 10,000± cubic yard failure moved about 8 to 10 feet per day at its height of activity. Upon failure, 2-3 gpm of ground water flowed from the toe. Another slide occurred nearby in February, in Provo, along the western-most trace of the Wasatch Fault scarp. It continued to move over a period of about two weeks but also experienced an almost instantaneous resurgence of slide action in March. This slide also issued water from its toe, about 1 gpm. On March 12 and 13, numerous cut and fill slopes failed in Emigration Canyon, Salt Lake County. One mud flow resulted. On March 20, the south lane of U.S. 40, near Keetley in Wasatch County, collapsed in a rotational failure in fill and valley alluvium. This 6,000+ cubic yard slide left a scarp about 40 feet high.

On March 21, seven slides were spotted by the senior author during an aerial reconnaissance of northern Utah County. These were small, ranging up to approximately 300 feet in length. One slide occurred in Lindon, several in northeastern Provo, one at the mouth of Little Rock Canyon, and two others on the east bench of Provo. On the same date, in Davis County, slides were observed in Farmington, Layton, and North Salt Lake City. On March 30 and 31, two failures occurred just above the high bench, low on the mountain front just south of the mouth of Emigration Canyon. Both were in colluvium and on man-modified slopes.

In early April, a landslide was recognized on the benchland in North Salt Lake City. Initiation of failure probably began in March. A large number and variety of slope failures developed along the Jordan River and along canals at the south end of Salt Lake County during April. In April, four slides were recognized between elevations 4950 feet and 5200 feet in the Edgemont area, south of Provo Canyon. On April 12, the ancient slide that formed the left abutment of the Grassy Trail Dam, in Carbon County, became reactivated. The Thistle landslide began slow movement on April 10, accelerating on April 13 to become one of the most significant failures during 1983.

Twenty-eight slides were observed during an aerial reconnaissance on May 9: four in Mueller Canyon east of Bountiful; two east of Centerville; several east of Kaysville; one in Shepard Creek; several in Weber Canyon; five in Mountain Green; eight on the south side of Weber Canyon opposite Mountain Green;

two in the vicinity of the Hill Air Force Road east of Highway 89; and two (which had become enlarged) in Layton. Large slides east of Birdseye were initiated on May 23. On May 25 a slide occurred on the lower bench along Crestwood Road in Kaysville followed by two slides on May 26 in Little Cottonwood Canyon. On May 30, a landslide created havoc in Cottonwood Canyon, east of Fairview. The Cottonwood Creek slide, on the terrace near Mountain Green, Morgan County, also occurred on May 30; Highway 31 was disrupted and the ephemeral creek blocked. The Aspen Grove slide in Ephraim Canyon occurred on May 31, as did the Rudd Creek debris flow in Farmington. On June 1, an abundance of activity occurred in Davis County at or above 7,000 feet.

On June 2, the Tank Canyon slide in American Fork Canyon became reactivated. Additional surges of Rudd Creek continued into early June. Later in the month, the Seely Creek landslide threatened to block the drainage above Joes Valley. The Reynold Gulch debris slide and debris flow occurred in Big Cottonwood Canyon. On June 16, Coldwater Canyon in North Ogden yielded a slump at its mouth on the south side. A large slump in Riverdale, along the bluff, occurred on the same date. Slides were observed in the vicinity of Electric Lake (Emery County), elevation 8,800 feet, on June 24.

By June 20, slope landslide, debris flow, and flooding had subsided sufficiently to allow the Emergency Technical Team of Davis County to disband. On July 12, the flow of the Logan Northern Canal in Logan was disrupted by a slide into the canal resulting in a mud flow. Near the mouth of Hobble Creek, in Utah County, a rain-triggered debris flow occurred on August 18.

Thistle landslide

The Thistle landslide may be one of the most expensive landslides in the United States, having cost in the neighborhood of $337,000,000 (Stephens, 1984). It alone was responsible for Utah's first Presidentially declared disaster. Movement was northeasterly into the valley of the Spanish Fork River, seven miles above its canyon mouth on the Wasatch Front (figure 14a). The blockage that it caused created a lake approximately 180 feet deep (figure 14b), disrupted major highway and railroad routes through the Wasatch Mountain Range, inundated the entire town of Thistle, and caused the mobilization of state, local, and federal government agencies and the Denver and Rio Grande Western Railroad into a major emergency response effort.

Movement was detected on April 10, with rapid motion occurring on April 13. Over 28 million cubic yards of old slide became reactivated and moved laterally more than 500 feet on a slope of about 10°. Failure occurred within silt and clay materials of low strength, with an approximate angle of internal friction (ϕ) of 22° and cohesion (C) of 210 pounds per square foot (Slosson et al., 1986). The moderately plastic, silt/clay material was largely derived from mass wastage of the North Horn and Ankareh Formations. Much of the old, tongue-like feature was comprised of a succession of earth flows (figure 15a). The slide deposit largely occupies a trough-shaped depression in bedrock, an ancient paleovalley eroded in Triassic (Ankareh Formation) and Jurassic (Nugget Sandstone) sediments (figure 16). This main body of the landslide extends upslope from the blockage for a distance in excess of 6000 feet. Further upslope is an area with a length about 500 feet of peripheral landsliding of lesser thickness, locally connected to the main landslide (figures 16 & 17). Maximum thickness of the main landslide mass (or landslide-caused dam height) is 220 feet on the floor of Spanish Fork Canyon (figure 15b). It includes about 20 feet of fill purposely placed on top to prevent possible overtopping. The width of the landslide varies from about 800 to 1900 feet and is typically about 1000 feet.

Post-failure investigation and recommendations are presented in Kaliser and Fleming (1986) together with landsliding and

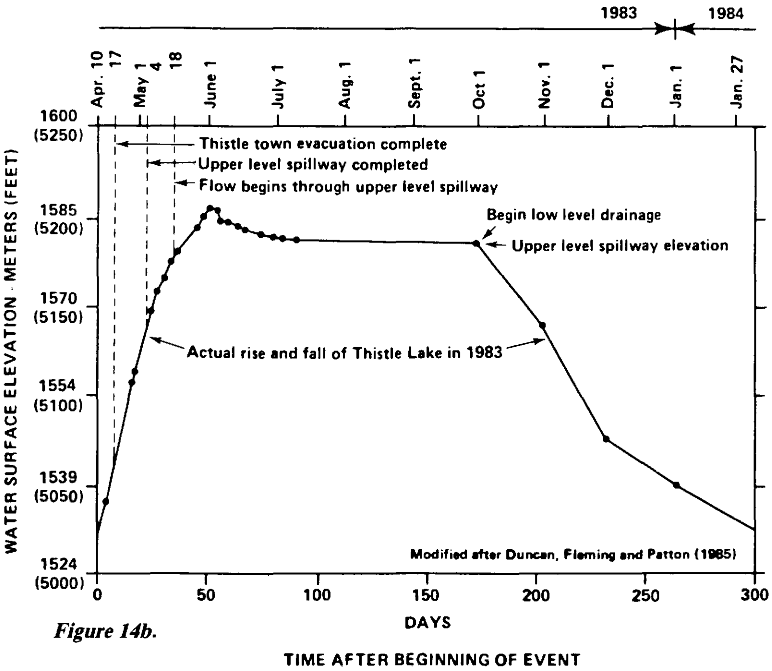


Figure 14b.

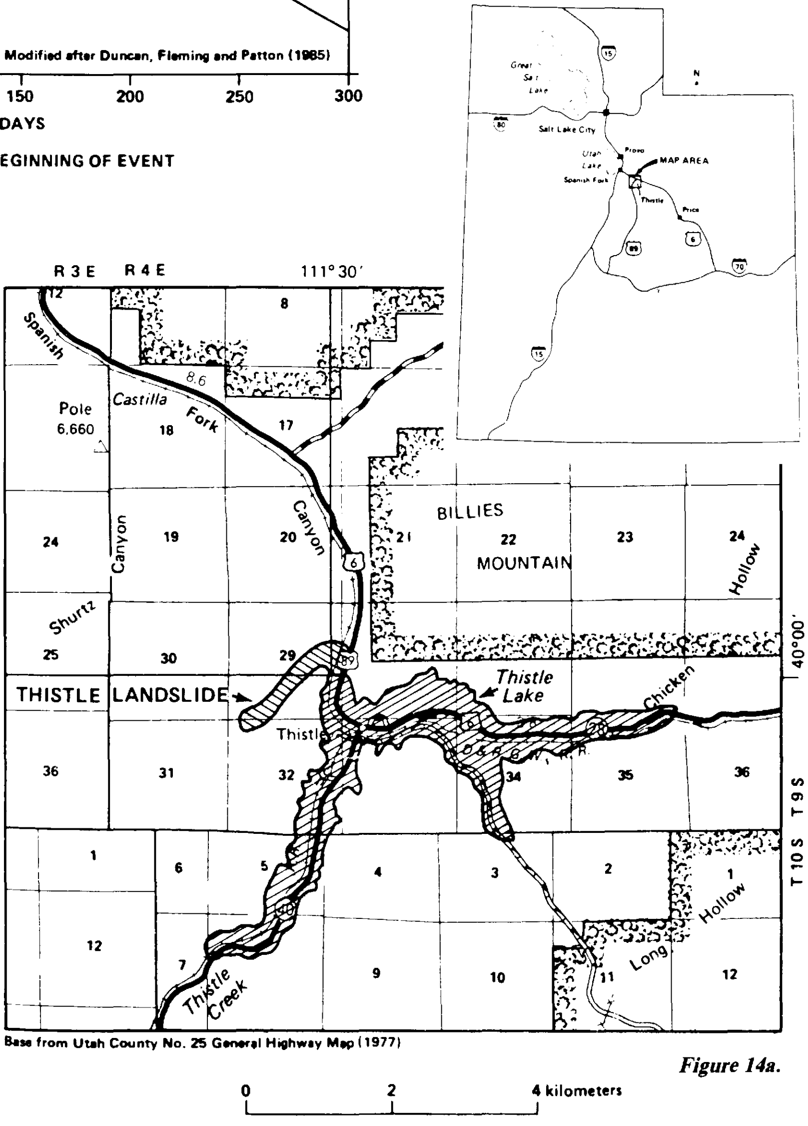
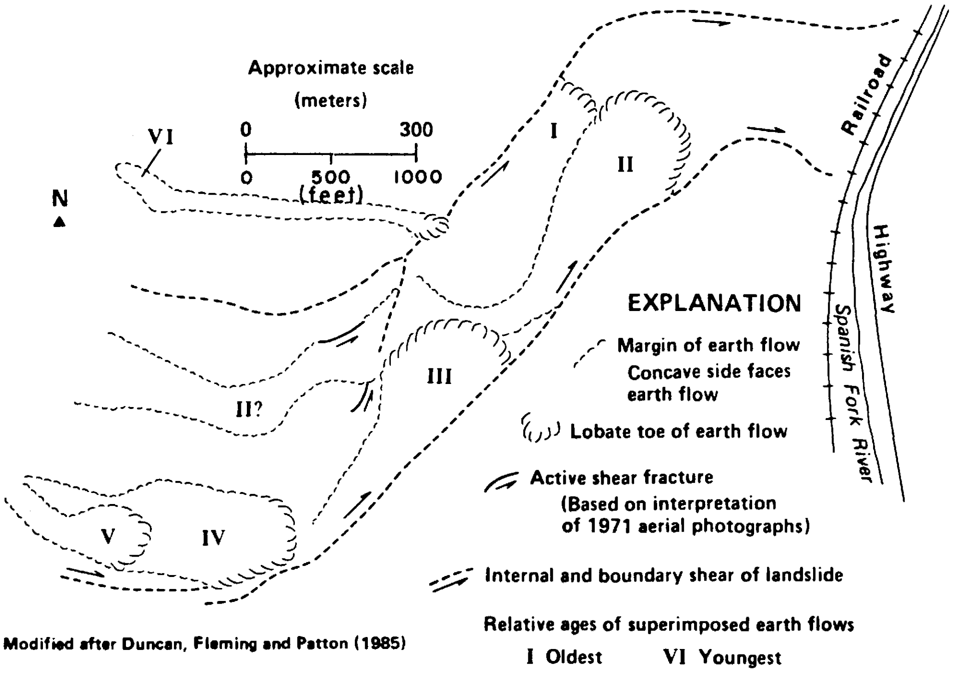


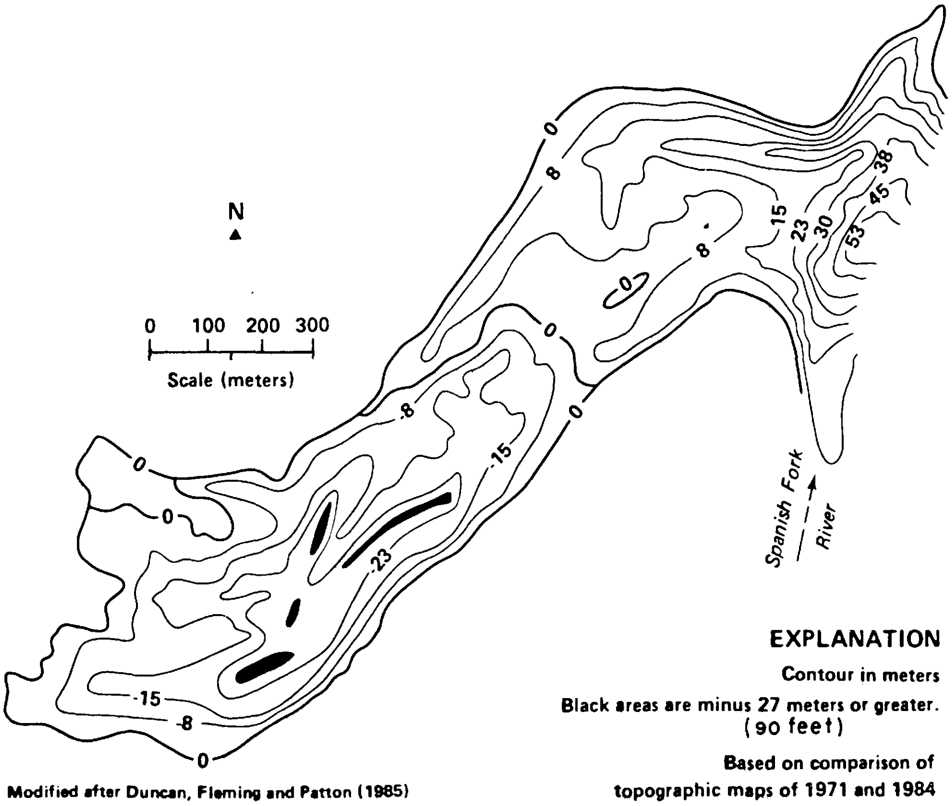
Figure 14a.

Figure 14a. Location and vicinity maps of the Thistle landslide.
Figure 14b. Key events in the rise and fall of Thistle Lake.



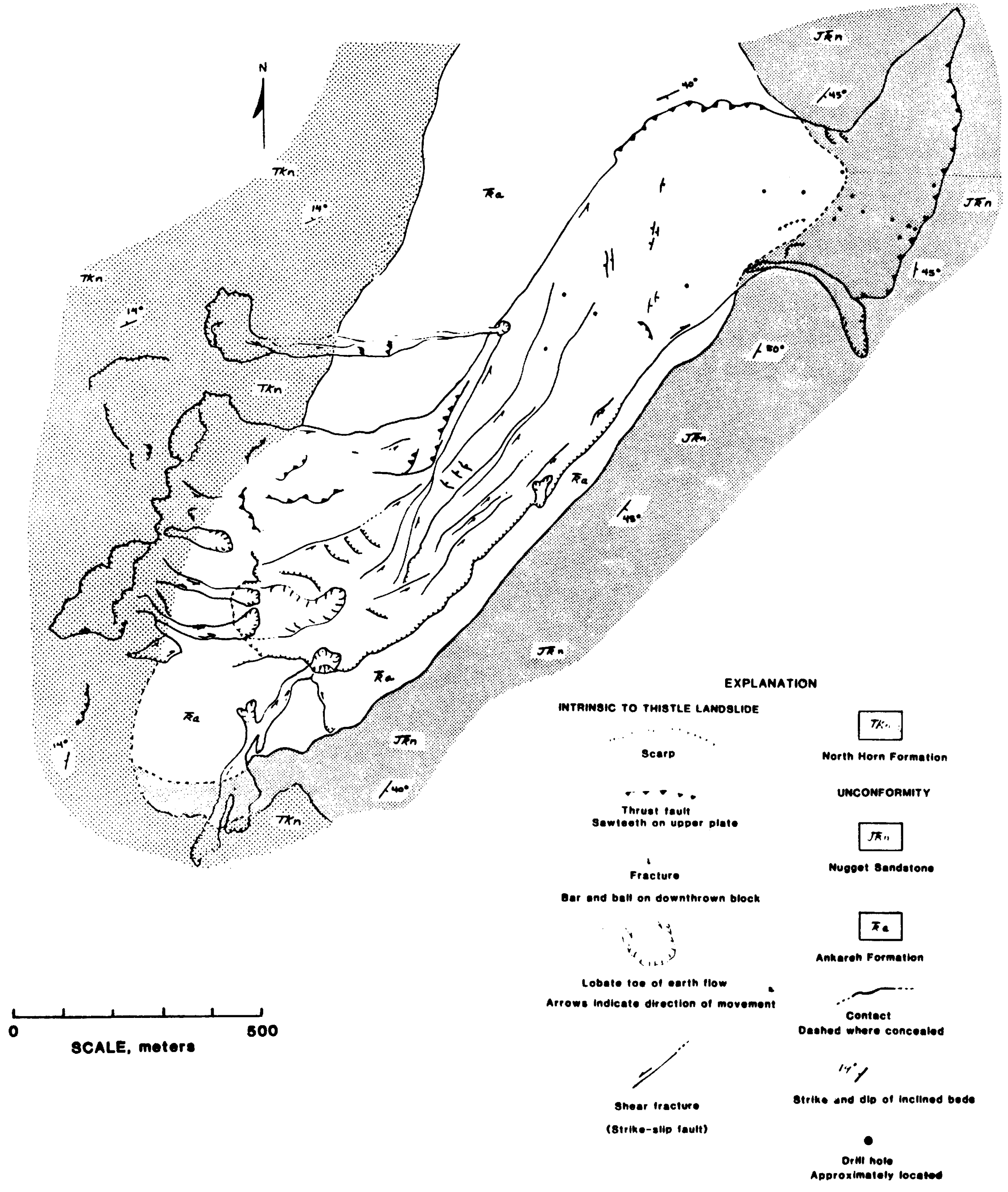
Modified after Duncan, Fleming and Patton (1985)

Figure 15a.
Map of pre-1983 Thistle landslide (from aerial photos).



Modified after Duncan, Fleming and Patton (1985)

Figure 15b.
Map of elevation changes caused by landslide movement
(includes peripheral landslide upslope from main one).



From Kaliser and Fleming, 1986

Figure 16. Geologic map of the Thistle landslide.

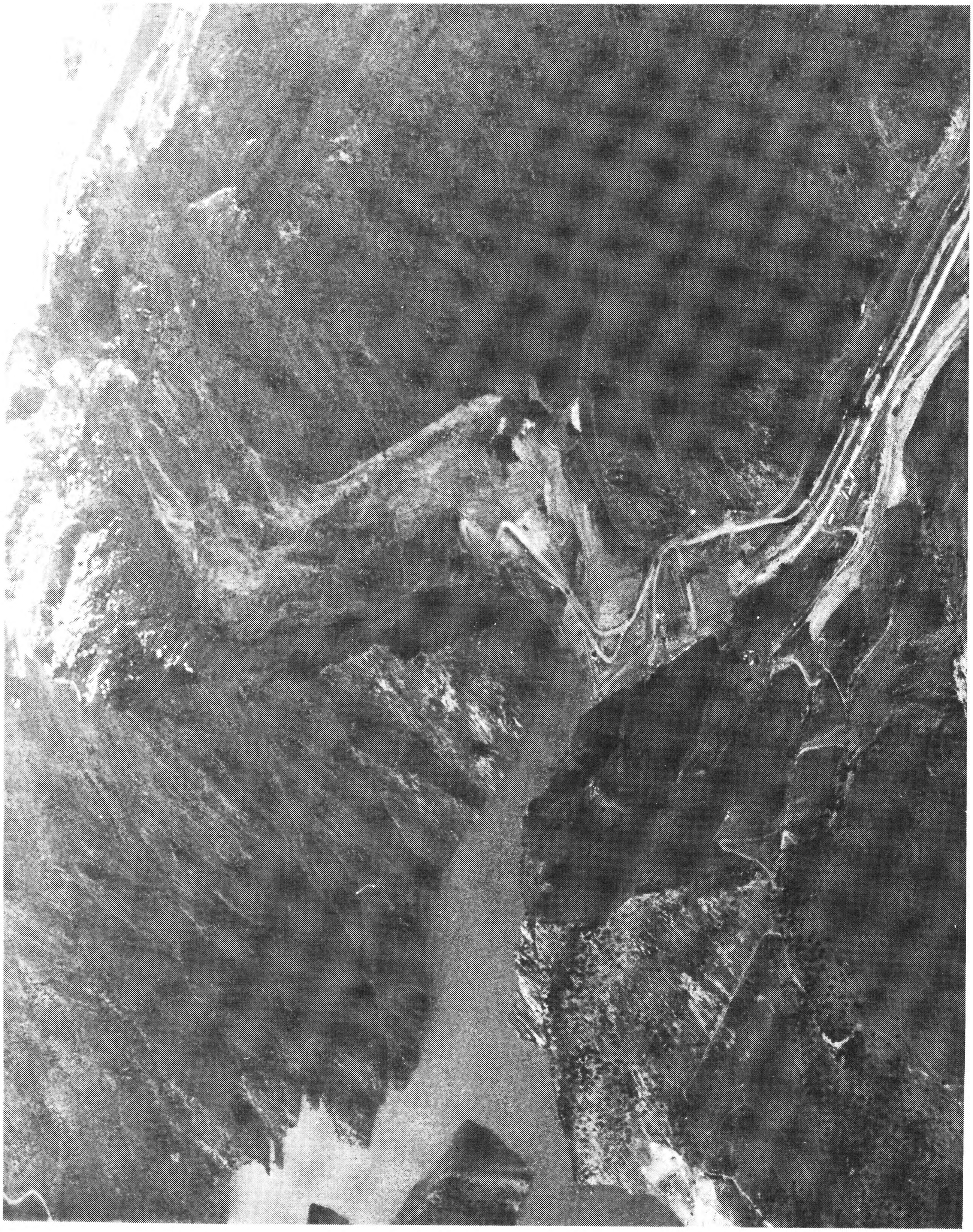


Figure 17. *Thistle landslide oblique aerial, looking southwest.*

damming chronology, the geologic, climatologic and hydrologic background, emergency phase operations, and movement history. Geology of the Thistle area is shown in Witkind and Page (1983) and the details of geology most directly relevant to the landslide are in Duncan, Fleming and Patton (1985). Discussion of sediment yield can be found in Simons, Li and Associates (1985). Engineering works constructed to alleviate problems created by the landslide dam are discussed in Hansen and Morgan (1986). References to cause and effect as well as the possibility to recognize, predict, and mitigate, was discussed by Slosson, Shuirman, and Yoakum (1985).

The extraordinary September 1982 precipitation was followed by the well above-average 1983 wet-year moisture through the period of rapid initiation in April. The September rainfall was recorded as being between 500 and 800 percent of normal and 252 percent of the next highest September (1963) measurement (with 77 years of record for the station). Precipitation for October through April 1983 was 152 percent of normal. In all likelihood, piezometric levels within the slide mass were raised to heights that were unprecedented in historic time.

First measurements of slide movement were made on April 16, at a point 250 feet west of the canyon wall forming the east abutment of the blockage. Lateral movement on that day averaged 2.5 feet per hour. Over the next five days, the average hourly rates were 3 feet, 2.5 feet, 3.1 feet, 2.25 feet, and 1.8 feet per hour. The rate of movement over this period became more uniform so that, on April 21, variation over the 24-hour period was only 1.2 feet per hour. More than 360 feet of displacement occurred during this six-day period of most rapid movement. By April 25, the average rate of movement had diminished to 1.2 feet per hour; on April 28, it had diminished to 0.8 foot per hour. Movement rates had greatly tapered off by early May.

Multiple thrusting of horizons within the slide was in evidence from the beginning (figure 18). On a single day, April 27, seventeen thrust sheets and pressure ridges were mapped in the lower portion of the landslide, with dips ranging from 30° to 90°, averaging 58°, in the N40°W direction which coincides with the alignment of the lower portion of the slide mass. Southerly hade measurements of between 0° and 30° indicated that the net thrust direction was slightly to the north, or down canyon.

The blockage or "dam" portion of the landslide currently has a base width of 1475 feet, a height of about 220 feet, an average cross-valley dimension of 650 feet, and a volume of about 6.5 million cubic yards. Drilling subsequent to the 1983 movement has indicated that lateral-earth pressures and pore-water pressures remain very strong. Although the existing landslide dam is unacceptable as a permanent water retention structure, there are alternatives for dealing with the Thistle situation (Montgomery, Inc., 1985).

Landslide-Caused Dams

In addition to the Thistle landslide, there were a number of landslides which threatened to block drainages, thus creating an unengineered dam. Most of these events involved small earth masses which never were very likely to result in total canyon blockages. Following Thistle, however, there was a significant level of awareness by local officials of such possibilities when even small landslides bordered stream channels. Several landslides created a real potential for such dams in 1983 and, in those instances, Utah Geological and Mineral Survey worked closely with local officials and prepared potential inundation maps for downstream risk assessment. Particular instances were:

(1) Seely Creek, Sanpete County

This mile-long ancient landslide/earth flow (figure 13-3)

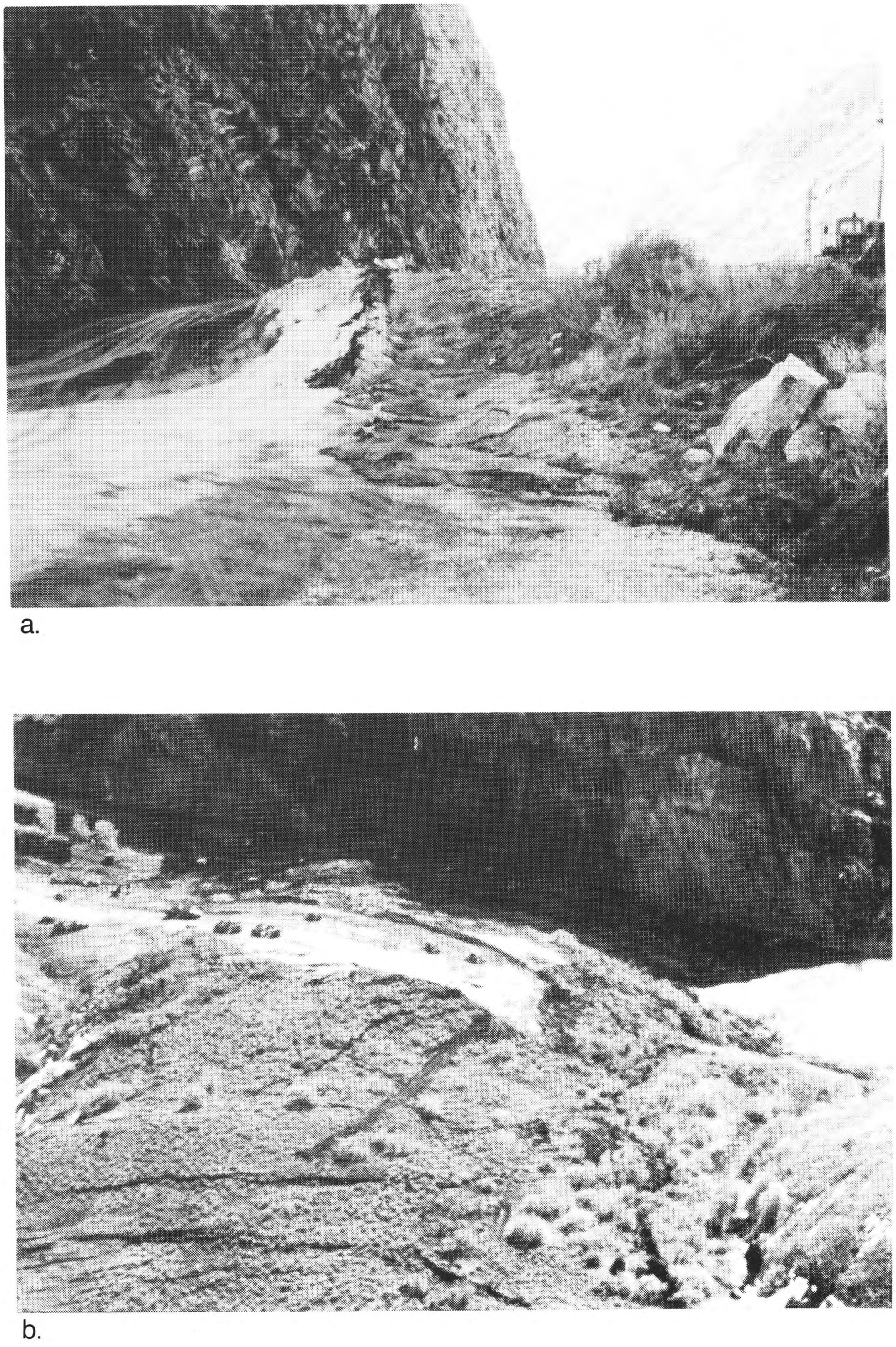


Figure 18.
Thistle landslide a) Early deformation of Hwy. 89 in Spanish Fork Canyon; appearance of first thrust. b) Toe of slide, about end of first week's movement.

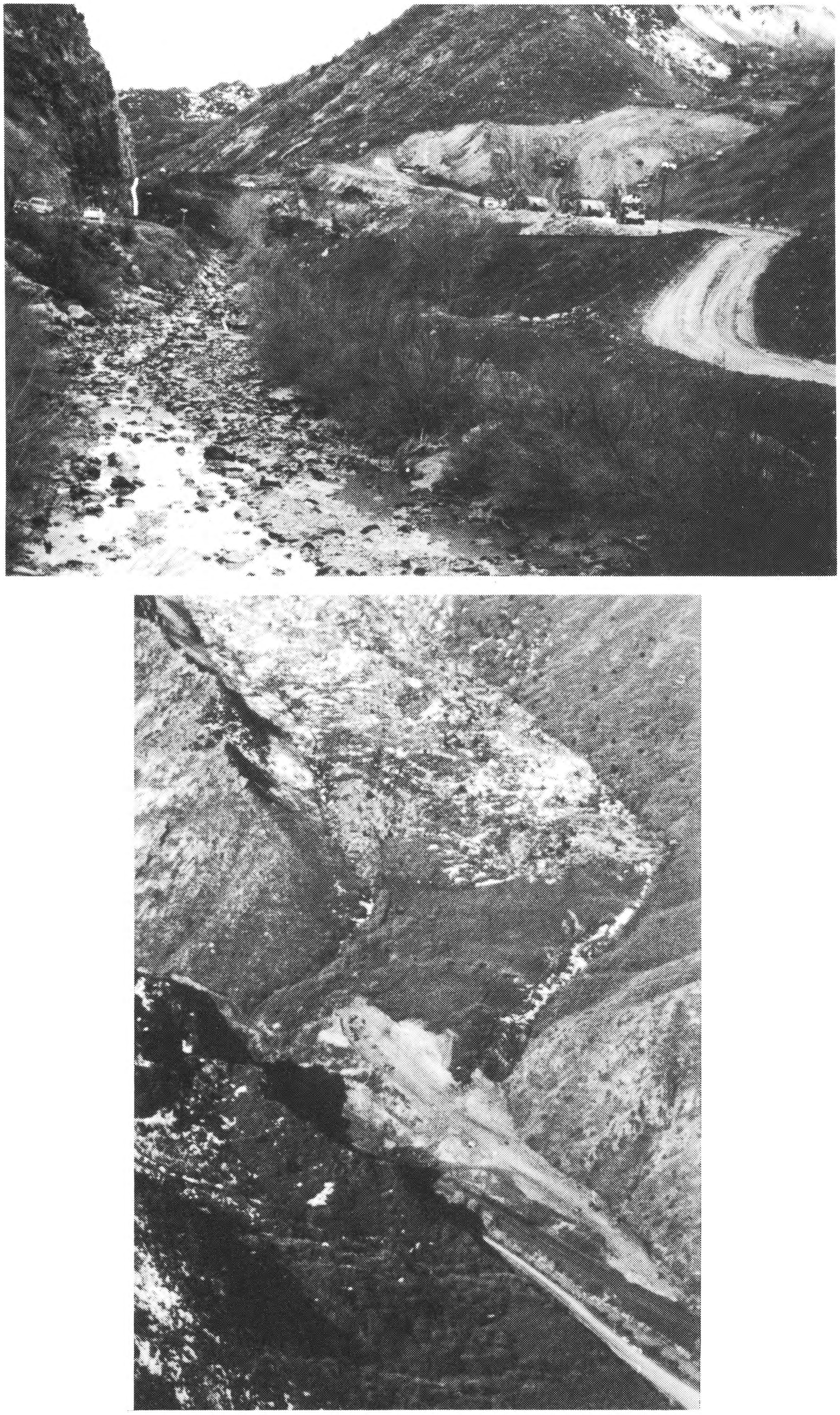
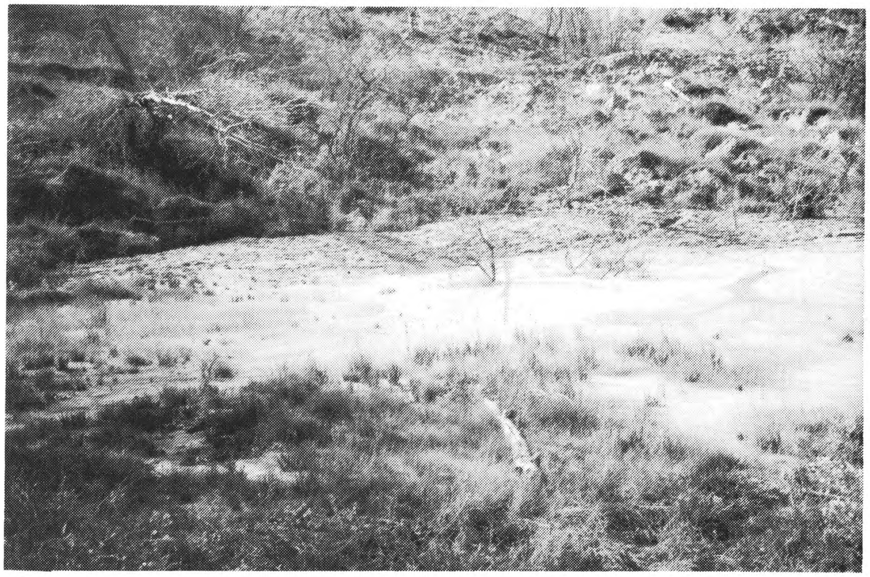


Figure 19.
Thistle landslide. Approximately one week later than shown in Figure 18.



a.

b.

Figure 20.
Thistle landslide a) Sedimented-in depression b) UGMS survey target placed on clump to ride along without burial.

experienced rejuvenated movement in June 1983. The landslide demonstrated well-developed lateral boundaries and a bulbous toe which encroached upon the channel of Seely Creek. Close monitoring of slide motion was established to determine if a landslide dam might occur and to allow time and readiness for emergency action by the State.

Joes Valley Reservoir lies 2.5 miles downstream and to the east in Emery County. A campground and boat landing facility were placed at risk. The calculated worst-case scenario did not project an overtopping of the dam because of its 7.4 feet of freeboard. The inundation map postulated a reservoir of 62.4 acres, with 2453 acre feet of water impounded behind a landslide dam 120 feet in height. An instantaneous failure would have resulted in a 52-foot-high flood wave at the mouth of Seely Creek, and a 10-foot wave would have entered the reservoir four minutes after failure.

Water was flowing over the spillway of Joes Valley Dam at the time of the calculation on June 27, 1983. Under those conditions, the reservoir could have been expected to rise approximately 2 feet (freeboard exceeded 2 feet).

Examination of 1957 aerial photographs by Godfrey (1978) indicated to him that this slide had moved repeatedly. He observed tension cracks "all the way up the slope from the area of active sliding to the base of the cliff."

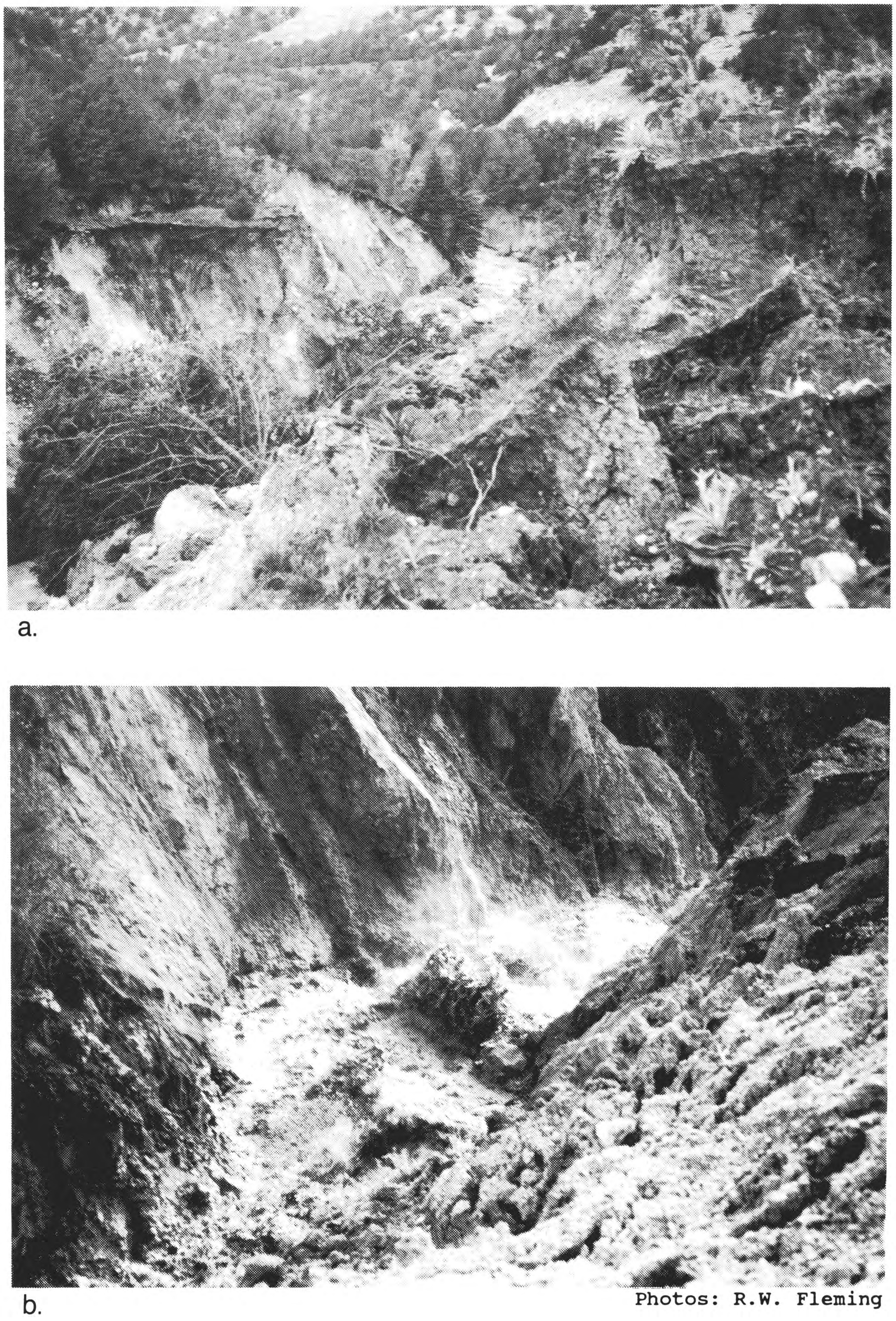
(2) Twelvemile Creek, Sanpete County

About one mile below "The Narrows" in Twelvemile Canyon, east of Mayfield, two opposing landslides were rejuvenated in 1983 (figures 13 & 14). The Twin Lake slide on the northern side of the canyon is about a mile in length and involves very large rotational blocks of bedrock moving towards the south. The slide on the south side of the drainage was about 0.5 mile in length and moving towards the north. Both slides were active simultaneously in June, 1983 and constricted the channel of Twelvemile Canyon (figure 21). However, a 12-foot wide channel, measured from the top of the banks, was kept open by erosion. The town of Mayfield (population: 516) lies at the canyon mouth, approximately 4.5 miles downstream. Farther downstream, Twelvemile creek flows into the San Pitch River which passes through portions of the town of Gunnison (population: 1,325).

The inundation map showed that a flood or a debris flow would affect only the northern portion of Mayfield and the floodplain of the San Pitch River in the south part of Gunnison. Models of both a clear-water flood and debris-flow scenario were devised in this situation because of the large debris flow and flood event which had occurred only a month earlier from the huge Twelvemile landslide farther up canyon. That event struck the Pinchot Campground, 3/4 mile upstream from the site of the potential dam created by the converging landslides.

(3) Thistle Landslide, Spanish Fork Canyon, Utah County

Two inundation maps were prepared for the Thistle landslide. In mid-April, an instantaneous breach map was generated for a potential reservoir depth of 160 feet. This was superseded on May



Photos: R.W. Fleming

Figure 21.
Twin Lakes landslide. Toes of two large opposing slides;
Twin Lakes on right a) early June, 1983 b) late June, 1983.

13, 1983 with a map showing six- and twelve-hour release times for a reservoir depth of 190 feet. On the latter map, the inundation zone limits for the scale of mapping (1"=2,000') were identical. Water depths along the flood path, however, were sufficiently different to depict both on the map. A significant portion of the city of Spanish Fork (population: 11,058) appeared in the inundation zones.

Benchland-terrain slope movements in 1983

Slope failures below an elevation of 5,200 feet (highest terrace of Lake Bonneville) are treated separately in this paper because, below that elevation and within the urban corridor of the state, there exists a prism of mostly loose sediments which contrasts with the geology in the mountainland above 5,200 feet. The majority of the volume of sediments below 5,200 feet are unconsolidated sands, silts, gravels, and clay deposited along the shores of ancient Lake Bonneville. In addition to these lacustrine and deltaic sediments, there are deposits of alluvium (mostly in present-day flood plains), colluvium of variable thicknesses on most slopes, thin veneers of aeolian deposits on the upper benches, and fan deposits consisting chiefly of debris-flood-deposited sediments. Most important to this discussion are limited areas where displaced bedrock blocks are buried at shallow depth beneath a relatively thin veneer of sediment cover which may be especially subject to failure.

Landslides, in general, are not common occurrences on the benchland. The major movements, by far, in size and volume occurred during the Pleistocene, as earthquake-induced liquefaction failures (Van Horn, 1975), the most noted of which occurred in the Farmington area. Nothing similar is known in historic or recent prehistoric times. There are relatively few zones of large-scale landslide activity. The exceptions are the bluffs of the Weber River (north and south sides) in Davis and Weber Counties; the bluffs of the Ogden River on the south side, especially east of Harrison Boulevard, in Ogden; areas on the north and south side of the Weber Valley in Morgan County, and smaller areas in City Creek, Salt Lake County, and Provo's east bench.

Most of the slope failures in 1983 on benchland along the Wasatch Front occurred during the months of February and March. One anomaly is worthy of mention even though it occurred in May of 1982 (Kaliser and Case, 1982). A 150,000 cubic yard rapid earth flow and the largest observed on the Wasatch Front occurred on Wasatch Boulevard at a gravel pit near the mouth of Big Cottonwood Canyon. Hydrogeology and subsurface geometry both played a key role in the failure. The distribution of Quaternary sediments in the shallow subsurface permitted rapid recharge from local drainage to be focused upon an environment that could not accept such pore-water buildup without instantaneous failure. Gravel excavation had removed natural buttressing on the benchland. Nothing similar occurred throughout 1983, nor anywhere else on the Wasatch Front. Events in 1983 were generally quite small, with the upper range being in the vicinity of 10,000 cubic yards. Activity on the benches was largely over before the slopes began to fail, at higher elevations, in the canyons to the east. The relative abundance of slides that occurred on benchland in 1983 offers thoughts with respect to causative factors.

Terrain modification by man

The majority of both translational and rotational slides occur in man-disturbed environments. Most frequently the disturbances along the Wasatch Front have involved grading for residential purposes, road construction or irrigation canals (figure 22). The grading has been observed to be influential to failure in three important ways: (1) additional stresses are applied to cuts made at too great an angle and/or support (resistance) is removed; (2) improperly and

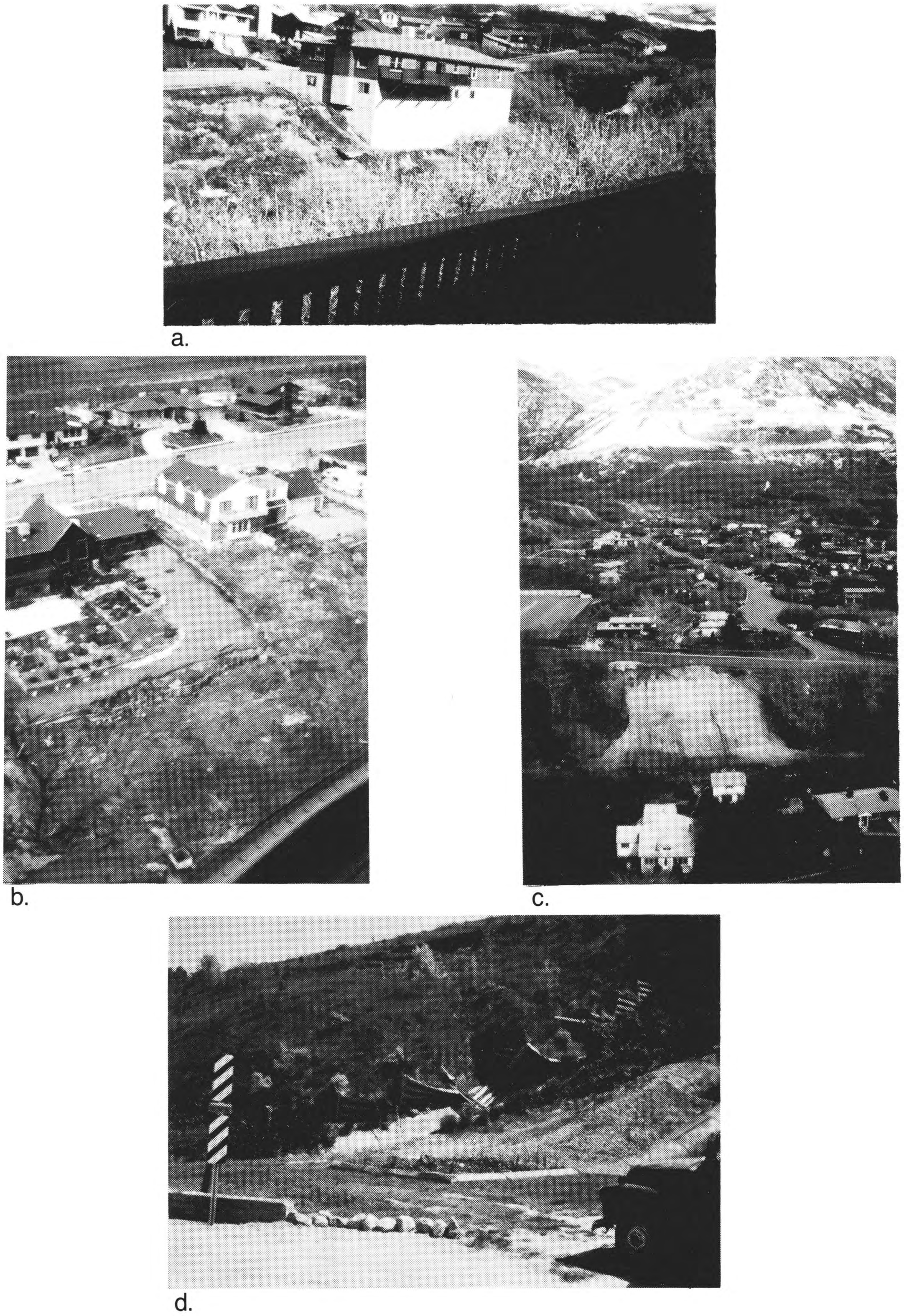


Figure 22.
Benchland landslide contributed to by grading. a) Fill over lacustrine sediments on drainage slope, North Salt Lake City. b) Fill over lacustrine sediments on drainage slope, Layton. c) Fill over lacustrine sediments on Lake Bonneville Terrace, Farmington. d) Fill over lacustrine sediments on south bluff Ogden River, Riverdale.

injudiciously placed fills load the slopes and apply excess stresses and/or load or increase in driving forces; and (3) benches or terraces that are created provide local conditions of ponding for optimal recharge of rainfall and snowmelt, but particularly the latter.

The slides that occurred in Emigration Canyon were mostly related to steep road cuts (40° or more), where colluvium and residual soil (red, sandy, silty clay) derived from Kelvin and Preuss Formations failed in thin, translational slices. South of Emigration Canyon, on the mountain front in the Chidian Hills neighborhood of Salt Lake City, two failures occurred within hours of each other on March 30 and 31. These failures were in 2 to 4-foot-thick colluvium on two different cut slopes, the first for a residential lot and the second for a very old, unimproved road. The same dirt road crossed the failed slope at the first site, so that it ostensibly provided a bench for infiltration of rain and snowmelt.

It is uncertain whether the Rudd Creek failure could not have been due, at least in part, to disturbance years earlier in connection with a culinary water system for the City of Farmington. Old pipe was seen exposed in a few locations along the trail that was taken up the canyon after the debris flow event. The water project was an old one, and a search for plans was unsuccessful. The springs that were originally tapped may have issued from the failed slope or may conceivably have affected ground-water conditions in the materials that became mobilized in the debris flow.

What started out as a fill failure in a short, deep swale in benchland in North Salt Lake City appeared to spread to the neighboring lot over a period of about 6 weeks and finally affected the newly constructed home (figure 22). Fill was apparently placed improperly, and probably uncompacted, on steep slopes at the time neighboring lots were developed. There was a spring at the toe of slope, but there is no clear evidence that it played a role in failure. Snowmelt penetrated the fill and caused it to slump. Additionally, the fill may have surcharged the slope, exacerbating the failure.

Natural terrain modification

The most common type of modification experienced along the Wasatch Front was the deepening and widening of drainage channels during flood periods. Severe erosion of the channel of Coldwater Canyon in North Ogden by a debris flow in 1983 most certainly led to the rotational slump/slide failure on the south side, at the canyon mouth. Movement toward the north was quite slow as the mass continued to slump.

Additional movement of ancient slide masses at Mountain Green, Morgan County was, in part, related to the erosion by Gordon Creek which had permitted retrograde movement from the toe to the head of the ancient slide. The prime mover of this slump/slide complex was saturation of recent and older slide masses which caused a rapid reduction in strength or shear resistance of the clayey material.

Two small slumps in the same, short, benchland-drainage in North Salt Lake City were largely the result of deepening of the ravine in historic time, due perhaps to redirected surface drainage. Both occurred in weathered, semi-consolidated, Tertiary age sandstone on opposite sides of the drainage. Scrub oak up to 12 feet tall covered the 35° natural slopes. Infiltration of rainwater and snowmelt had increased as a residential subdivision was developed above the zones of failure. Gravel extraction at an earlier time may have also adversely affected surface drainage. A spring also exists at the head of this drainage, less than 1/4 mile away. None of the other numerous, similar drainages in the North Salt Lake City vicinity have experienced any slope failures.

On the westernmost fault trace of the Wasatch Fault system in Provo, along Old Willow Lane, a slump occurred on the face of the 35° scarp. Movement was first observed over a period of about weeks in February and additional instantaneous movement in March. On March 16, 1983, about 1 gallon per minute issued from the lower part of the slide. No other evidence of historic or prehistoric slope failure was seen in the vicinity of this location.

Morphology of prehistoric slides is not uncommon in the location of 1983 events. This is unequivocally the case at Mountain Green, Morgan County (Kaliser, 1972); along the Weber Basin Canal in Morgan and Weber Counties; and on 1500 East in Provo. Even at Rudd Creek, the wedge of unconsolidated material perched in that small drainage looks very much like an ancient landslide mass.

The rotational slide south of South Weber Drive in Riverdale has reactivated precisely along the lines of the ancient slide mass. There is no reference data of historic movement of the greater slide mass but at least one small debris flow off of the toe of the ancient slide mass has occurred historically.

Distribution of thin covers

It is not uncommon to view a veneer or thin cover of contrasting surficial geologic material exposed in a new slide. At the Browning Arms property (Morgan County), a rotational slide developed along Cottonwood Creek. This slide or slump formed within the slope alongside the flood plain. A veneer of alluvial gravel undoubtedly aided in infiltration and recharge of the underlying, varved (layered) Bonneville sediments.

In Utah County, blocks of Great Blue and Manning Canyon Formations occur commonly in the benchland but are buried beneath thin sequences of the Lake Bonneville and other Quaternary materials. Most frequently, there is no or very little surface expression of the buried mass. In 1983, there were some 25 slides that were the result of either perched ground water overlying these buried, low permeability, shaley lithologies, or at least heavy infiltration into the lacustrine beach deposits, greatly reducing shear strengths. The above-mentioned 10,000-cubic-yard slide (1500 East) in Provo is clearly the result of such a subsurface anomaly (figure 23). Photographs taken prior to the February, 1983 movement show a displaced block of bedrock perched in a road-cut exposure just below the Bonneville terrace (elevation about 5200 feet). Plasticity of the material derived from the calcareous shale permitted earth movements of 8 to 10 feet per day.

At Edgemont, east of U.S. Highway 189, there were several slides related to similar subsurface environments. Seven feet of gravelly, silty, colluvium covered weathered, dark-gray shale on one 27° natural slope. This slide occurred at the top of a road cut (38°) over a distance of 70 feet and for a length of 100 feet. Resistant limestone crops out not far downslope on the same bench; 100 feet higher on the slope is a natural terrace which collects surface moisture. This terrace was nonexistent immediately north and south. Contributing factors seemed clearly to have been: 1) presence of a road cut (38° slope) through the mass; 2) presence of a porous colluvial material over the weathered shale to a depth of 7 feet; 3) the shale occurrence between resistant limestone beds; and 4) presence of a natural bench immediately upgradient to trap infiltrating water from melting snow. The importance of the latter is illustrated by the fact that no such bench occurs immediately north and south and where no such slope failures were found. In the next draw to the north, an old slide three times the size of the 1983 failure is apparent, perhaps historic in age.

It can be very important to know whether one is simply confronted with a veneer of contrasting material or if the entire slide mass is comprised of the material exposed at

Figure 23. *Debris slump on high east bench of Provo.*

the ground surface. In the former case, the slide may well be deeper and rotational in nature. In order to comprehend the ultimate behavior of a slide in benchland, it has become important to determine whether the slide is confined to the same material exposed at the surface or whether a buried contrasting material is a possibility. It may be too easy to jump to conclusions with respect to what is, in fact, limiting the failure only to a veneer of surficial materials.

In Logan (Cache County), there were several slides along the old river bluffs in the vicinity of the Logan Northern Canal. The gravelly, sandy-silt colluvial cover on the steep slopes bounding the canal became saturated and slumped downslope into the yards of residences. Some of these failures have involved the underlying Bonneville-age deltaic sediments as well as the colluvial materials. It is believed that the primary dip or geometry of the sediments likely controls the migration of perched ground water to the free faces of the bluffs.

In Little Cottonwood Canyon (Salt Lake County), a thin colluvial veneer exists over semi-consolidated glacial till. This relationship is exposed within a cut slope on the north side of the road east of Tanner Slide. This veneer was responsible for a small failure east of Tanner Slide (avalanche path) in Little Cottonwood Canyon (Salt Lake County). Some 20 feet of vertical section slumped on May 26 due to the presence of a very local ground-water anomaly. The anomaly was substantiated by the fact that well-defined drainages immediately to the north and south experienced no slope movements. Vegetative contrasts also occurred in the immediate vicinity, more obvious at the higher elevation than down along the mountain front.

Geologic structures

In both Logan and Ogden, west of the mapped fault zone of the Wasatch Fault system, minor local structures related to faulting are sometimes observed in the headwall scarps of slides. These take the form of small, open joints, sometimes with partial infillings of reworked material. Offsets, or micro-faults, have also been observed. It is most frequently not possible to determine whether these structures are tectonically created or the result of stress release of soil masses behind the bluffs. Small slope adjustments may have occurred in prehistoric earthquakes, causing the fractures to open and close. This fault-related fracturing of bedrock allows more rapid infiltration of ground water accompanied by weathering/decay of the affected rock units and, in turn, a weakening of the rock material. It is likely that these structures have a definite effect on vertical infiltration of soil moisture and, especially, lateral migration of ground water. Because of these near-vertical planes, pore-water pressures develop rapidly within the soil masses and create a triggering mechanism.

An example of where geologic structures may have been of influence in the slope failure is the landslide on the north side of the mouth of the Ogden River. At this location, the penstock to the nearby powerplant was broken twice in 1982 by a slope failure just below the surge tank; the second failure occurred on December 9, 1982. Five years prior, sand and gravel had been excavated from a borrow area at the toe of the same slope. The complex, 300-foot long by 300-foot wide landslide is rotational at the head, translational in the main body, and an earth flow at the toe (Grundig, 1983). Materials involved are Bonneville-age sediment over bouldery colluvium mantling bedrock. The strike of the Bonneville sediments (N50°W) and the 10°SW dip are anomalous, the result of either ancient sliding or deformation in the Wasatch Fault zone. Small offsets were also observed. Some 20 gallons per minute of ground water issued from the slide above a several-foot-thick clay bed, and it can be surmised that the subsurface flow was at least somewhat controlled by the local structure as there is a 10°SW dip in out-of-bench or free face, conditions of structure conducive to bedding plane failure (or partial bedding-plane failure).

Rainfall-triggered debris flows

With the exceptional amount of infiltration related to snowmelt along the benches of the Wasatch Front, one would think that spring rains should trigger numbers of failures, especially on steep slopes. This was not true, however. The senior author is personally aware of only two such events in 1983. One that he witnessed was just west of the mouth of Hobble Creek, in Bonneville-age deltaic sediment. On August 18, 1983, 1 inch of rain fell in 3/4 hour, following 2.5 inches of antecedent rainfall for the prior four days. A strategically located, clayey silt horizon created a perched water table from which a discharge of two gallons per minute occurred. A coarse sediment debris flow resulted in the location of ground-water seepage. Another instance was later noted along another bluff to the north of Provo. It is unknown whether or not this was during the same storm period. In the latter case, the spring flow was considerably greater, and the saturated sediments flowed over a road.

Rock slide

Only a single example of a rock slide has been documented along the Wasatch Front in 1983. Movement experienced was that of creep only, and the mass involved was complicated by being bound by a free or excavated face created decades ago in a shale (clay) quarrying operation (figure 24). During 1983, the movement spread upslope and to the north so that it crossed a lithologic contact within the Precambrian Big Cottonwood Series, the shale unit crossing over into the quartzite unit to the north. Within the quartzite at the head of the slide, there is an ancient rock slide, as evidenced by its geomorphic expression which shows no evidence of historic activity.

This slide never matured to the point where any portion of its toe was discernible. The depth of the failure remains unknown but one can speculate that the slide is not shallow from the existing pattern of ground cracking that has emerged. The rock is highly fractured and weak, having been tectonically disturbed in the zone of the Wasatch fault.

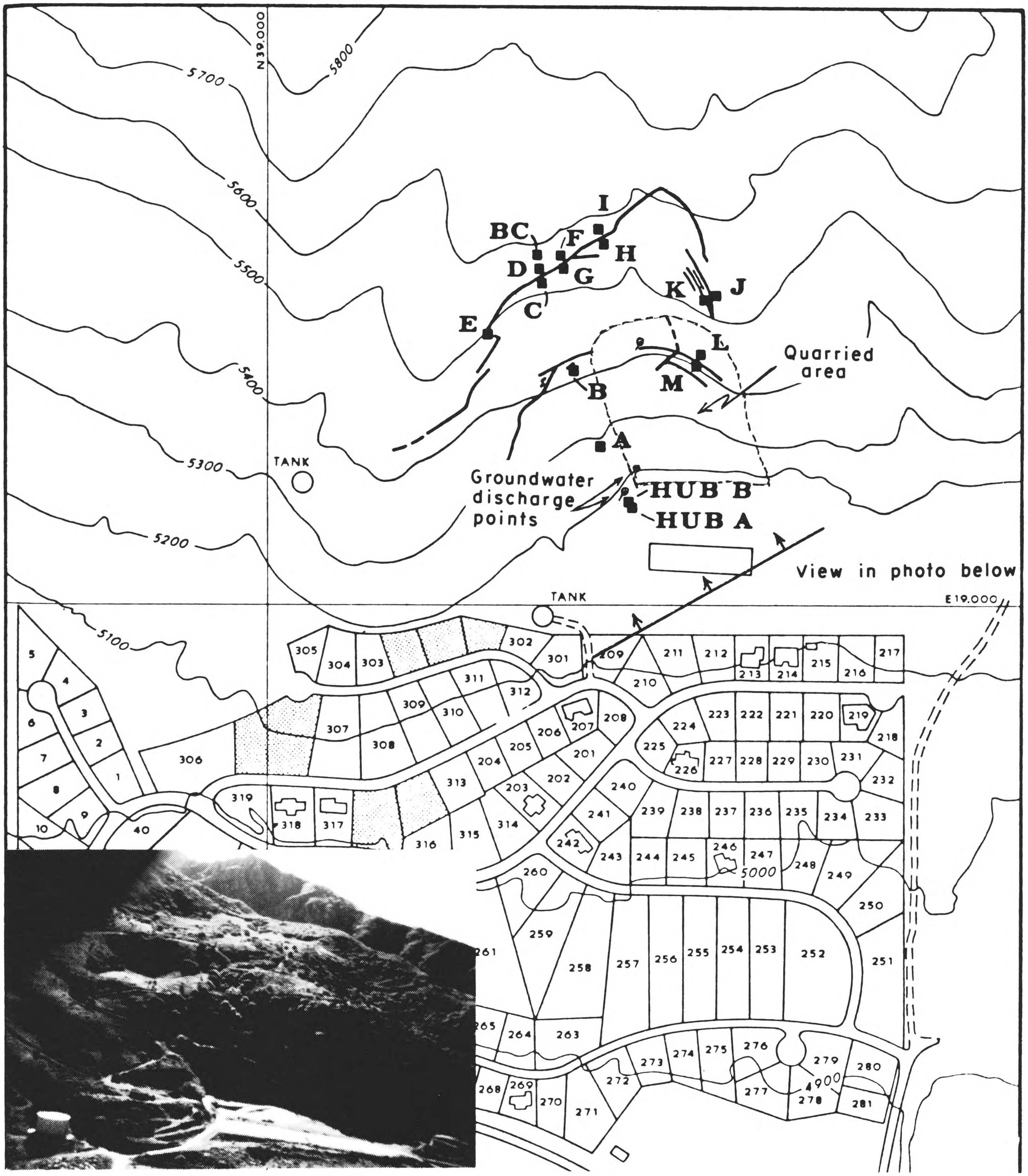


Figure 24. Ground crack and survey point location map, Canyon Cove Landslide.

Survey measurements were taken for a number of stations in and just outside of the slide area from April 29 through October 19, 1983, by Salt Lake County Engineer Roy Baty in cooperation with UGMS (figure 24). Table 5 shows results from four stations near the crown of the slide. By mid-June, movement appeared to have largely ceased. Daily strain rates of 0.002 to 0.08 foot per day have been calculated. Activity prior to April 29 is not known, except that ground cracking did evolve prior to that date.

This slide poses some very real questions of risk to both public and private properties. Many lots in the subdivision are undeveloped. Both developed and undeveloped lots, however, lie in the path of a resulting landslide failure and/or debris run-out zone. The water tank (figure 24) might also topple and fail within such a zone. Given the high topographic relief of this slide and the large number of unknowns, consideration must be given to the potential for an instantaneous failure and a catastrophic run-out. This slide, therefore, illustrates concerns that arise over risk from an earth movement in the urban environment.

Wasatch Front mountainous terrain slides

The Rudd Canyon debris flow of May 30 in Farmington, the county seat of Davis County, focused considerable attention upon the debris flow hazard on the Wasatch Front, particularly in Box Elder, Weber, Davis and Salt Lake Counties (figure 25). All of the debris flows were triggered by slope failures of the debris slide type. Approximately 100 debris slides occurred in 1983 in the mountainous terrain in Davis County alone, where most of the slope-failure activity appeared to be concentrated in northern Utah.

As the Wasatch Front coincides with Utah's urban corridor, this stretch of slope activity becomes quite significant. From north to south, the affected canyons along the Wasatch Front are listed below along with the approximate elevations of the debris-slide crowns. Also indicated are whether the slides occurred on the north or south side of the drainage and reportings of estimated debris-flow runouts. In parentheses, following the name of the drainage, are listed:

- the average main-channel gradient;
- the volume, in cubic yards, of the largest single debris flow event in 1983;
- the estimated volume, in cubic yards, of the largest, single, partly-detached landslide mass (figure 26) observed after the activity in 1983.

The listing is from north to south. Elevations and locations were chiefly from notes taken during joint UGMS/USFS aerial reconnaissance missions undertaken in 1983. Gradients and volumes (converted) are from Wieczorek, et al., 1983.

BOX ELDER COUNTY:

Facer Creek (.307/3,900 ± 650/39,000±6,500)

North	South
7,800' 7,600'	7,200' 6,150'
7,800' 5,400'	7,000' 6,000'
7,800'	6,200' 5,900'

Note: Runout of one or more debris flows occur as far as the mouth of the canyon

Willard Creek (.195/10,500±1,300/13,000 ± 2,600)

North	South
7,950' 7,200'	6,500'
7,600' 7,200'	

Note: Runout of one or more events has occurred down the lower half of the drainage.

WEBER COUNTY:

Coldwater Canyon (.205/15,700 ± 2,600)

North	South
(none)	8,000' 7,200' 7,100'
	7,700' 7,200' 7,100'
	7,600' 7,200' 5,000'
	7,400' 7,200'

Note: Runout of one or more events reached the mouth of the canyon.

DAVIS COUNTY:

Corbet Creek

North	South
(none)	7,650'

Middle Fork, Kays Creek

North	South
(none)	6,850'

North Fork Holmes Creek

North	South
6,400'	(none)

Note: Runout occurred to the canyon mouth.

Holmes Creek (.209)

North	South
7,150'	(none)

Note: Partial runout occurred.

Baer Creek (.166/3,100+525/26,000+6,500)

North	South
8,200' 7,150'	7,850' 7,600'
8.050' 7,000'	7,700' 6,600'
7,900' 7,000'	7,600' 6,250'
7,000'	6,200'

Note: Runout occurred as far as the canyon mouth;

2 slides on north side, 1 on the south side.

Half Canyon
7,600'
Note: Runout reached the mouth of the canyon.

Shepard Creek (.175/6,500±1,300/2,600±260)

North	South
7,300' 7,100'	7,500' 6,150' 5,750'
7,200' 7,100'	7,200' 6,100' 5,400'
7,200'	6,400' 5,950' 5,350'
	6,250'

Farmington Canyon (.127/22,000±3,900/52,000±6,500)

North	South
8,100' 7,400'	7,000'
8,000' 7,400'	5,800'
7,900' 7,000'	5,800'
7,550'	

Note: Halfway Creek (northern tributary) runout reached the main drainage.

Rudd Creek (.314/84,000/92,000/130,000)

North	South
7,500'	(none)
7,400'	
7,200'	
7,000'	

Note: Runout from a debris slide situated in the main drainage reached beyond the mouth of the canyon and did damage.

Steed Creek (.341/13,000±2,600/33,000±6,500)

North	South
8,050' 7,500'	(none)
7,900' 7,400'	
7,500'	

Hornet Creek Trib.

North	South
6,500' 6,300'	(none)
6,400' 6,100'	
6,400' 6,050'	

Note: Partial runout occurred on Hornet Creek.

Ricks Creek (.203/1,460±260/52,000±650)

North	South
7,800'	8,000'
7,750'	
7,600'	
7,600'	
7,550'	

Barnard Creek (.195/8,400±1,300/13,000±2,600)

North	South
6,900'	7,500'

Parrish Creek (.177/1,300±260/65,000±13,000)

North	South
7,950'	7,650' 7,400'
7,850'	7,500' 7,050'
7,750'	7,500' 6,950'
7,750'	

Centerville Canyon (.140/2,600±260)

North	South
7,300'	7,400' 6,200'
7,000'	7,350' 5,850'
6,800'	7,200'

Ward Canyon (.126/20,000±2,000/2,600±650)

North	South
8,300' 7,600'	6,900'
8,200' 7,050'	6,200'
8.050' 6,100'	6,000'
8,000'	

Note: Runout occurred of both a north tributary and the main drainage to the canyon mouth.

Barton Creek (.120/29,000±5,200/55,000±6,500)

North	South
7,950' 6,700'	8,150' 7,200' 6,850'
7,300' 6,600'	8,000' 7,050' 6,800'
7,200' 6,400'	7,250' 7,000' 6,850'
7,100'	5,800'

Note: Runout occurred to the canyon mouth.

Mill Creek

North	South
8,250'	6,400' 5,700'
7,050'	6,150' 5,300'
6,000'	5,950' 5,300'
5,700'	5,950'

SALT LAKE COUNTY:

Mountain Dell Canyon
7.950' 7,700'
7,900' 7,600'
7,900' 6,850'
7,800'

Box Elder Hollow Trib.
7,900' 7,500'
7,600' 7,500'
7,600' 7,600'

Headwaters, near Morgan County line

8,300'
8,200'
8,100'
8,050'
7,500'

Red Butte Canyon
7,700' 7,500' 6,900' 6,800' 6,350'
7,500' 7,200' 6,800' 6,700'

Emigration Canyon (Pinecrest Area)
7,200' 7,100' 6,950' 6,700'

Parleys Canyon
a. Pharoah Glen (south side)
7,700' 7,300' 7,100' 6,800'

b. Mount Aire (south side, upper portion of basin)
8,100' 7,800' 7,800' 7,650' 7,500'
8,000' 7,800' 7,650' 7,500'

c. Lambs Canyon (south side)
7,800' 7,700' 7,700' 7,600' 7,450' 7,400'
7,250' 7,200' 7,800' 7,700' 7,700' 7,500'
7,400' 7,300' 7,200' 7,100'

Mill Creek
7,850'
a. Church Fork (north trib.)
6,800'
Note: Runout occurred as far as the main Mill Creek drainage.

Big Cottonwood Canyon
8,200' (east of Maxfield Basin)
a. Reynolds Gulch
North
8,300' 8,300' 8,200' (east of the Spruces)

Little Cottonwood Canyon

North	South
(none)	8,950' (northeast wall Peruvian Gulch)
	8,100' (west of Hogum Fork)

Slides on the north and south sides of canyons (south and north exposures, respectively) are more or less evenly distributed over the Wasatch Range.

Using color infrared photography taken on June 12, Pack (1985) inventoried the landslides from Holbrook Canyon north to Baer Canyon in Davis County. He documented over 90 slides, although he was unable to provide a temporal relationship. Spatially, however, debris slides occurred in all the major canyons, and many occurred in the vicinity of past debris slides (ages unknown). Occasionally, they are in clusters. "Half canyons" (canyons on the Wasatch Front which extend only approximately half way to the divide or spine of the Range) yielded no debris slides except for Rudd Canyon, according to Pack (1985). However, the technical team serving as observers during the

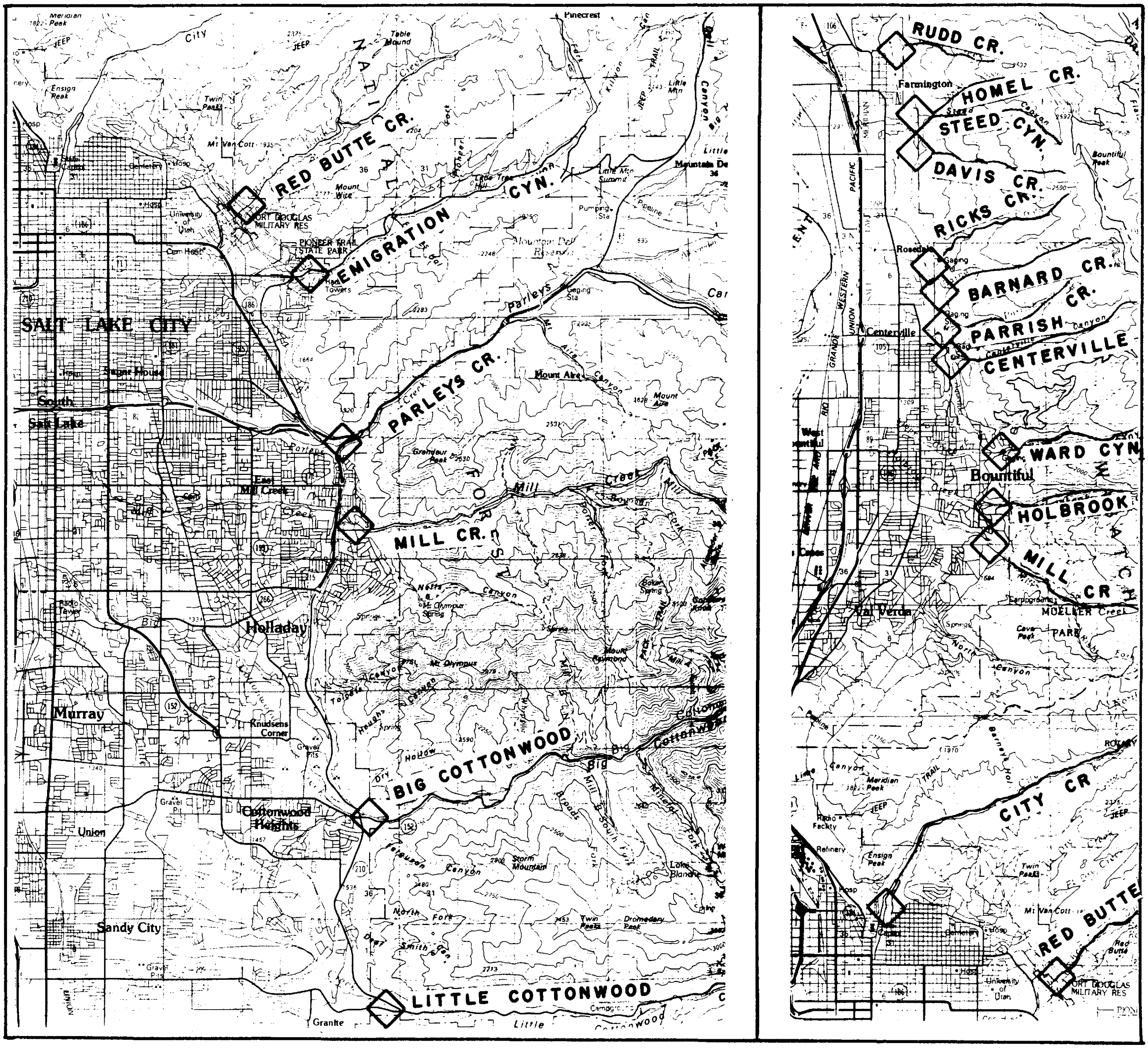


Figure 25a.
Wasatch Front canyons containing 1983 debris slides; Salt Lake county north to Farmington.

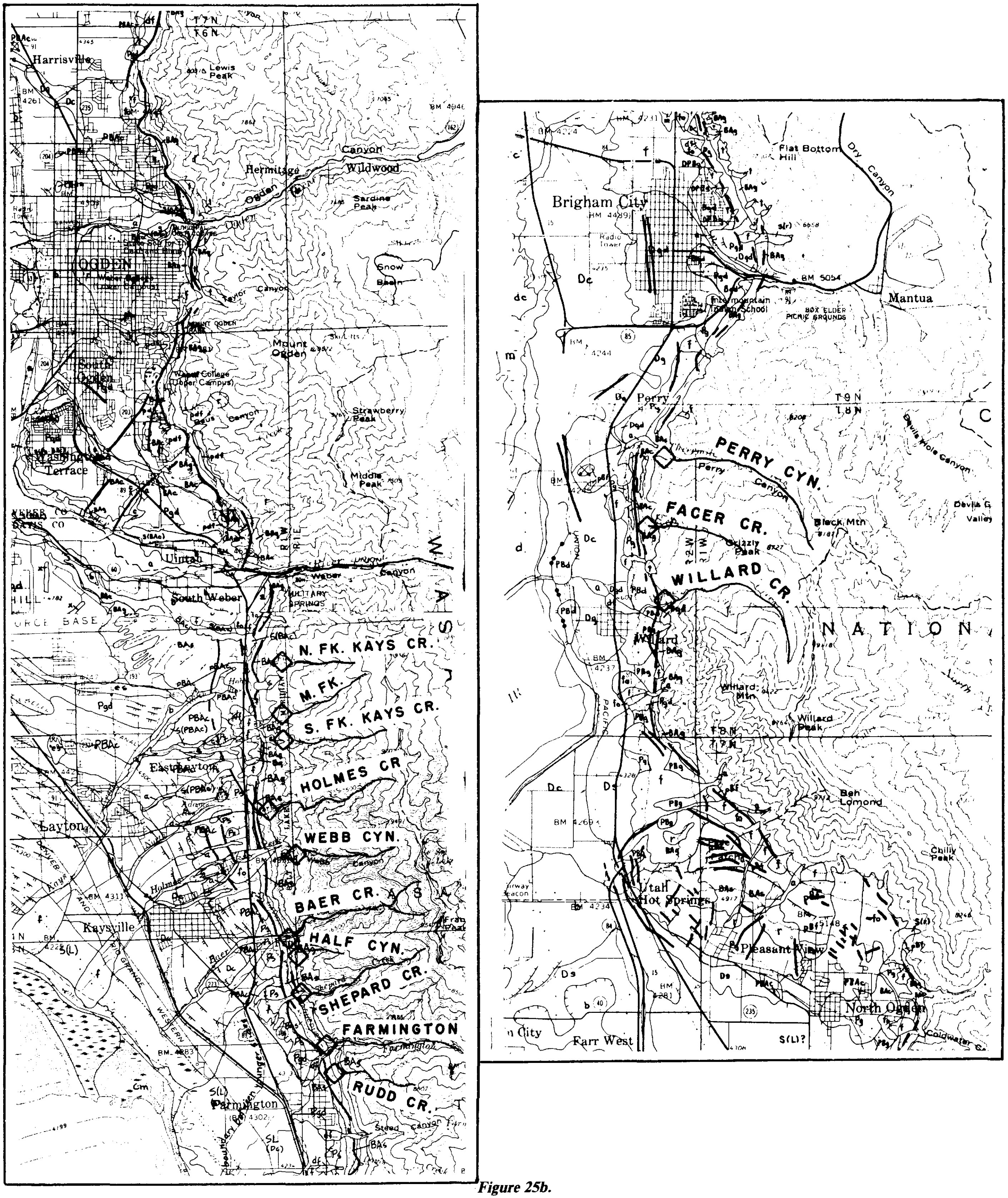


Figure 25b.
Wasatch Front canyons containing 1983 debris slides; Farmington north to Brigham City.

crisis period did map a slide in Half Canyon, between Baer and Shepard Canyons. Mountain front, west-facing, faceted spurs also yielded no debris slides, although spouts of water were observed occasionally on these slopes by the senior author. These "spouts" were formed by water jetting from an orifice in the rock, obviously under artesian head.

Pack (1985) shows a density per square mile (from 0.7 to 4.3) for the 14 catchment zones he examined. He states that there is a "general uniformity of two to four events per square mile over the watersheds." With a number of Davis County watersheds excluded from this area of study, however, these results can not be considered conclusive. There was also no correlation with size of slide nor clarification as to how coalescing slides were catagorized. In several canyons, slide areas were seen to grow, and coalesced over a few weeks.

Characteristics of Wasatch Front debris slides

Observation during the entire crisis period by the writer and others and later examination of a number of the slides in the field, some with Paul Winkelaer of the U.S. Forest Service, Wasatch National Forest, plus documentation by Robert Pack (1985) have led to an ability to, in part, characterize the debris slides with respect to shape, materials, moisture regime, geomorphic setting and geology.

Slope failure sequence: The first signals of many debris slides were seen as initiating from propagating ground cracks. These cracks first appeared at the crown and frequently developed in an arcuate shape typical to the first sign of slope failure. Sometimes flanking fractures would develop prior to failure but, commonly, these occurred too close in time to the moment of failure to provide a warning. Upon failure, the failed or dilated material often liquefies and flows immediately, or blocks of material are displaced downslope until they became disaggregated mechanically. By the addition of water, either from the slide zone or from the drainage into which the failure occurred, the mixture then begins to flow.

Downslope failure of a mass from the slope may then trigger other incipient failures in juxtaposition so that a new generation of ground cracking and slope failure may follow the evacuation of the initial debris slide. Steep topographic gradients often occur below areas where debris slides are initiated, causing slope and channel scour or erosion. Removal of lateral support for soil higher on the slope may then result in new instability, ground cracking, and failures.

Following the Rudd Canyon failure, several detached blocks were observed in the zone of evacuation of the slide. Continued aerial reconnaissance showed these to move partially or totally downslope. A slice 75 feet in width, delineated by a continuous, well-developed ground crack, was observed on the mid-canyon slide crown, but did not subsequently move to any noticeable degree. Other longer ground cracks rapidly propagated on the canyon slope bounding the slide area on the north, but these never matured much

Figure 26.
Partly detached landslide mass perched in debris slide in steep mountainous terrain. Note channel scour below the clustered slides, indicative of debris flow run-out.

Table 5 Vertical Displacements (in feet) for Canyon Cove rock slide, Salt Lake County.

Number of days		3	6	13	26	39	52	173
Date	4/29	5/2	5/5	5/12	5/25	6/7	6/20	10/19
Left Flank ("M)	0	0.19	0.21	0.38	1.4	1.6	1.68	1.88
*	0.06	0.01	0.02	0.08	0.02	0.01		
Center ("H")	0	0.06	0.05	0.19	0.49	0.54	0.78	0.73
*	0.02	——	0.02	0.02	0.004	0.002		
Right Center ("G")	0	+0.02	+0.03	-0.03	0.35	0.43	0.56	0.55
*	0.01	——	——	0.02	0.006	0.01		
Right Flank ("C")	0	0.10	0.14	0.17	0.49	0.59	0.71	0.72
*	0.003	——	0.004	0.02	0.008	0.02		

Survey by Salt Lake County in cooperation with U.G.M.S.

* Average daily strain rate, feet per day: i.e., 0.06 = 6/100 feet per day.

further in 1983. It is very likely that the failures which develop will become avenues for rapid infiltration of rainwater and snowmelt.

During the Rudd Creek event, the senior writer observed that surges continued at about twenty-minute intervals for three hours after failure. The interval lengthened throughout the night. Observers were placed both on the mountain and at the canyon mouth during the crisis period, and their careful notations are of interest with respect to observations subsequent to the first debris flow on May 30. A portion of the observers' logs appear thus:

June 4

10:00 AM	Some bank slippage (small) Very muddy flow
12:49 PM	Dust and muddy water
12:50 PM	Debris flow front approximately 8 feet high with large boulders
12:56 PM	Flow moving faster; more water content; 10 to 12 feet deep
1:00 PM	Large slide, big boulders 4 to 10 foot surge fronts
1:50 PM	Still 2 feet above previous normal flow stage Flowing mud with some debris
7:06 PM	Large rocks and debris; thick mud
7:18 PM	Stage has dropped; mud has thinned
7:24 PM	Return to normal

June 5

2:00 AM	Intermittent rain
10:26 AM	5 foot wall of mud, boulders and water
10:30 AM	Rise of stage by 8 inches; muddy, rocky
10:37 AM	2 foot above previous normal stage
10:45 AM	4 foot surge front
10:47 AM	2 feet above normal stage
11:57 AM	Stage slightly above normal

On June 11, following intermittent rain all day and heavy rain at 5:00 PM, the flow was becoming muddy at 7:35 PM, then quite dark with considerable mud and rock at 7:54 PM.

Blockage was reported at 7:57 PM three-quarters of a mile above the mouth, and at 7:59 PM, a mud flow occurred followed by another at 8:23 PM. On June 14, a ground crack enlarged at 2:19 PM at the site of the previous slide-caused blockage, three-quarters of a mile above the mouth. Pierson (1985) noted that during the time of the June 5 flow, four surges occurred within 15 minutes of each other. The discharge returned to normal rates only minutes after each surge, but dilutions back to normal concentrations of sediments took hours.

These observations seem to indicate: (1) rapid vacillation back and forth between debris flow and debris flood conditions; (2) high-intensity rain initiated resurgences in activity; (3) channel bank sloughing caused debris flow surges; (4) instantaneous blockages caused debris flow surging; and (5) the presence of detached-mass creep well after recession of the snowline to higher elevations (2 weeks in this instance).

<u>Morphology</u>: Pack's examinations in the field enabled him to conclude that five types of debris slides were recognizable based upon shape. These are: linear, fingered, twinned, triangular, and fanned. This characterization may be an over-simplification; nevertheless, these shapes are presented below.

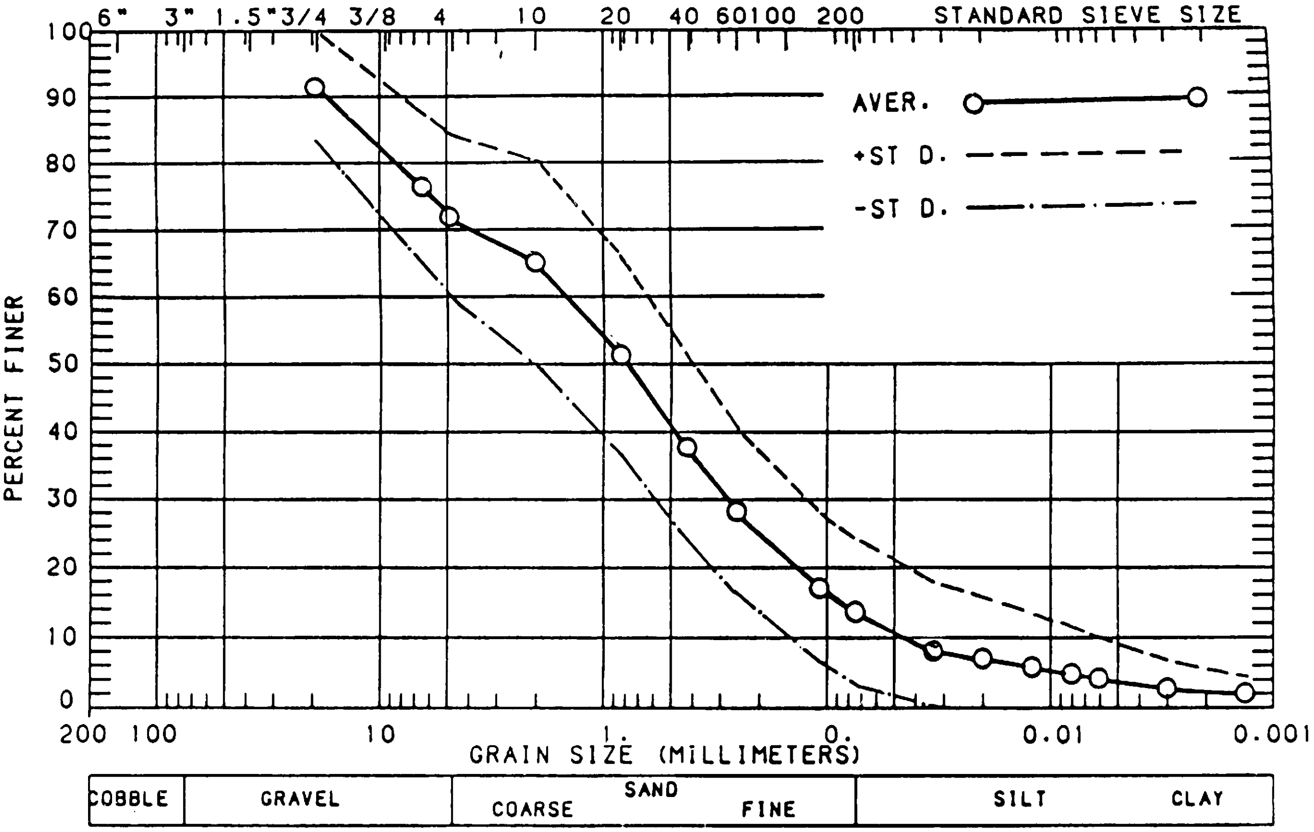
- The "linear"-shaped debris-slide has a large length-to-width ratio. The width of the debris flow which results is generally the same as that of the slide.
- "Fingered" debris-slide morphology is where there is close association of a number of linear landslides. This configuration may also be analogous to a webbed foot or a branching tree.
- "Twinning" refers to the case where each flank of an arcuate ground crack fails, so that a pair of debris slides results. Fleming (1985) has hypothesized that dilation of the soil mass occurs at these locations, and subsequent saturation induces failure, often close in time.
- "Triangular" morphology is where the length-to-width ratio of the slide is low, but the debris is quickly concentrated into a gully downslope.
- Where the slope morphology immediately downslope does not permit the toe to concentrate, there is a fanning out instead. Loss of energy downslope results in the deposition of thin deposits on top of the original ground surface.

<u>Earth materials</u>: Earth materials vary considerably between Davis County and elsewhere due to the nature of the parent material. In Davis County, there is relative homogeneity due to the areal extent of the Farmington Canyon Complex with its generally restrictive range of lithologies. These metamorphic rocks consist largely of mica schist and quartz monzonite gneiss with quartz veins, pegmatites, aplites and phyllites. Pack (1985) collected 80 samples from 14 debris slides and found rather uniform results from the mechanical and Atterberg limit testing (figure 27). Colluvium, residual soil, well-weathered bedrock, and even the developed "A" horizon (topsoil) have similar percentage means of fines (minus 200 fraction) of 15.7% and standard deviations of 8.8. Frequently, a clay-rich zone, seen as a thin horizon, exists between the weathered bedrock and the residual soil. Analyses of this clay-rich zone show a contrast, with a mean of 41.3% for fines and a standard deviation of 11.6. This latter zone of fines (clay/silt) appears to be the failure surface along which the debris slide material is initially translated downslope.

The colluvium, residual soil, and weathered bedrock from Farmington Complex terrain are generally nonplastic. Maximum values of plasticity index (PI) were 4.6 for colluvium, 7.8 for residual soil, and zero for weathered bedrock. The limited, thin, buried, clay-rich zones tested with PIs of 3.9 to 15.3, with an average PI of 9.7 (8 samples). Unified Classification System designation for the former soils is SM, silty sand, and for the latter, SC-CL, clayey sand or silty clay.

Unfortunately, no testing of materials has been done for areas underlain by other bedrock, but the sedimentary rocks that comprise these are very likely to yield residual soils and colluvium with a higher percentage of fines and higher PIs. One can speculate that the percentages of fines, in fact, would be sufficiently high and the materials sufficiently plastic enough to be the single greatest factor that prevented long-distance run-outs in Salt Lake County. In City Creek Canyon, for example, the Tertiary-age pyroclastic rocks and the conglomerates both yield colluvium and residual soils with a significantly greater percentage of fines, particularly clay.

Moisture regime: It may be argued from the evidence at a number of debris slides that there was not total-section saturation at the time of failure. Reconnaissance of some of these debris slides revealed clear evidence of piping and blowouts in the lower portion of the slide headwall. Thus, it appears that



From Pack, 1985

Figure 27.
Average grain size distribution curve for 65 soil samples taken from 1983 debris slide areas on Farmington Canyon complex terrain, Davis County.

mobilization occurred without total saturation, but that there was sufficient pore-water pressure to put the slide in motion and essentially carry, or raft, portions that were not saturated.

In June of 1983, Utah State University personnel (Pack, 1985) placed standpipe piezometers adjacent to several of the debris slides soon after failure. At Rudd Creek, two piezometers were installed on the upper bench at depths of 5 and 10 feet on June 10. They remained dry one half-hour after placement and, on the next visit on June 22, they were still dry. At a slide in Steed Creek drainage, three piezometers were installed at depths of 7.1, 10.3, and 10.5 feet. All three remained dry although water was observed in a fracture near one piezometer and flow was emerging from the scarp face directly downslope of another at an equivalent depth below original ground surface. In September, the latter showed only a 7 inch rise above its tip. These data suggest that much of the soil volume may have remained unsaturated, with the water taking distinct paths. These data, again, suggest that unsaturated portions appear to be picked up and rafted by/with the fluid portion.

At four other sites, twenty-one piezometers were hand driven by the Utah State University team to depths of as much as 18.6 feet. Starting on June 10, readings were taken at intervals of from one to three weeks for approximately three months. Twelve of the piezometers showed no water from the day they were installed. The remaining nine piezometers offer data for speculation. One, at a depth of 5.3 feet, in Ward Canyon, recorded a positive head of 0.5 foot while an adjacent instrument installed to a depth of 2.1 feet remained dry. No seepage was observed in the vicinity. Later, laboratory testing confirmed installation was done in soils of hydraulic conductivity varying by a factor of about 1000. The University team concluded that remarkably high pore-pressure gradients existed within the shallow soil column. While this may very well be true, close inspection in the field by the senior author and Paul Winkelaer (U.S. Forest Service soil scientist) was unable to confirm such lateral variability in soil textures over short distances. We suspect that the manner of placement of the piezometers may have had much to do with the results.

At the site in Ricks Creek, seepage was in evidence throughout an extended area around the piezometers. Two of the devices, however, at depths of 10.1 feet and 15.8 feet, remained dry throughout the measurement period, further arousing suspicions of what was really happening. Two piezometers that were in soils with high permeabilities showed rapid fluctuations. In July, one instrument installed to 12.2 feet in soil with a K of 0.06 cm/sec., receded 7.7 feet and dried up within one week's time. A second instrument, installed to a depth of 10.6 feet in soils with a K of 0.08 cm/sec., showed random fluctuations over a 3 foot interval during the entire summer.

In three of the nine piezometers with water levels, the levels remained static or increased slightly during the summer. In the others, the levels generally declined through late June, July and early August, and then increased from mid-August to early September. These responses seem strange and could be a result of their method of installation.

Infiltration just prior to failure must have been quite rapid because the debris slides occurred at or near the zone of maximum snowmelt (snowline), and failure was generally within a period of hours of recession of the snowline.

<u>Geomorphic setting</u>: Repeated observations were made of breaks-in-slope above the crowns of the debris slides, with frequent gross differences apparent between slope angles above and below. Above the slides, there is generally a bench of lower gradient; below the slide, the topographic

gradient commonly increases. The benches tend to decelerate downslope flow of snowmelt as well as pond water where topographic lows exist.

Quite commonly, the slides occur in swales. This configuration concentrates ground water interflow as well as surface runoff, and results in greater infiltration and higher pore-water pressures. The presence of a swale may also signify the presence of more easily erodible material or more porous material which accepts water more readily and allows a rapid increase in pore-water pressures.

Local geomorphology has a strong influence also upon the runout or resulting debris flow from the debris slide. The position on the slope where the slide occurs controls its transport distance to flood flows. The slope below may tend to disperse the debris flow or to concentrate it so that it has greater impact on joining a drainage below. The morphology of the confluence point can control whether or not blockage occurs, its duration, and how much of an impoundment is constructed. Upon breaching, the local morphology will control the confinement of the breach and, therefore, the ease with which the flow may be diluted. The morphology immediately downslope of the breach will control erosive capability as well.

Geology: Geologically, the rock unit in northern Utah with the greatest areal extent, as well as the greatest number of slides, is the Precambrian Farmington Canyon Complex, which consists largely of schists and gneisses. Tectonic fracturing of the bedrock during uplift of the Wasatch Range allowed the development of granular residual soils which normally occur as a veneer on this steep terrain. Nearly all of the debris slides in Davis County were in Farmington Complex terrain. Exceptions, however, in Bonneville sediments are shown in figure 28.

In the northern slides of Box Elder and Weber Counties, the terrain is Precambrian-age Mineral Fork metamorphosed sediments, except for one slide that appeared to be in Cambrian-age Maxfield Formation or equivalent limestone.

In Salt Lake County, slides in the Mountain Dell drainage were in lower Tertiary age Knight Formation conglomerate and upper Cretaceous-age Echo Canyon Formation conglomerate. In Red Butte, Emigration, and Parleys Canyons, the terrain with debris slides is that of lower Triassic-age Woodside, Thaynes and Ankareh Formations, mostly red continental sediments but also some marine (Thaynes) deposits. In Mill Creek, both the Ankareh and the Jurassic-age Nugget Sandstone were involved with slides. Farther south, in Big Cottonwood Canyon, one slide each occurred in the Mississippian Donut Formation (limestone and shale), the lower Triassic Thaynes and Ankareh Formations, and the Permian-age Weber Quartzite. In Little Cottonwood Canyon, one slide occurred in Tertiary granitoid terrain and one in non-differentiated Cambrian sediments.

It is not easy to establish whether sliding has occurred at some prior time at the same location as the 1983 slope failures. The failures are so shallow (normally less than 12 feet) that past events are easily masked by mass wasting and vegetative recovery.

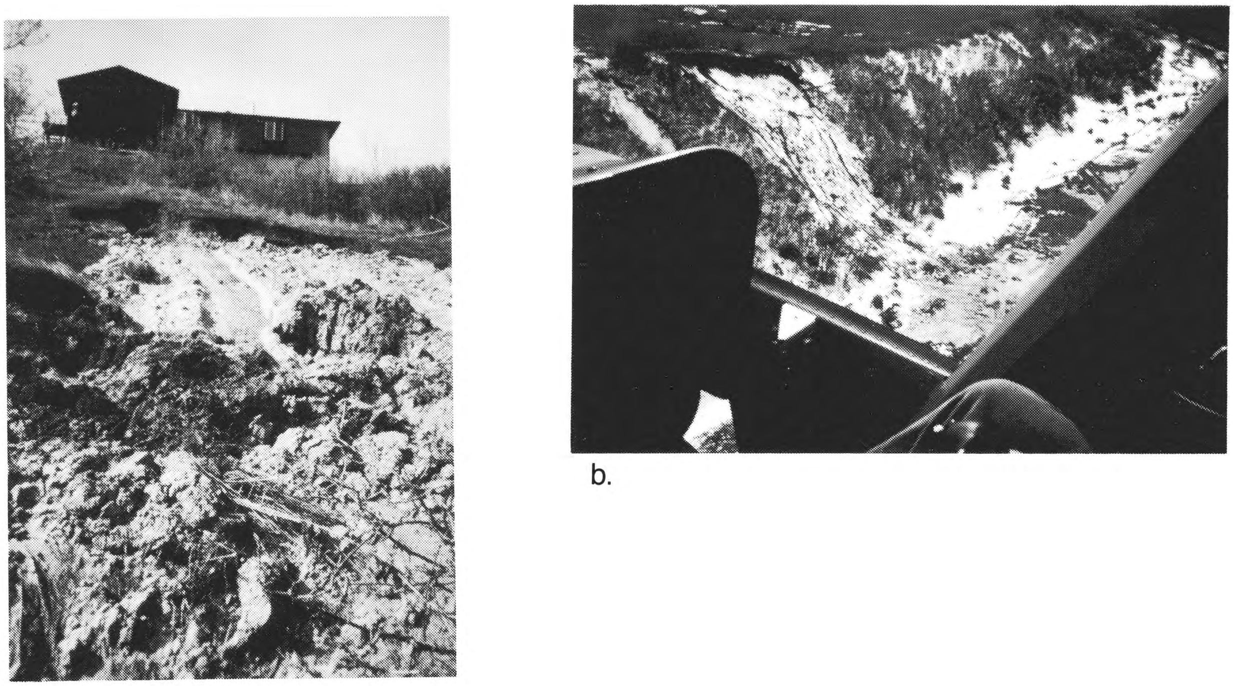
Sequence of events leading to debris flows on the Wasatch Front

While activity was occurring in the benchland, snow was continuing to accumulate at higher elevations of the Wasatch Front during the spring of 1983. In late April and during the month of May, the snow line receded gradually at lower elevations while snow continued to accumulate to a considerable thickness higher on the range. From April 20 through May 19, over 3 inches of rain fell in Salt Lake City and over 12 inches of water equivalent was added to snowpack in the mountains. At this time, failures of soils on mountain slopes in Davis County began to occur at elevations coincident with the snowline and location of snowmelt. Combined rapid infiltration from snowmelt plus added rainfall caused saturation and initiated debris slides and associated debris flows. As the debris slide begins to move, dilation occurs; the material becomes more fluid, and subsequently becomes debris flow.

Surveillance of terrain by the author produced early reports of debris flows on May 9 resulting from sliding about elevation 6400 feet in Shepard and Baer Canyons. A warming, with an average temperature of 61°F in Farmington, occurred on that date, causing acceleration of melting of the residual snow.

Pack (1985) reconstructs what happened thereafter. Recession of the snowline was only gradual through mid-May. Wet weather prevailed and temperatures averaged about 3°F below normal. There was a lapse in slide activity on May 21. A strong warming trend ensued with temperatures 5 to 10 degrees above normal and lows above freezing in upper elevations. Rapid melting resulted in a receding snow line.

With several days of high temperature, flooding began in cities within Davis County on May 26. A significant debris slide occurred along Bigler Creek in Farmington Canyon on May 29, and muddy water was reported


a.

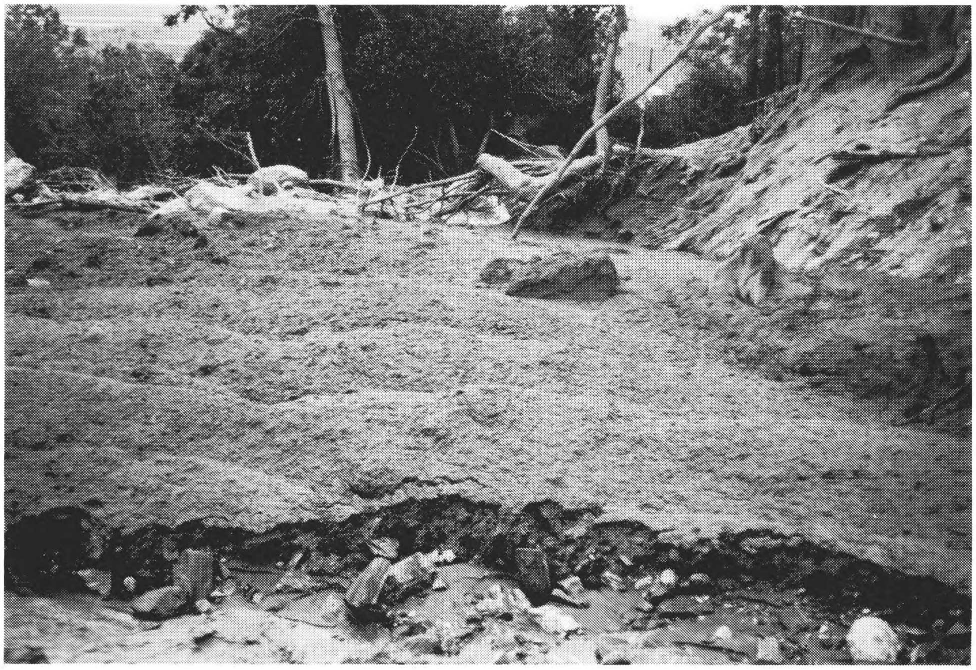
b.

Figure 28.

Debris flows from benchland debris slides. Note very steep slopes of origination but minimal travel distance.

a) Layton; fine lacustrine sediments stopped on slopes. b) Layton; sediments deposited on valley bottom, beyond toe of slope.

a.



b.

Figure 29.
Debris flows from Rudd Creek. a) Note high relief on edge and heavy concentration of organic debris.
b) Note surface of flow deposition.

that same day from Rudd Canyon in Farmington. On the 30th of May, temperatures reached 76°F, and the large debris slide in the upper channel of Rudd Canyon occurred and initiated a succession of debris flows (figure 29). With the slide at an elevation of 7,000 feet, the channel's steep gradient allowed transport of the mobilized material to flow over 2,000 vertical feet and emerge at the canyon mouth and slowly engulf a residential neighborhood in Farmington, the county seat. Activity elsewhere caused debris floods and muddy waters in a number of drainages.

Ward Canyon experienced a destructive event on May 31, which caused great damage in the city of Bountiful. A debris slide occurred at 11:00 PM at an elevation of 8,280 feet on the north side of the canyon. It traveled as a debris flow for 3.5 miles to the mouth of the canyon and then dissipated into a debris flood.

Additional slides were reported in Farmington Canyon on June 1, but the activity was confined to enlargement of the May 29 slide (Pack, 1985). Also on June 1, debris slides in Hornet and Steed Canyons caused concern to south Farmington residents. These occurred at elevations between 7,680 feet and 8,080 feet, on the north sides.

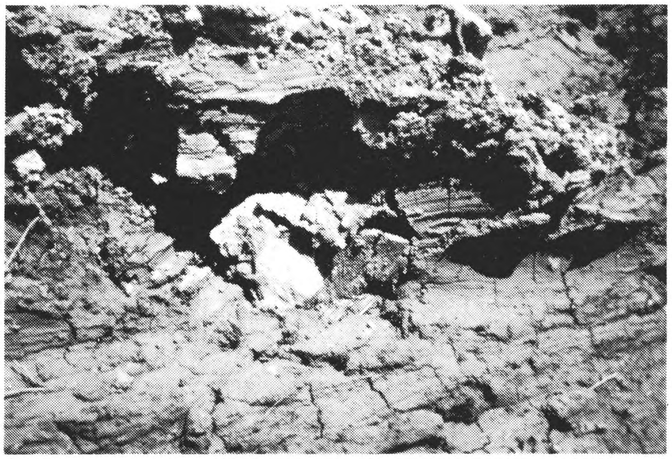
Baer Canyon activity was of sufficient concern on June 2 that eighty or so families evacuated Fruit Heights. On June 4, at 1:15 PM, another debris flow in Rudd Canyon caused partial evacuation of Farmington. An aerial reconnaissance was conducted jointly by UGMS and the USFS. This effort was concentrated at or near the snowline elevations. High temperatures and melting of snow continued through June 9. By June 12, most of the debris slides between Holbrook Canyon on the south and Baer Canyon on the north had taken place. On June 19, a slide at elevation 8,320 feet, in Ford Canyon, was observed near the snow line.

Aerial observers watched rather closely for the propagation and separation of ground cracks and detached and semi-detached masses of earth moving on the slopes. The majority of masses moved very small amounts and stopped. Some failed completely within a period of days. Upon failure, water was normally seen to issue from one or more locations on the fresh debris slide scars at rather significant rates of discharge. Immediately following a failure and for a period of hours thereafter, the discharge appeared muddy. This fact enabled observers to judge the time of failure. Not infrequently, discharges appeared to be under great pressure as they shot forward as a stream of water. Rarely, one would observe the same phenomenon with an absence of failure on the mountain slopes. It was clear to observers that there was a coincidental relationship, and that the activity was triggered in the snowmelt zone.

Run-out criteria: Since the debris slide generally results in a debris flow, there are additional considerations that are important for an assessment of run-out capability and potential damage downstream. The debris flow consists of material in a state of transport where the sediment is carrying the water rather than vice versa. The substance of the flow is a sediment slurry with greater or lesser amounts of vegetative debris and boulders. During the episode of a debris flow, its consistency is by no means uniform; indeed it may change over short periods of time with a succession of surges down the channel (figure 30). What may be regarded as a single debris-flow event may, in actuality, be a large number of individual events in rapid succession. Some hiatus may then be followed by another sequence of surges.

The debris flood occurs at the point in the transition when water takes over and predominates as the transporting medium. The debris flood may be highly charged with coarse fraction as well as fine-sediment fraction and vegetative debris.

a.



b.

Figure 30.
Debris flow into Little Clear Creek, Indianola. a) Bend at confluence with main drainage.
b) Material and striations indicate two episodes of flow.

Factors relevant to assessment of run-out capability are:

- Gradient of slope or channel below the source slide
- Flow and variability of flow in the channel(s) down gradient
- Ground-water discharge from the slide vicinity
- Characteristics of the channel(s) downstream
- Angle of intersection of downstream channels
- Volume of channel-fill material downstream
- Gradient changes of channels enroute to canyon mouth
- Opportunities for blockage along channel below
- Stability of channel banks downstream
- Occurrences of beaver dams or other obstructions in channel
- Distance to first channel, to main channel, and to canyon mouth
- Gradient and other characteristics of alluvial fan at canyon mouth
- Changes in shape or geometry of canyon/channel
- Modifications by man on alluvial fan surface at canyon mouth

Potential for larger complex slide-caused debris flows

Thus far, the subject of debris flows has been discussed as it pertains to small source slides, very frequently with volumes less than 1,000 cubic yards and almost all under 20,000 cubic yards. Larger landslides, including massive world-class slides, also have the potential for generating associated debris flows, although, thus far the frequency of occurrence has been rather low in Utah. Nevertheless, one prime example does exist, and it comes from the largest slide (720 acres) in Twelvemile Canyon, Sanpete County, east of Mayfield (figure 13-4). This slide ranks as one of the largest in the entire nation. In June 1983, a debris flow originated from the toe of the slide and rapidly traveled for a distance of 2.5 miles down the canyon as far as the Pinchot Campground. A couple parked in a pickup truck at the Campground narrowly escaped and had to abandon their vehicle.

A much slower velocity earthflow came out of the south flank shear zone of the Thistle landslide (Utah County) in May, turning south into the reservoir that was backing up behind the landslide-caused embankment.

Not a great deal is understood about the genesis of debris flows and earth flows from large disturbed landslide masses composed of differing earth materials. Factors that may have relevance in such cases include:

- Moisture content
- State of remolding or dilatancy
- Availability of highly disturbed earth materials
- Particle size distribution of the whole
- Percentage of matrix to coarse clastics
- Pore-water pressure and its variability in the mass
- Clay mineralogy of the fine fraction
- Network and hydraulic interconnection of voids in the mass
- Height and steepness of the leading edge of the slide mass
- Slope gradient beyond the slide's leading edge.

Ultimate volume deposited by a debris flow

A source landslide may transport a volume of earth and vegetative material down slope, down canyon, and, possibly, beyond the mouth of the canyon onto the alluvial fan. It is not uncommon for a volume of material, often considerably greater or in excess of the area of failure, to be deposited at the terminus of the slide activity. Additional contribution, which may be more than twenty times the original landslide source, often is derived from the slopewash (slope cover) and channel fill along the transport drainages. Material may have been accumulating in these drainage for dozens, hundreds, or even thousands of years, perhaps, in some cases during most of the Holocene period of geologic time (last 11,000 years). Where historic debris flows have occurred, even 50 years has been adequate time for channel-bank sloughing and hillside creep to place considerable material back into the channels.

Debris flows very frequently scour the channels and leave behind a "U"-shaped (or trough-shaped) section of channel throughout its length, which may be floored in bedrock in places or even over considerable lengths. A great deal of material is thereby mobilized in the process of the rapid evolution of a debris flow. Earlier, individual flows in a sequence appear to consist of higher organic content from stripping of the "A" soil horizon and vegetative litter from slopes. This material is believed to cause the peculiar stench which has been observed associated with many of the 1983 debris flows soon after deposition.

When a debris flow emerges from the canyon mouth onto the alluvial fans, the slope gradient decreases markedly, perhaps by a factor of three or more. The velocity of the flow then becomes greatly retarded and a wall of material with a convex, lobate leading edge moves outward over an expanding radius as it traverses the fan surface. The ground surface may not be affected by erosion, but objects resting on the fan surface will most likely be pushed or carried along with the flow and deposited in front of or in the flow. The flow acts strangely compared to a flood; objects, linear features, or cultural features (such as hedgerows, fences, car bodies) can cause the flow to terminate its forward progression and retain its morphology of last moment of mobility. The flow features, particularly in muddier flows, are commonly preserved until desiccation causes the details to deteriorate and only the gross features remain. Normally, a sediment-charged flood flow continues in time beyond a debris flow so that the deposited flow material or fan is soon dissected and a channel with sorted debris within it is re-established. This new channel may occupy a course across the fan which bears little resemblance to the pre-event channel. The new hydrologic drainage system may be such that it threatens an entirely new area on the fan or in its vicinity. If debris flow surges continue for some period of days, erosion of early deposited material may remove a good percentage of the total volume to points downstream, blocking culverts, filling ditches, and otherwise clogging the drainage system.

Consequences of debris flows: a summary

Some of the consequences of the debris flows have been touched upon in the preceding narrative. Because of the very large number of debris flows in 1983, their volumes of material, potential for real disaster, and uniqueness as a distinct phenomenon, their consequences as experienced in 1983 are enumerated below.

- Raising the grade of acreage near the mouth of canyons.
- Changing the ground-surface morphology so that land parcel boundaries are no longer recognizable.
- Burying lifelines so that rights-of-way are at best difficult to identify and define for a period of time until drying out allows excavation.
- Scouring of channels so that they are deeper, straighter, cleaner and wider than previously. Channel crossings

by aqueducts, etc., are jeopardized and service interrupted for an area very many times in size and population the directly impacted area.

- Evacuation of families for some period of days, with resulting uncertainty about reoccupation, financial losses, neighborhood integrity, etc.
- Psychologic effects of evacuation or destruction upon all affected parties, particularly children, both in the near term and well into the intermediate term, if not into the long term.
- A planning need to define not only a short-term but a long-term risk zone, with careful consideration of both engineered and non-engineered action and each of their repercussions.
- Need to define optimal time for family recovery of belongings: when risk of additional flows in the short term is significantly reduced, the debris flow material is adequately dried out, but not so well dried and indurated that excavation becomes extremely difficult and costly.
- An objectionable odor permeates everything affected.
- Political and community pressure is exerted for the clearing and opening of thoroughfares for maintenance of access to unaffected neighborhoods, communities and commercial zones.
- Since a water flow follows for some extended period, even from an abnormally dry channel, there is a need to redefine surface drainage with consideration to the entire downstream system.
- Sediment loading affects the drainage system downstream. It may impact natural water bodies, reservoirs, marshes and flood plains. Downstream users will likely have a water quality problem to face for what might turn out to be a considerable period of time.

Partial reactivation of the large, complex, Couch Creek landslide

Reactivation of a very small segment of the old Couch Creek landslide (figure 31), east of Mona (**SE 1/4,** Sec. 34, T11S, R1E) caused a power company signal reflector to move and become inoperative in April, 1983. This west-facing, large landslide mass sits on the Wasatch Mountain Front at intermediate elevation where it presents a conspicuous protruding and hummocky lobe (figure 31). Its volume is about 25,000,000 cubic yards (Shroder, 1971). The slide likely consists of very large blocks of Manning Canyon Shale and Great Blue Limestone in a matrix of weathered rock material and colluvial debris. The dimensions given by Shroder (1971) are possibly minimums: 1,400 feet in width at the head, 3,100 feet in width at the toe, 6,100 feet in length, and 100 feet in thickness. Shroder indicated that the landslide last moved in the Pleistocene. The 24 foot x 30 foot passive reflector had been anchored to a concrete foundation situated on the ancient landslide mass at an elevation of 6,380 feet. Any disturbance which tilted the tower less than one half degree was sufficient to prevent signal transmissions down the line. The first interruption of transmissions occurred on April 13, but restoration occurred naturally without help from technicians. On April 15,

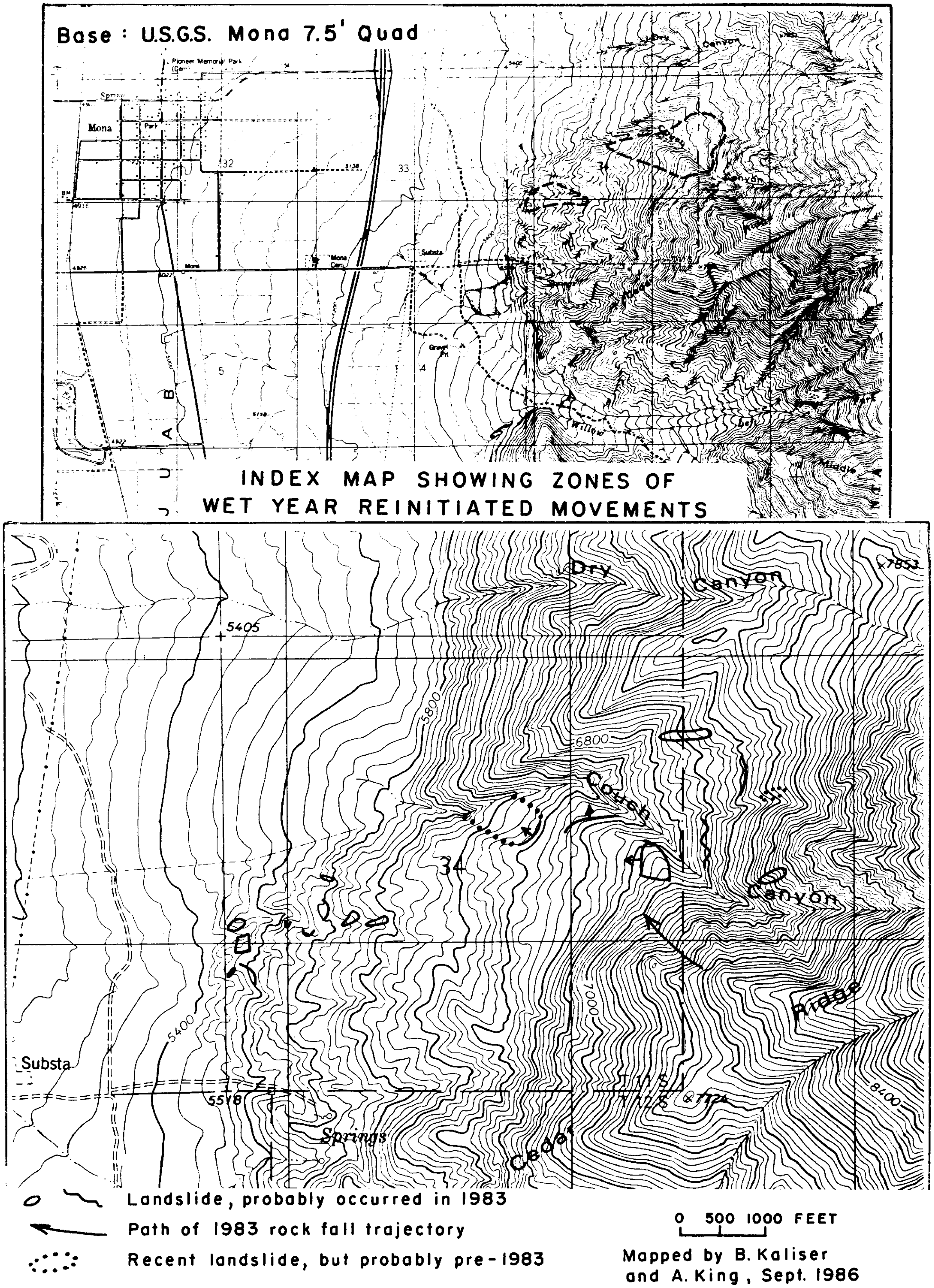


Figure 31. Active slope movements on the Couch Creek landslide.

transmissions were interrupted again, and horizontal and vertical adjustments in excess of one inch had to be made to the tower. One week later, on April 23, additional adjustment was required: 1 inch horizontally and 0.75 inch to 1 inch vertically. Another 0.5 inch of horizontal and 0.5 inch of vertical adjustment was required on May 9, because of signal fading. By May 17, all horizontal displacement ceased; only vertical displacement was still a problem, requiring 0.5 inch of adjustment. At this time a crack in the ground was noticed just up slope from the tower. Another 0.5 inch of vertical adjustment was made on May 25, and the same amount on June 6. The reflector was removed from service on June 11, 1983.

A visit to the reflector tower site in August 1986 revealed the foundation to be uncracked and totally intact. The nearest ground crack observed at the time of the previous visit was 20 feet from the tower. This crack was open approximately 1 inch. Re-examination of the site showed evidence for creep having probably occurred toward the north, west, and southwest, a most unusual situation but one that is the result of the unique characteristics of this particular site. The 1983 history of movement at the reflector site is particularly interesting because it records a minimum period of about one month of creep in an unconsolidated landslide deposit.

Wet-cycle movement elsewhere within the Couch Creek slide mass included everything from ground cracking coincident with old slide scarps (but with no rejuvenation of corresponding toes), to complete, fully mature slumps and translational failures.

Interpretation of aerial photographs and reconnaissance of the slide in the Autumn of 1986 have revealed that all of the new failures were in 1983 but that additional movement occurred in 1984.

Individual new slides that have developed on the Couch Creek slide mass (figure 31) are discussed below:

1. <u>Translational debris slide</u>: 76 feet long x 32 feet wide x 1 feet thick (2 feet maximum). Right lateral shear surface only is well-developed; in early state of maturity. Situated on right side slope of a small drainage.
   Material is non-cohesive, SM with gravel. Dry on 9/18/86.
      32% gradient along the length of the slide (direction: N85°E)
      30% gradient of slope into the drainage (direction: N45°E)
      34% gradient above the crown of slide. Note break-in-slope.

2. <u>Translational debris slide</u>: 128 feet long x 200 feet wide at toe (180 feet wide at crown). Slide occurs on north side of drainage, with 50 feet of relief. Contributing cause is downcutting by erosion through the slide mass and oversteepening of the adjacent slope. Headwall scarp is coincident with older failure; about 9 feet of displacement for a distance of 100 feet along the headwall. Thin-skin failure; buckled ground downslope; no toe.
   Material is SM with gravel.
      40% gradient from crown to break-in-slope on the slide.
      55% gradient above crown (slope of pre-1983 scarp).
      71% gradient from the break-in-slope to the bottom of the disturbed zone (88 feet in distance).

3. Translational debris slide: 96 feet long x 70 feet wide at crown x 3 feet average thickness. Scarp height is 2.5 feet. Blocks or slices are present. Potential exists to create blockage of the ephemeral drainage.
   Material is cohesive and dry on 9/18/86.
   - 68% gradient above the crown.
   - 57% gradient from crown to break-in-slope on slide (31 feet in length).
   - 71% gradient from break-in-slope to toe (66 feet in length).

4. Rotational debris slide: 264 feet length x 80 feet toe width, 130 feet crown width with a 7-feet-high scarp. Slide material is a cohesive clay derived from black shale. Both right and left lateral bounding shears are present, as well as a well developed, internal, longitudinal shear. Slide features also include pressure ridges, transverse and radial fractures, intact blocks, exposed failure surface and disturbed trees. Although one spring exists near the scarp and two discharge from the toe (9/18/86 observations), the material is dry except in one location where there is a new pond on the slide. The slide encroaches on the ephemeral stream; and a change of stream gradient has resulted. There is both evidence of former blockage and possibility of future blockage of the stream channel. Gradient of pre-slide surface and current overall slide is 39%.

   Gradients along stream channel: 13% upstream from slide toe encroachment; 7% from right toe margin for distance of 35 feet across toe; 22% for next 35-foot distance; 34% for length of 51 feet to the left toe margin; 16% for 60-foot distance below the toe.

   Evidence was observed for fire having occurred in recent years (pre-1983) above crown of slide. There is a flowing spring in the draw above the right flank of the slide.

5. Rotational debris slide: 120-foot crown width. New ground cracks coincide with pre-1983 slide features; includes backward-tilted blocks. Closed depression, now cracked, appears in upper right flank. Slide is much wider on lower slope than at the crown; may be translational in lower portion. Slide is relatively deep in its head region; shallow in lower region.
   Material is cohesive GM (clayey, silty gravels) and dry on 9/18/86.
   - 58% gradient above crown (old scarp)
   - 24% gradient on head, but also variable.
   - 68% gradient on steep, lower part, with much more disturbance, involving 1 to 2-foot thick blocks of surficial material.

   Note: There is a 60 feet x 20 feet x 5 feet thick rotational slide below the right flank, consisting of 3 slices, possibly the result of movement of the larger slide.

6. Rotational debris slide: 650 feet long x 480 feet wide (at crown) x 30 feet average thickness (50 feet maximum). New (1983) movement is evident in this historically active portion (not noted in Shroder, 1971) of the Couch Creek slide, bordering on the south side of Couch Creek. Several tilt blocks are involved with numbers of disturbed trees. Tension cracks exist above the crown. Real potential exists for stream blockage.
   Material is somewhat cohesive GM (clayey, silty gravels) and dry on 9/18/86.

7. Translational (?) debris slide: 411 feet long x 40 feet wide at toe, and 100 feet wide at crown with 10 feet average thickness. Topographic relief is over 200 feet, with slide bordering on Couch Creek, to the east of slide No. 6. There are tension cracks above the crown and numbers of disturbed trees. The nearly vertical scarp varies from 12 feet to 40 feet in height. A 15-foot-high ridge occurs at the toe, in the western part. Slide is shallow in eastern part; deeper to the west.
   Material is a GM/GC, (ML/CL with >50% gravel), cohesive and dry on 8/19/86.

8. Complex rotational-translational longitudinal slide zone with springs issuing from base of upper scarp: This is a pre-1983 slide area. Zone is 460 feet long x 125 feet wide at upper crown and narrows abruptly; consists of 4 slope failures. Gradients vary from 19% to 48%. Slide is very thin, averaging 2 to 3 feet in thickness.

9. Complex rotational-translational zone: 250 feet long x 30 feet wide, with an average thickness of 6 to 7 feet. Springs with 59.5^{o} to 60.5^{o} F water are in abundance, and each yields less than 1 gpm on 8/19/86. Gradients vary from 30% to 49%.

10. Rotational-translational debris slide: 90 feet long x 220 feet wide on south side of deep ephemeral drainage. Relief is about 100 feet. Original gradient of slope bordering channel was 54%. Gradient of the channel at toe of slide is 45%, very high.

11. Near the east corner of the ancient slide mass, between elevation 6,800 feet and 7,000 feet, the pattern of ground cracking suggests slight new (1983) movement to the west of a potentially large mass. Dense vegetation hindered exploration of the toe to the west and, thus, no observations were possible on 9/18/86.

Two long, continuous new scarps (2.5 feet and 4 feet average height) and three landslide masses were mapped to the north of the Couch Creek drainage from the south rim of the landslide mass. No additional data pertaining to these five features have been obtained. One of these slides (figure 31) appears to be older than 1983.

A northwesterly trending rock fall trajectory (figure 31) is clearly revealed as a discontinuous path through scrub oak and shrubs. The rock came to rest at the apex of a very steep fan, above the 7000 foot elevation. The detachment zone is approximately 15 feet x 30 feet in area.

Limited investigation of the new-wet cycle failures on the Couch Creek landslide has provided some tentative conclusions:

- The new failures display a diversity of slope movements: translational, rotational and complex, but no earth or debris flows have resulted.
- Dissection of the massive slide and the locally steep, high relief that it has created has been a major factor in reducing stability of portions of the old slide.
- The irregular distribution of weak shale blocks, weathered to clay, is both a direct cause of instability locally and a factor in determining ground-water migration paths.
- The irregular distribution of pore-water pressures in the old slide mass is likely to have been a critical factor.
- Creep of larger portions of the old slide mass than has been discerned is a distinct possibility.
- There is a suggestion at the site of one slide that removal of vegetation in a recent fire may have contributed to increased infiltration by water.
- The majority of the new slide features coincide with morphologic features associated with movement of older slides. In at least some of these slides, the older morphologic features are clearly younger than the original age of the slide; therefore, there have been recurrent movements, possibly in Holocene time.
- A minimum of 1.5% of the volume of the old slide has undergone reactivation in the current wet cycle.

Wasatch Plateau

Godfrey (1985) reported movements which occurred in 1983 and involved a total real estate of about 6,500 acres on the Wasatch Plateau (figures 13-1,13-2,13-3,13-4,13-5). These occurred on geologic terrain as indicated in table 6.

Table 6.
Formations on which landslides occurred on the Wasatch Plateau.

Geologic Age	Formation Name	Thickness in feet	Number of slides	Percentage of slides
Tertiary	Flagstaff	300'-500'	22	5
Cretaceous	North Horn	2,000'	342	80
Cretaceous	Price River	600'	29	7
Cretaceous	Black Hawk	1,500'	28	7
Cretaceous	Star Point	450'	2	<1

The occurrence of landslides as shown in table 6 is not surprising. The data is consistent with our previous knowledge of the landslide susceptibility of the Cretaceous and Tertiary sedimentary rocks. Shroder (1971), for example, indicates that 75% of the landslides he studied on the Wasatch Plateau were associated with the North Horn Formation. Weak, fine grained rocks of Upper Cretaceous-lower Tertiary-age North Horn Formation are overlain by the Tertiary-age Flagstaff Limestone. Lithologies of the North Horn Formation consist of varicolored siltstone and claystone with sandstone, conglomerate and limestone beds locally. Upon weathering, some of the claystone units alter to montmorillonite to bentonitic clays. Broad uplift in mid-Tertiary time, centered in the San Rafael Swell about 50 miles southeast of the Wasatch Plateau, caused the rocks to dip to the northeast. Erosion subsequently created canyons of high relief which cut into dip slopes on the west side of the plateau.

In 1983, 4,769 acres underlain by the North Horn Formation were involved in landslides that had undergone movement (Godfrey, 1985). This acreage amounted to 86% of the total acreage involved in slope movements. In areal extent, this acreage comprises 0.6% of the Wasatch Plateau, and 1.2% of the outcrop area of the North Horn Formation.

Of the area comprising the Wasatch Plateau north of Salina Canyon, 0.7% was involved in slope movements in 1983. As was true of past landsliding on the Plateau, the largest number of 1983 movements occurred between elevations of 6,000 feet and 8,000 feet. Most were shallow debris slides, but significant reactivation of pre-existing, deep landslides has occurred, mostly on portions of large ancient slides rather than the entire mass of the slides.

Significant landslide events on the Wasatch Plateau

<u>Twin Lakes Slide</u>: The Twin Lakes landslide (figure 13-4) gained notoriety because its rejuvenation necessitated the decision to breach the dam impounding Twin Lakes. The rejuvenation process progressed rather rapidly, or more accurately retrograded, from the toe (figure 32) of the old landslide up slope toward the head region. The slide is a complex bedrock slide 3,100 feet long and wedge-shaped in plan view. The width of the crown is 1,660 feet; the width of the toe is 1,250 feet. Elevation of the crown is 7,020 feet with 590 feet of relief on the slide from head to toe. Three scarps in the upper portion of the slide are in Flagstaff Limestone. Two of the associated bedrock benches cracked during 1983 movement. The lower bedrock scarp indicated displacement of some 1.5 to 3.5 feet, while the middle scarp showed displacement of 4 to 8 inches. The debris portion of the slide, below the bedrock blocks, underwent extensive remolding in 1983 and was comprised of material derived from the North Horn Formation (figures 32,33,34). Failure appears to have occurred within North Horn claystone. It appears to have moved some 20 feet (R.W. Fleming, 1987, verbal communication). The floor of the valley also provides evidence for 20 feet of lateral movement of the entire slide toward the channel of Twelvemile Creek.

The slide was observed to be moving at a rate of about several inches per hour in June, 1983. It underwent movement through August of 1983 (R.W. Fleming, 1987, verbal communication). The slide ceased moving in 1984, having been about 80% rejuvenated. Fleming estimates the depth of the failure plane to be about 90 feet low on the slide toe and perhaps 160 feet higher up, on the foot.

Movement of the slide retrograded in increments up slope through two of the three Flagstaff Limestone blocks. One could only speculate, therefore, on the time required for reinitiation of movement on the remainder of the old slide. Cracking of the upper bench would have caused Twin Lakes reservoir situated on the bench to drain into the bulk of the slide mass. The additional water would likely have exacerbated the movement, causing the eventual blockage of Twelvemile Creek. By breaching the dam and controlling both the reservoir drawdown flow path of the water thus released, loss of water into the slide and blockage of the creek were avoided.

<u>Aspen Grove Slide</u>: Unlike the Twin Lakes slide, the Aspen Grove slide in Ephraim Canyon (figure 13-3), was an earth flow which occurred in Flagstaff Limestone bedrock.

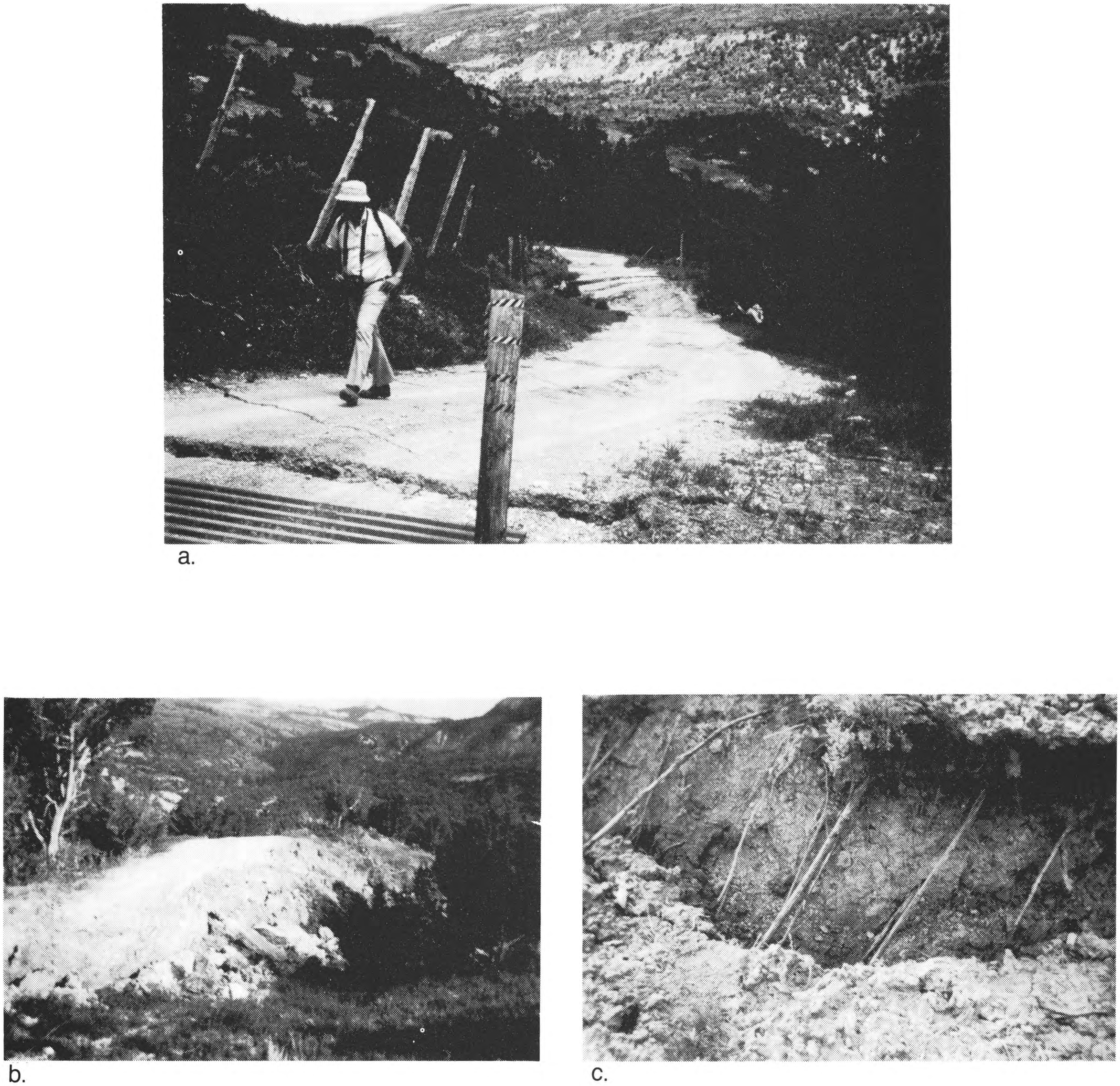
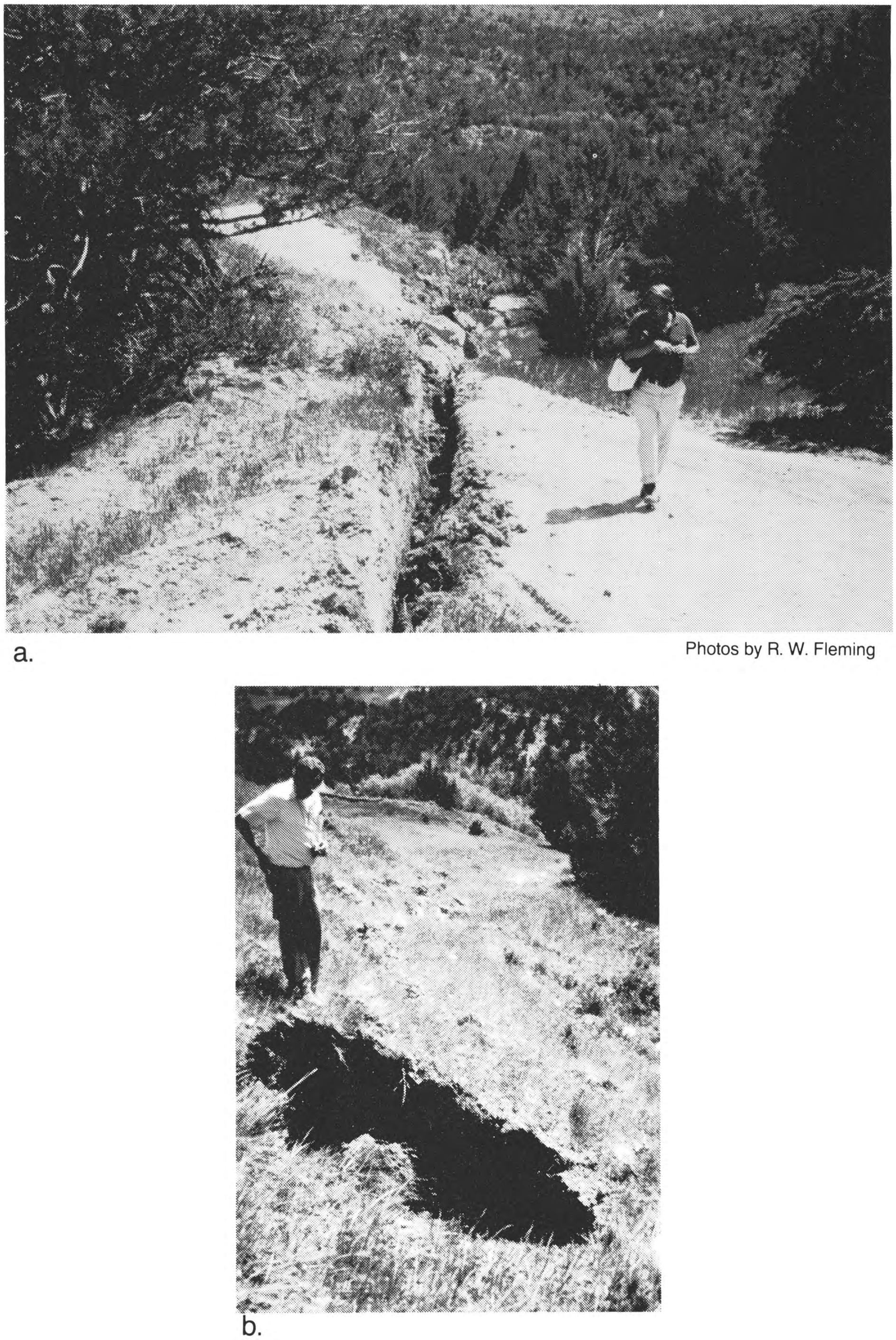
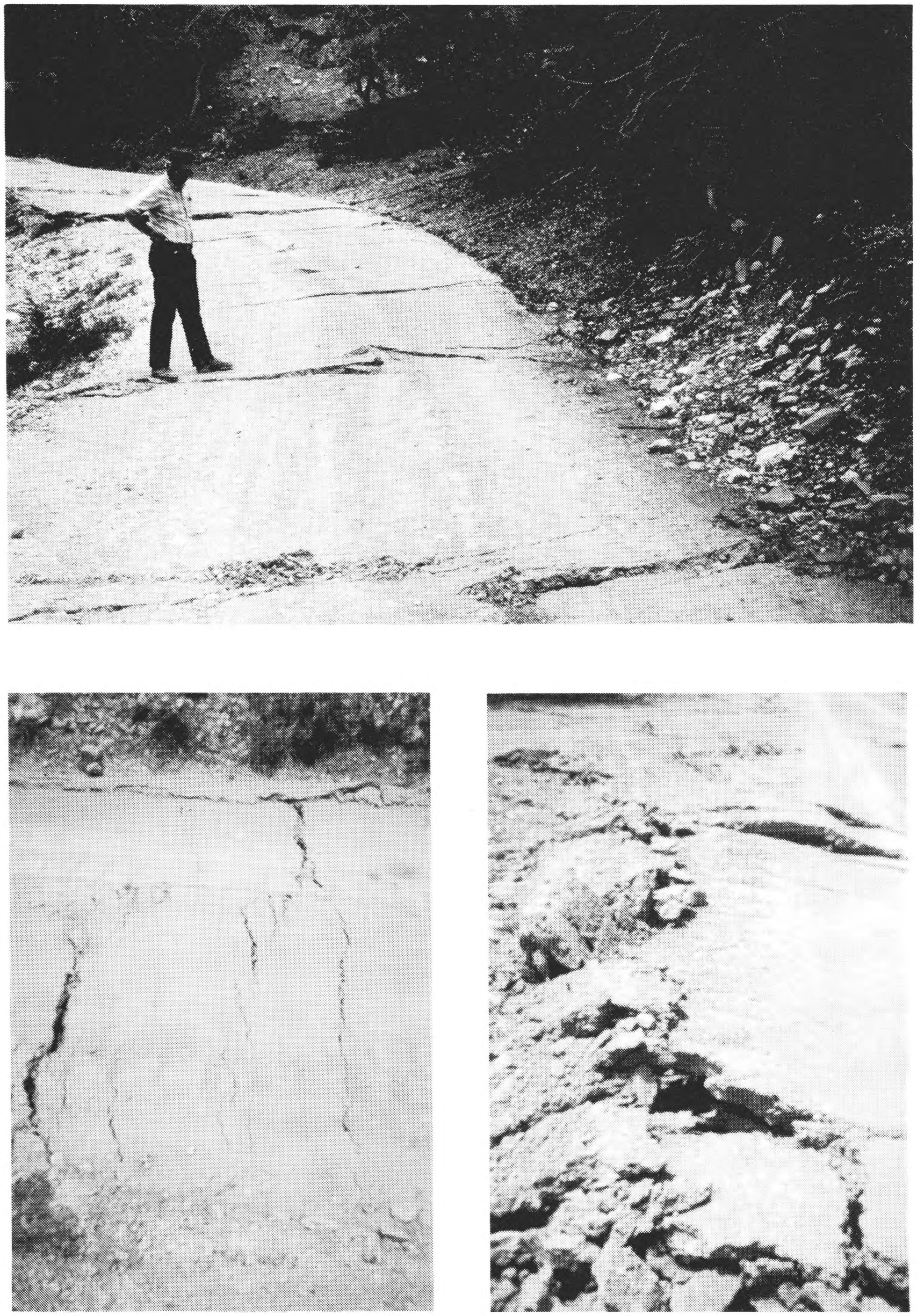


__Figure 32.__ Twin Lakes slide. a) & b) Heaving of road across toe. c) Stretched roots demonstrate direction of movement.



Photos by R. W. Fleming

Figure 33. *Twin Lakes slide, June, 1983. a) Flank shear. b) Collapse feature.*



Photos by B. N. Kaliser and R. W. Fleming

Figure 34.
Early Twin Lakes slide deformation. Early toe deformation displays shearing at right angle to thrusts, a phenomenon rarely observed. June, 1983.

Slide material consisted of North Horn Formation debris. Fleming (1987, verbal communication) is of the opinion that the failure surface is a bedding plane dip slope. The transposed sequence of debris from the North Horn Formation sliding downslope onto Flagstaff Limestone strongly suggests reactivation of an ancient debris slide with the original source area juxtaposed by faulting. The slide is rather long and narrow, 3,600 feet long (1984), and 100 to 200 feet wide. Depth to the failure surface is relatively uniform at 23 feet in the upper part but is as much as 33 feet lower down. In 1983, the slide had progressed to a length of 1,970 feet. Soil ridges accompanied by a highly variable displacement rate from the head of the slide to the toe, are evidence of an earth flow. Cracking on the slide was first observed on May 31, 1983 and movement continued until late July of that year. The slide was bounded laterally by flank shears in 1983, except for the lower 150 feet. Maximum displacement was 5 feet, diminishing in the lower portion (R.W. Fleming, 1987, verbal communication). This slide has been monitored by the U.S. Geological Survey with 15 quadrilaterals, lines of stakes and, in 1984, by peizometers. In 1983, the Survey measured 2 inches of movement a day on June 8, and 0.5 inches per day on June 11 in the upper part. In Ephraim Canyon, the Major Flat slide, lower in the drainage, broke the city water line on June 11, 1983.

Partial Inventory results, east of Mt. Pleasant

Five drainages on the west flank of the Wasatch Plateau, east of Mt. Pleasant, were inventoried in 1985 by the U.S. Geological Survey for UGMS (Lips, 1985). The 45-square-mile study area included the drainages of Twin Creek, Pleasant Creek, North Creek, Birch Creek, and Cottonwood Creek. Scale of mapping was 1:24,000.

Because the work was done subsequent to the 1984 activity, it is possible to make some comparison between 1983 and 1984 landslide activity. A high percentage of the mapped slides have no year of initiation of movement ascribed to them, so table 7 should be used for information only. Exact dates are not provided on the map for 1983 occurrences. Debris flows mapped had travel distances up to 3.8 miles in length. Slides less than 30 feet in longest dimension were not mapped.

TABLE 7: Comparisons of slide quantities for 5 western Wasatch Plateau drainages: 1983 vs 1984

	Debris Slump	Debris Slide	Block Slide	Debris Flow
1983	1	2	0	36
1984	16	35	2	28

Sediment Loading

Sediment loading is an element of landsliding, including debris flows and debris floods, that usually escapes sufficient attention. Nevertheless, sediment loading has been a major factor well outside the bounds of the debris-flow deposition zone. Debris-flood surges greatly aggravated the situation in Bountiful and elsewhere.

1. Storm sewer systems were heavily charged with coarse debris which proved to be a major problem for removal, particularly concurrent with the flood runoff period. Efficiency for removal from even clear water events has been considerably reduced. Damage to the lines also occurred.

2. Canals, ditches, and irrigation lines, particularly those situated on the flat, valley-floor environment, became lined with fine-grained material which dried out to concrete-like consistency.

Cross sections of lined channels were reduced in dimension which, in turn, affected efficiency. Many unlined conveyances experienced decreased efficiency due to smoothing and an overall reduction in friction.

3. Ponds and reservoirs downstream became settling structures, whether originally created naturally or by man.

    a. Hydrologic detention basins became lined with sediment and more-or-less sealed, thereby no longer functioning properly.

    b. Colloidal material interfered with water treatment.

    c. Natural fish breeding grounds and hatcheries were destroyed by the sediment in suspension and by the sediment which settled out over the habitat.

    d. Cultivated land was covered with clay which buried and destroyed crop yields.

    e. Infiltration capacity of the soil was retarded except where the soil was tilled immediately after storm/flooding conditions.

    f. Wetlands were filled with sediment, resulting in biota destruction which, in turn, affected water-fowl and other wildlife.

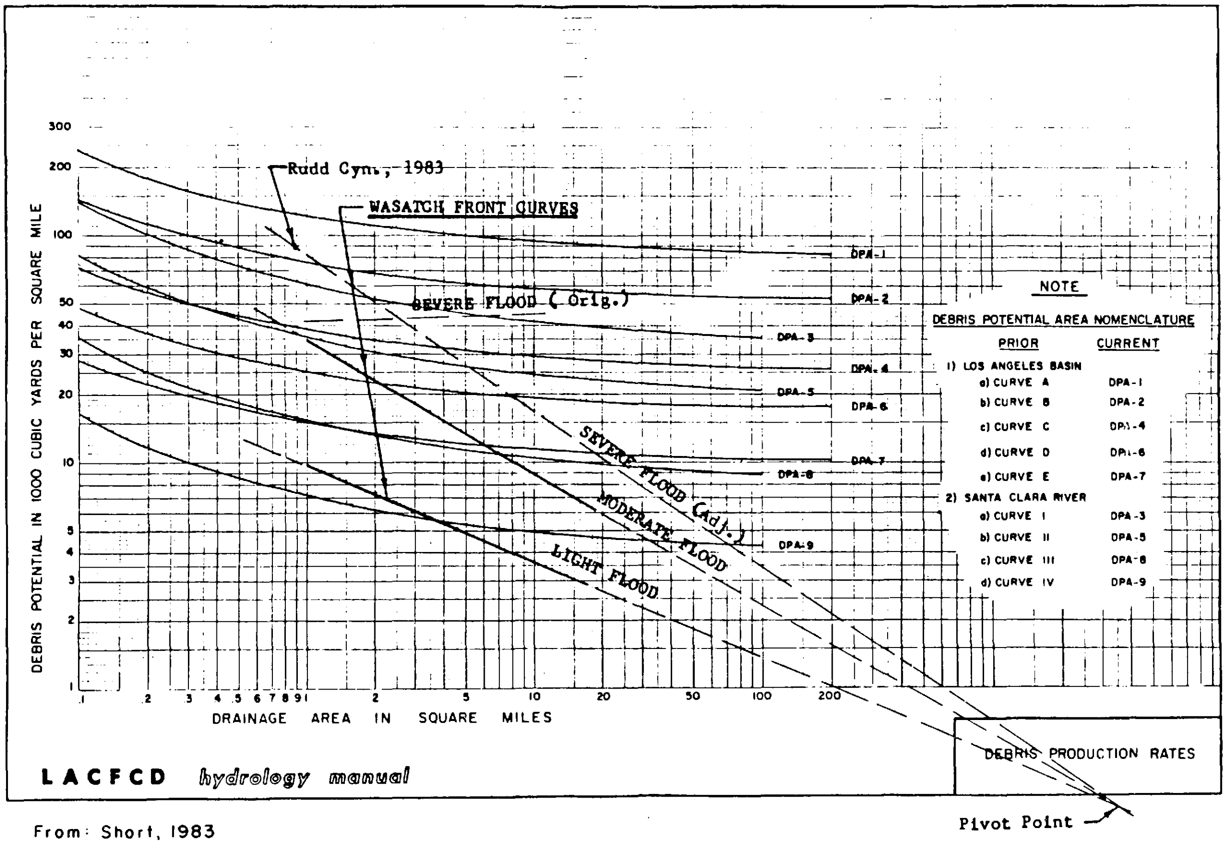
    g. The possibility exists for the sealing, temporarily or permanently, of zones of upward ground-water leakage (i.e., seepage zone recharging a surface pond). This is difficult to confirm during high water runoff periods.

    h. Reduction of water storage capacity occurred to reservoirs built for water supply, flood control or wildlife enhancement. This has resulted in lowering of the effective lifetime of the facility and a modification, perhaps gross, of the cost-benefit ratio used by its designers.

    i. Transport of sediment into sanitary sewer systems occurred in urban environments along the Wasatch Front through inflow into manhole covers and loading of the wastewater system with inorganics.

    j. Deposition of a sufficiently thick film of impermeable material over ornamental shrubbery and landscaping destroyed aesthetic appearances of a considerable number of residential, public, and commercial properties.

In 1983, Dan Short of the Los Angeles County Flood Control District fitted Wasatch Front curves to the debris production rate graph for southern California (figure 35). Since no curves had ever been established for Utah, this was the most suitable for use at this time.



From: Short, 1983

Figure 35.
Wasatch Front curves fitted to those for Southern California.

Aggravated Erosion

Aggravated erosion, caused by a large snowmelt supplemented by rain, initiated the 1983 slope movements in the benchland and mountainous terrain and initiated the following effects:

- Removal of support of soil wedges in tributary channel junctions. Destabilization of the upslope soil masses will continue to act as a sediment source.
- Exposure of a sufficiently new section of soil and loose rock may exert a gross effect upon the recharge capability of perched, and even normal, ground-water regimes.
- The latter effects may demonstrate a lasting influence upon the discharge rates on culinary water springs tapped by communities.
- Removal of soil cover from channels makes the ground-water regime more susceptible to contamination from fecal matter (from herds of deer and other wildlife, as well as from domesticated animals) entering bedrock aquifers (Kaliser, 1971) directly through scoured channel walls and floors.
- Entrenchment of Lake Bonneville terraces has opened up the hydrologic system to a major source of sediment and aggravates the entire benchland

erosion problem in a manner unattributable to man.

- New exposures of both soil and rock, as seen in erosion cuts, allow geologists to map the areal, structural, and Quaternary geology of the mountain-front zone more precisely. Locations of splinter branches of the Wasatch fault may be easily resolved in places where new exposures have been created. Exposures of earlier debris-flow deposits may permit dating of earlier events and establishment of recurrence intervals.

- New possibilities for sliding have been created by removal of toe material on both virgin slopes and slopes comprised of old or ancient landslides. New slides may involve an entire new zone of instability with deeper landslide movements. Initiation of such new movements results in a long-term problem of indefinite, ultimate magnitude, and establishes potentially dire consequences in the urban corridor. Mill Creek in Bountiful (Davis County) is an example of a stream that has entrenched itself through lacustrine (Lake Bonneville) sediments and highly weathered metamorphic rock, causing at least shallow-bank failures which encroach upon residential properties on both the north and south sides of the drainage.

- Erosion is so affected by the zone of frontal faulting (Wasatch fault system) that bedrock appears over regular stretches of the channel, which changes the channel gradient repeatedly and thus modifies the local hydrologic regime just prior to streams entering into the urban corridor.

- Destabilization of larger earth masses near the canyon mouths provides loose materials necessary for the initiation of debris flows in proximity to the urban corridor where even minimal run-out distances create havoc.

WET YEAR EFFECTS

Diverse terrain in Utah has been subjected to the effects of wet years: everything from flat valley floors, benchland, and foothills with flat to very steep slopes, to mountainous terrain with steep to very steep slops. Accumulations of sediment varies from only a very thin veneer of soil cover in mountainous terrain to hundreds of feet or more of soil and alluvium in the Great Basin.

In the Great Basin, there are valleys with no outward surface or sub-surface drainage. The water can only collect in the valley-fill sediments or spread over the surface as a growing body of water. Vegetative cover is also diverse, from almost none on the playas to dense shrubs on north-facing mountain slopes.

Man's influence during the 136 years of recorded history in Utah has not been minuscule anywhere. Grazing, timbering, grading for roads, utilities, and other facilities has occurred nearly everywhere to some extent or other. Even lake levels have not escaped the influence of man. Great Salt Lake, it is believed, would have been five feet higher in 1983 had there been no consumptive use of water due to man's activities in the lake basin since 1847 (Arnow, 1984).

Water tables have, in general, risen throughout the state. In many local environments, ephemeral or perched water tables have been created, some in areas where there had been none for hundreds of years.

Effects of Rise in Shallow, Unconfined Water Table

A rising, shallow, unconfined water table is to be expected as a result of an exceptional period of precipitation early in the wet cycle. Numerous communities situated on valley floors were subjected to problems from an overall rise in the unconfined water table in the valley. Many Utah towns and cities have portions of their unincorporated areas underlain with a ten-foot-deep water table (more or less) in normal years. The significant rise to even shallower depths has had the following consequences:

- Basement flooding
- Failure of septic tank systems
- Overloading of municipal wastewater treatment systems by ground-water infiltration
- Buoyancy of buried storage tanks
- Appearance of new wetlands in draws and slight depressions
- Aggravation of excavation-wall instability
- A greater likelihood that spills of all types of fluids, at the ground surface or in the shallow subsurface, can reach the ground-water regime and migrate laterally
- Aggravation of solid waste disposal leachate problems
- Cause or aggravation of structural settlement problems or ground subsidence
- Hydrocompaction of poorly consolidated alluvial materials
- Spring contamination
- Loss of agricultural yields
- Frost heave
- Road deterioration
- Aggravation of earthquake ground shaking

In addition, other environments such as benchlands, foothills and alluvial fans skirting the mountains experienced shallow ground-water problems because of perched horizons. These occurrences of shallow ground water may result in a greatly enlarged problem zone or in an historically new wet zone, thus taking homeowners and public works personnel alike entirely by surprise. From the appearance of the cumulative departure curve for precipitation at Salt Lake City (figure 11), it would not be surprising that shallow water tables could significantly change from this wet cycle. They previously had been on a steady course of descent, or in the case of perched horizons, they may have been dry for a long period.

Local perched ground-water occurrences in urban environments

Approximately three-fourths of a mile west of the Wasatch Mountains, in Ogden (Weber County), perched ground water surfaced at elevation 4,595 feet on residential lots on the north side of Kingston Drive (3550 South). Along Polk Street (1400 East), four homes experienced flooded basements since the first of July, 1983. On no prior occasion in the 30 to 32 year history of these homes had water entered basements.

This local, perched water situation is likely the result of the westward migration of ground water through alluvium in the unnamed drainage south of the Wasatch Elementary School. This area is currently subdivided into residential lots and has demonstrated no evidence of surface flows since time of subdivision. A delay time of two months from recharge to surfacing of water problems from this local, perched ground water zone has been observed and was predictable.

Basement flooding

Flooding of basements, especially in winter, not only inconveniences the homeowner but also provides an unhealthly environment with high humidity and standing water. Pumping of basement sumps by homeowners at today's utility rates can be costly. This problem in 1983 became so significant in certain communities that federal aid was sought. In Plymouth (Box Elder County), a $115,000 drainage scheme was devised and installed when thirty-one homes were affected, two of which required evacuation.

Homeowners with individual sumps lived in fear that a power outage or pump malfunction would leave them inundated once again. Costs for intermittent sump pump operation on a round-the-clock basis may exceed $30 per month for electricity alone.

Failure of septic tank systems

Although even small communities in Utah have installed sewage treatment plants and discouraged the use of individual waste disposal systems in recent years, many homeowners continue to dispose of waste into septic tanks. Problems with septic tank drainage fields may not only impact single residences but frequently the larger community because the effluent may come to the surface at some distance from the originating property. In March, 1983, for example, effluent was reported in the basement of the Fountain Green City Hall. In that city, some fifty homes had malfunctioning septic systems.

Overloading of municipal wastewater treatment systems by ground-water infiltration

A component of the fluid treated in all collective wastewater systems is called "inflow and infiltration;" the latter is ground water which enters the pipelines when they have less than perfectly sealed joints and are below the water table. Infiltration is a significant problem through much of the state aggravated by the wet cycle and rising water tables. Large new areas, involving systems of many linear miles of sewer lines, can become submerged beneath the water table, whether normal or perched. Unfortunately, no community or sewer district in the state has sufficient knowledge of conditions within their jurisdiction to know when such a threshold is near or reached. For this reason, the problem has been studied in particular. The potential cost to all sectors of the state's economy is rather significant from this single effect of high ground water. Two examples are provided:

- The town of Garland (Box Elder County) spent $450,000 to reduce infiltration from the range of 80% to 90% down to the range of 12% to 18% in 1983.
- The relatively new treatment plant at Lakepoint (Tooele County) experienced ground-water seepage into the lagoons, thus overtaxing the facility.

Buoyancy of buried storage tanks

Storage tanks that are buried in the ground at shallow depth may be impacted when the water table rises beneath them, especially if the storage tanks are only partially full. Underground tanks will undergo stress at their points of contact with pipelines. Should the tanks spill some of their contents as a result of disturbance, ground-water contamination can occur.

Photo by R. W. Fleming

Figure 36.
Aggravated erosion from debris flow blockage. Photo is of Little Clear Creek, north of Indianola, Sanpete County. (see Figure 13-1).

Appearance of new wetlands in draws and slight depressions

As the water table approached the ground surface, new marshes and wetlands appeared. Their existence is regarded as ephemeral. These new wet zones may have resulted in breeding grounds for mosquitoes inasmuch as they appeared during the breeding season. Water fowl and other wildlife were also temporarily attracted to these sites. Such localities as those near the Salt Lake International Airport runways can be a very real safety concern with the increased wildlife population.

Contribution to excavation wall instability

Excavations commonly go down ten or more feet in depth for building foundations and utilities. With rising water tables, open excavations have increasingly encountered ground-water seepage. Excavation walls that emit water are known to be subject to failure and can be dangerous. Greater shoring facilities are required for such excavations, and installation costs go up as excavation procedures change to accommodate shallow ground water -- both in cases where dewatering was not a requirement.

Greater likelihood for spills of all types reaching the ground-water regime

Spills of fluids at the ground surface infiltrate a shorter column of soil before contaminating the ground water reservoir when the water table is at shallower depth. Spills that would, therefore, be normally uneventful can become problems requiring a clean-up effort with a large expenditure of time and money.

Aggravation of solid waste leachate problems

Sanitary landfill sites are often situated near low points on valley floors where, in normal years, there may not be much distance to the unconfined water table. Should the water table rise to the base of the landfill, a plume of leachate or contaminated ground water would likely result.

Cause or aggravation of structural settlement problems or ground subsidence

Some older buildings were distressed as soil under foundations suffered hydrocompaction as a result of saturation from a rising water table. The best documented example is that of Cyprus High School in Magna, (Salt Lake County). Settlement of the old school occurred in January, 1982 to the point where evacuation was ordered. Another well-documented example was on Salt Lake City's east bench, where a commercial facility underwent so much stress that an interior wall popped out. At this facility, fill material settled, and shallow bedrock likely provided the sill upon which ground water perched after infiltrating through coarse sediments at the mouth of an intermittent drainage higher on the bench. Other suspected occurrences of this phenomenon were investigated but not confirmed.

New ground-water discharge points surfaced beneath lifeline of structural foundations, permitting consolidation and settling, heaving, piping, and erosion to occur for some interval of time. At times, new springs threatened culinary water systems by aggravating erosion which, in turn, undermined an existing spring nearby. Also recognized in 1983 were instances where the emergence of new springs and seeps aggravated the instability of slopes on which spring-collection systems were functioning as municipal culinary water sources. Landslides then wiped out the original spring source and made it extremely difficult to reconnect to another discharge point from the same aquifer.

Numerous "sink holes" appeared in March and April 1983 along the Wasatch Front urban corridor. All of these fell under the category of "cultural collapse," none being natural. Cultural collapse refers to the collapse of ceilings of old, historical, subterranean structures such as cesspools, root cellars, mine tunnels, and dug wells. There were some two dozen of these structures reported. The most spectacular of these was near the mountain front, in coarse sediments, where a previously unknown exploration-adit ceiling collapsed in two locations on a single residential property.

Spring contamination

Springs which discharge shallow ground water may be in danger of contamination if the infiltration distance from the ground surface to the ascending water table is reduced because of reduction of filter distance.

Upon the slope failure of numbers of debris slides, the discharge of voluminous ground water from point sources has been observed, indicating that subsurface piping must be an active process.

In the urban environment, in particular, the shallow ground-water reservoir contributory to a spring may have risen to engulf leach fields, old solid waste sites, and the like. Water quality must be monitored if the springs provide a source of culinary water.

Loss of agricultural yields

Considerable acreage of farm land and pasture land suffered from low yields due to the higher than normal water table which waterlogged the roots. Providing subsurface drainage may not be practical where the period of the wet cycle is uncertain. Tooele County, for example, had at least 5,000 acres affected in this manner. Homeowner landscaping was also affected by waterlogging of surficial soils.

Frost heave

A high, shallow water table, closer than normal to the ground surface, can bring the capillary fringe zone virtually to the ground surface and, thus, aggravate the frost heave problem. Soils susceptible to frost heave occur as a veneer over much of the state, having been deposited by water and wind. Soils require the existence of shallow ground water for development of maximum heave. Upheaval of sidewalk, driveway, and curbing has most frequently been the result of such forces.

Road deterioration

Softening of subgrade is a frequent consequence of saturation caused by shallow ground water. The zone of soil saturation above the water table, called the "capillary fringe zone," can also pose problems. Pressure in this zone is such that pore water migrates upward, against gravity, assisted by evaporation. The fine-textured, noncohesive soils which promote this fringe zone are common throughout Utah. Allowing moisture to leave the ground-water reservoir and migrate toward the ground surface may greatly aggravate effects of soil consolidation and frost action in the winter. Roads, curbs, sidewalks, and canal linings suffer considerable damage where the fringe zone has shifted to shallower depths. In areas that are subject to severe frost cycles, such as the Uinta Basin, this problem became quite significant in 1983. Street and highway drainage can be costly and road maintenance highly aggravated. In 1983, the small town of Garland, (Box Elder County), experienced some $14,000 in damages to streets which would not normally have required maintenance for at least another year or more.

Aggravation of earthquake ground shaking

One earthquake occurred on October 8, 1983, during the wet cycle in the Salt Lake Valley, with a Richter magnitude 4.25. Damage to single-family dwellings and multi-story public buildings was concentrated in zones where the normal water table depth was 5 to 10 feet. However, other factors must also be taken into consideration when an assessment of earthquake damage occurs; therefore, the evidence that the high water table aggravated ground motion is inconclusive, but there appears to be a reasonably good correlation. What was clear was that the damage was unaccountably high for such a low-magnitude event and was probably related to the shallow water table in conjunction with the type of underlying soil.

A most important consideration, but one that remains untested, is the effect of the high water table upon the potential for liquefaction, especially along the Wasatch Front. What is not generally recognized is that liquefaction would likely be widespread over portions of the benchland and even along mountain drainages where perched ground water occurs in Lake Bonneville shoreline sediments. Generally, the shallower the water table (close to ground surface), the greater the effects and impacts of liquefaction.

Erosion and Sedimentation

It now appears that erosion and sedimentation in 1983 were commonly attributable to disruption of soil and rock related to landsliding in the watershed. This fact was not readily appreciated because observation of the drainage basins was not possible until much later in the year. At times, landslides intermittently blocked live drainages directly and sent surges of rock and sediment downstream upon breaching. More commonly, however, the slides mobilized as debris flows which then became debris floods with considerable impact downstream as channel sections were enlarged or clogged. Stone Creek, in Bountiful, was one such example. The duration of the peak discharges was apparently longer than at any time in Utah history, possibly as a result of rapid snowmelt as well as cloudburst activity.

From studies of eleven streams on the Wasatch Front from North Ogden to Salt Lake City, Lindskov (1984) found that nine equaled or exceeded the 100-year flood condition in 1983. For one of the drainages (Stone Creek, east of Bountiful), he determined that the peak was greater than forty times the maximum previously known flood. During field reconnaissance in 1983, one of the writers observed a point of blockage and ephemeral impoundment in that drainage below the debris slide which was then converted into a debris flow when impounded water saturated the debris slide. The situation at Stone Creek was, therefore, likely a damming and breach, with a sudden release of bulked (sediment laden) flood discharge. The remainder of the drainages showed peak discharges ranging from slightly greater to about five times those previously known. Julander and Hawkins (1985) calculated that two other Salt Lake County streams appeared to have had 200- and 900-year events and, using most conservative estimates of return periods, Davis County watersheds ranged from 90 to over 10,000 years for peak discharges. The flows greater than a 100-year flood were caused by sudden surges of waters that had been blocked or trapped by the extensive bulking caused by rapid introduction of large volumes of sediment.

Erosion, sediment transport, and deposition are geologic processes of considerable importance. Erosion, of course, has deeply dissected the youthful, high mountains for which Utah is famous; sedimentation provided the landforms on which most all of the population resides. The processes must have been most active during periods of high precipitation. Results of the geologic processes experienced in 1983 and requiring remedial action by man were:

A. Erosion
  1. Severe erosion of concave curves (meanders) of streams.
  2. Breaching across meanders/loops.
  3. Scouring to bedrock, particularly in steep channels.
  4. Severe erosion on mountain slopes covered with thick accumulations of colluvial soil.
  5. Spillway damage.
  6. Bridge abutment damage.
  7. Culvert (constriction in channel section) damage (clogging and/or scouring).
  8. Lined and unlined canal damage.
  9. Changes in canal gradients.
  10. Changes in cross section from natural to man-made channel or vice versa.
  11. Aggravated erosion where channels cross Lake Bonneville sediments, on benchlands.
  12. Aggravated erosion of trails or roads where runoff is concentrated.
  13. Appearance of new springs on interfluvs.

B. Transport
  1. All size particles have been carried downstream, including a large anomalous debris earlier transported during debris flow stages.
  2. Contaminating substances have been transported long distances.
  3. Multiple phase changes from a debris flow to debris flood have resulted in complexities of scour and sedimentation.

C. Deposition
  1. New contributions to portions of alluvial fans that have already become urbanized has resulted in costs for clean-up, drainage re-establishment, regrading, emergency response and repair to public and private facilities (i.e., Farmington Canyon fan).
  2. Where canal or ditch gradients diminish, deposition has caused nuisances--if not worse (i.e., Weber Basin system).
  3. Upstream of blocked culverts, bridges, etc., deposition threatened subsequent to washouts (i.e., Coldwater Canyon, North Ogden).
  4. Deposition engulfed new structure on extremities of flood plains (i.e., City Creek, Salt Lake City).
  5. In ponds, lakes, and reservoirs, deposition has accelerated the eutrophication process (i.e., Red Butte Reservoir, Salt Lake City).

6. On fields and pastures within the valley floor, deposition has affected crop yields and grazing capabilities well into the future (i.e., Indianola, Sanpete County).
7. Modification of the terrain on alluvial fans made it very difficult to locate buried utilities for repair, replacement, and system changes.

Closed Basins, Lakes, and Playas

Inundation of valley floors where there is no external drainage is a phenomenon that results in deposition of fine sediments and salts over time. In the recorded history of Utah, the state has never before seen the areal extent of pluvial lakes in the Great Basin that occurred in 1983.

The lakes appear chiefly on federal lands. Unfortunately, the U. S. Bureau of Land Management was able to furnish very little information on geomorphic or geohydrologic changes occurring in 1983. Waters and brine, both on the surface and in the subsurface, were not monitored for changes in chemical characteristics as the areal extent of the water bodies grew. Sevier and Salt Marsh Lakes in Millard County, Salt Flats Lake at Wendover and Rush Lake (both in Tooele County) are all prominent examples of playa lakes that were unprecedented in size in 1983 according to testimony from county residents and evidence collected from satellite imagery. Of obvious significance was the rise of Great Salt Lake and Utah Lake, both of which continued their ascents beyond the end of the 1983 water year (September 30, 1983).

Small lakes have caused the following problems:

- Increases in shallow, unconfined water tables over broader area.
- Loss of wetland ecological niches.
- Ephemeral inundation by wind action acting on the surface water bodies.
- Dissolution of near-surface salts.
- Drowning and destruction of cross-valley roads.
- Drowning of water wells and short-term, if not long-term, aquifer contamination.
- Drowning of vegetation.
- Loss of rangelands.

Great Salt Lake

Because there is no outlet, the level of the Great Salt Lake is controlled by evaporation. In a normal year, the average lake peak is about 4,198 feet above sea level; official flood stage is 4,202 feet. On July 7, 1983, however, it peaked at 4,205 feet, its highest level since 1924. The 5-foot rise in 1983 was the largest rise of record for one year. This amounted to an increase of 6,000,000 acre feet and 267 square miles. Its historical level of record (4,211.5 feet) was attained in 1873. Even small rises in lake level result in large areas of inundation because of the flat topography of the shoreline and bounding basin area. The change in inundated area in 1983 was 700,000 acres - from a low of 600,000 acres to a high of 1,300,000 on December 13, 1983.

In 1983, the lake also experienced its smallest decline of record. The lake dropped 0.4 foot on October 1 and then began rising again. By December 15, the lake had achieved elevation 4,205.56 feet - the highest since 1887. On January 1, 1984, the level was up a full 6 inches to 4,206.15 feet.

The lake is divided by the Southern Pacific Railroad causeway. Differences in inflow in the two portions mean that levels in each are non-uniform. On July 15, 1983, the southern portion was 3.25 feet higher than the northern portion.

Damages in the vicinity of Great Salt Lake in 1983 included recreational areas, mineral industry, and transportation routes. Damage costs (Stephens, 1984) were estimated at $49,313,00 for industrial and utility, $28,016,000 for public facilities, and $601,000 for commercial (actual figures may be substantially higher). The estimated total of $77,930,000 accounted for one-eighth of the total wet-year costs.

Utah Lake

Utah Lake is part of the drainage system into Great Salt Lake. The compromise level was established by law in 1885 as elevation 4,489.34 feet, above which the lake is "not supposed to rise." Regulation is by means of a dam and a gate at the outlet. On June 24, 1983, the lake peaked at 4.98 feet above "compromise." The 68,000 acre foot impoundment behind the Thistle landslide prevented the lake from rising an additional 7.2 inches. For purposes of comparison, it is interesting to note that during the flood years 1923 and 1952, Utah Lake peaked at 3.4 feet and 3.7 feet, respectively, above "compromise." During the period of 1890 to 1983, the lake ranged from 12 feet below to 3.5 feet above "compromise" level. One foot above "compromise" means a volume change of 100,000 acre feet.

Damage costs as a result of the lake rising were incurred by agriculture, State Parks and Recreation Division, and the federal government for protection of I-15 and the Provo airport. The resultant costs were appraised as public sector $3,724,000 (Stephens, 1984); agricultural $300,000,000 (Mike Hollands, CH2M Hill, verbal communication, 1987); commercial $305,000; residential $621,000; and industrial/utilities $56,000. The total of just over $8,000,000 accounted for 1.3% of the total wet-year costs.

Inflow and Infiltration

A special attempt has been made to evaluate the inflow-infiltration (I-I) for sewer districts throughout the state (figure 37) in order to examine the impact of the rising, shallow, unconfined water table in the current wet cycle and to acquire knowledge of how the economics of sewage treatment may be affected by this phenomenon. Such a study has not previously been conducted in Utah.

The records of 38 sewer districts were utilized from a total of 117 districts in the state because they provided an adequate data base. Table 8 shows the distribution of the 38 districts in each of the climatological divisions and figure 37 shows the locations of the districts. Of the six climatological divisions of the state, the North Central division contains the greatest number of districts and highest quality of records.

In each of the six climatological divisions, the precipitation for 1982 and 1983 exceeds the normal (30-year average) by considerable amounts (figure 33). This is again illustrated on figure 37 as percentages of the normal for each of the two calendar years. Also shown on figure 38 are results, statewide, of the sewer district inflow-infiltration examinations. Increases are evident in the quantities of inflow-infiltration throughout the state in 1983.

In 1983, it appears that an excess of approximately 14,000 million gallons of I-I was processed. The figures for the years 1978 through 1981 were used for acquiring average value. The years 1982 through 1983 have been in the height of economic recession; therefore, growth to the sewage systems can be discounted as a factor in yielding the higher figures.

Cost for sewage treatment in the state has been calculated as averaging $360 per million gallons. Cost for processing excess I-I in Utah in 1983 was, therefore, over $5,000,000. Inasmuch as this is a cost that is borne by nearly everyone and a cost that is largely overlooked, it is identified here as another significant wet-cycle concern.

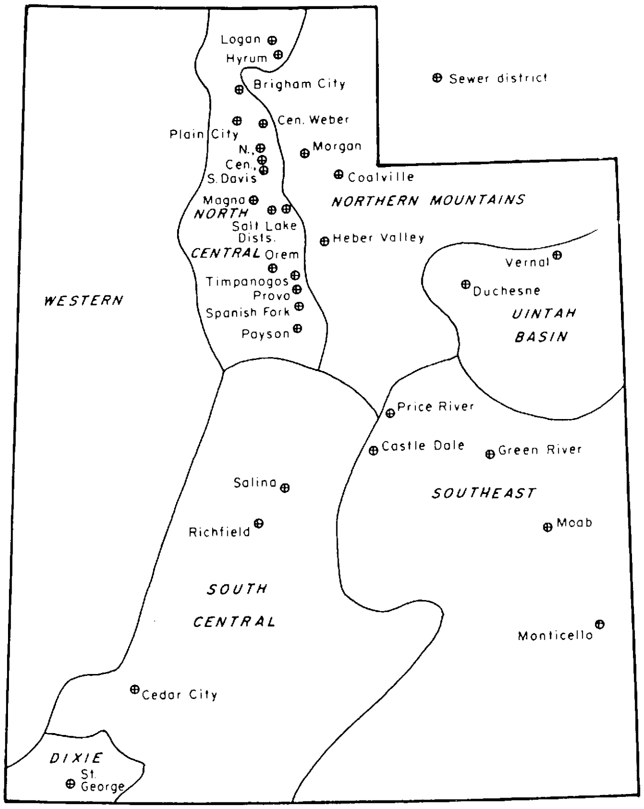


Figure 37.
Locations of sewer districts and climatological divisions used in this study.

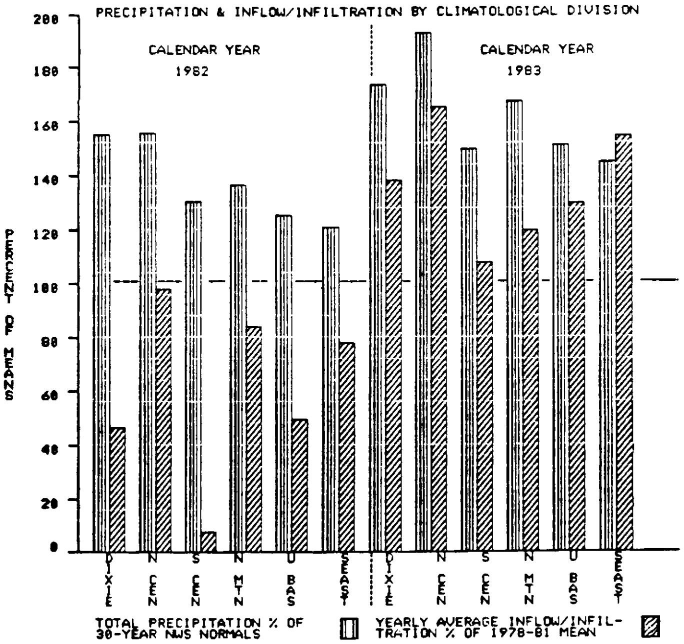


Figure 38.
Precipitation and inflow-infiltration by climatological divisions for 1982 and 1983.

TABLE 8: Sewer Districts and Number of Weather Stations in NWS Climatological Divisions of Utah

Division	# of Weather Station (elevation range)		Sewer District
DIXIE	2	(2768-4050 feet)	St. George
NORTH CENTRAL	11	(4222-5070 feet)	Brigham City
			Central Davis
			Central Weber
			Granger-Hunter
			Hyrum
			Logan
			Magna
			Midvale
			Murray
			North Davis
			Orem
			Payson
			Plain City
			Provo
			Salt Lake City
			Salt Lake Suburban #1
			Salt Lake County Cottonwood
			Sandy
			South Davis: North Plant
			South Davis: South Plant
			South Salt Lake
			Spanish Fork
			Timpanogos
			Tooele
SOUTH CENTRAL	12	(4958-7915 feet)	Cedar City
			Richfield
			Salina
NORTHERN MTNS	6	(4820-8748 feet)	Coalville
			Heber Valley
			Morgan
UINTA BASIN	4	(4750-5518 feet)	Duchesne
			Vernal
SOUTHEAST	7	(4070-6138 feet)	Castle Dale/Orangeville
			Green River
			Moab
			Monticello
			Price River

Wildlife Resources

Despite the appearance in 1983 of very many new ground-water discharge points, vastly expanded areas of wetlands and historically unprecedented disturbed terrain, there has been no attempt in Utah to define the effects upon wildlife.

Landsliding exposed new springs which are not likely to be long-lived. The springs have appeared at locations, however, that appeared to have been devoid of water prior to the landslide, particularly those at high elevation. The blowouts that resulted in debris flows frequently occurred at relatively high elevation sites. Deer have been observed congregating around such springs, but no systematic observations have been made, even for a single spring site.

Slump-type landslides have created new ponds, both ephemeral and permanent; these are sure to attract wildlife. The extent to which the disturbed ground discourages visitations to the ponds is unknown. While in the active phase, landslides emit sounds as the earth is churned and vegetation breaks and snaps. It is not known whether animals flee from these sounds.

With the higher water table, wetlands have expanded and inundated new areas, thereby affecting the distribution of vegetation. Certain plant species die when submerged, subsequently removing food sources. Water fowl are particularly affected and must find alternate sites. Water fowl conservation is a significant government program in northern Utah, unfortunately there is no documentation of actual effects.

Fish

There are two aspects to the effects that 1983 earth movements have had upon the state's fish population. The first is the effect upon the state's hatcheries. The second is the effect upon the natural habitat and reproduction.

Hatcheries have been hit with significant sediment during this wet cycle, but not from normal spring runoff. On July 25, 1983, Loa Hatchery, located in Wayne County, was hit by a debris flow which was either caused or aggravated by flood waters escaping from a canal following a cloudburst event over Graveyard Hollow. Sediment was deposited in the hatchery raceways and troughs. The hatchery came very close to losing all 300,000 fish; fortunately, a number of people were on hand and able to keep the screens clear to prevent the fish from suffocating. At the final count, only 1,200 three-inchers were lost. Others probably died within a short time from severe stress. Scouring to bedrock occurred between the canal breach and the hatchery. Damage washout amounted to $8,000. The cost to prevent a reoccurrence amounted to $2,000 to clear the debris and $6,200 for replacement of 310 feet of 42-inch pipe.

Springville Hatchery experienced a fish kill of about 40,000 fish; it resulted from a cloudburst over Rock Canyon (Utah County) in July of 1983. A debris flood most likely was responsible. Damage was about $2,000, not including the 500 pounds of fish valued at $750.

Midway Hatchery in Wasatch County spent $2,000 to build up dikes to prevent a problem on Snake Creek. The situation at Midway appears to have been one of sanding from increased ground water hydrostatic pressure which introduced increasing quantities of sand in May and June of 1983. The results were that Systems 1 through 6 acted as sediment settling basins, preventing the continued growth of the young fish. Some 500,000 fish are normally reared at this location.

Fountain Green Hatchery in Sanpete County is situated very close to debris flow runouts caused by slides along the San Pitch Range. Some movement of fill material occurred in 1983 along the edge of the pond where a water line was installed several years earlier, but there was no damage.

Storage capacity losses of reservoirs and ponds meant that fish populations were considerably reduced. Since documentation of storage losses experienced in 1983 is poor, the full impact is unknown. Red Butte Reservoir in Salt Lake County is sure to have lost storage from multiple debris flow events impacting the drainage in 1983. A reservoir basin in north Farmington (Davis County) was completely filled by the debris flows in 1983. Other reservoirs impacted in 1983 by earth movements included Tibble Fork (American Fork Drainage, Utah County), Minersville (Beaver County), Mill Site (Ferron area, Emery County) and Towne Reservoir and Twin Lakes (both in Twelvemile Canyon drainage, Sanpete County). The State Division of Wildlife Resources owns 2,000 acre feet of storage in each of the Minersville and Mill Site reservoirs.

The biggest unknown, unfortunately, has been the fish habitat losses on streams, with most severe damage from debris floods. Glen Davis, State Fisheries Chief, estimates a 90% loss on Salt Creek in Juab County. No drainages have been quantified, but it appears that entire fish populations have been lost from Wasatch Front drainages, except perhaps for the uppermost segments. Even where total mortality has not occurred, increases in turbidity of the waters are apt to have affected reproduction rates.

One positive note should be considered in this wet cycle. Increases in ground-water recharge should mean higher base flows for streams which would probably result in some enhancements of fish populations. This condition could only occur provided the drainages have escaped significant erosion, scour, and sedimentation events.

COSTS, IMPACTS, AND MITIGATION RELATIVE TO THE 1983 EVENTS

Examination of costs expended in 1983 can prove useful in the determinations of the impact of geologic hazards related to the wet period on the state and local economy and in making judgments with respect to the distribution and magnitude of occurrences rather than merely speculating upon potentials as is so often done.

Table 9 is from a recent National Research Council publication on reducing losses from landsliding in the United States (Committee on Ground Failure Hazards, 1985). It has been keyed to enable one to see the status of efforts to reduce the costs of landsliding in Utah, including pre-1983 and crisis-period actions. The voids at the federal, state, local, and private levels are readily apparent from the table. Much remains to be done in Utah.

Cost of Damages to Local, State and Federal Government and Private Sector

Based upon tables published by the Utah Disaster Relief Board (DRB) in December of 1986 (Appendices I and IV in Burnett, 1986), costs are available by political subdivision for the events of 1983. They differ from earlier figures published by the Division of Comprehensive Emergency Management (1984, Pages 5 and 6).

The Disaster Relief Board makes grants to help repair, restore, reconstruct, or replace public facilities which suffer damage or destruction by flooding or slope movement. Such facilities, in this case, include county- and municipality-owned flood control, dam, public power, sewage treatment and collection, water way, water supply and distribution, and watershed development facilities; non-federal and non-state streets, roads, highways, and bridges; and any federal non-state roads, highway or bridge damage which is not covered by federal highway funding (Burnett, 1986, Pages 1-2). From the listing, it is apparent

TABLE 9 Partial listing of public and private roles in reducing the costs of landsliding in Utah.

Federal	State	Local	Private
Emergency Management			
Conduct research on real-time prediction of landslides, and develop techniques for monitoring and surveillance.	Monitor landslides and landslide-prone areas.[1]	Issue warnings of imminent landslides.[1]	Cooperate with, and make resources available for, emergency operations.[2]
Provide expert advice to state and local governments during an emergency.[1]	Assess hazard and risk.[1]	Coordinate resources of private sector for emergency response.[1]	
Provide technical assistance, training assistance, and funds to state and local governments for emergency planning, training, and response.[1]	Mobilize resources and provide expert assistance for response and rescue operations.[1]	Manage emergency operations.[1]	
Long-term Hazard Reduction			
Fund and undertake research on landslide mechanisms, and disseminate research results.[2]	Fund and undertake research on landslide problems in the particular state, and disseminate research results.[3]	Implement research results.	Conduct research and use research results.
Develop methods for inventorying landslides, and inventory landslides on federally managed lands.[3]	Inventory landslides within the state.[2]	Monitor landslides.	Share information about potential landslide hazards and monitor landslides.[3]
Require federal agencies to avoid or design for landslides in federal construction programs.[3]	Require or provide disclosure of landslide hazards during real estate transactions.[3]	Require recognition, avoidance, or design for landslides as part of land-use planning and development.[2]	Recognize, avoid, or design for landslide hazards in land acquisition, development, and construction.[3]
Improve design and construction techniques for minimizing landslide damage to federal building, highways, and other facilities.[3]	Require state agencies to avoid or design for landslides in state construction programs.[3]	Enact and enforce grading ordinances and building codes to minimize landslide occurrence and damage.[3]	Incorporate geotechnical engineering advice in construction and management of buildings and facilities.[2]
Manage federal forest lands to minimize landslide damage.[2]	Establish special assessment districts to pay for landslide mitigation.	Issue warnings and post signs to discourage entry and use of landslide-prone areas.	Incorporate geotechnical engineering advice in investment and loan decisions.
Provide financial incentives and disincentives to encourage making appropriate provisions for landslides in federally financed development activities.	Establish landslide warning systems.	Avoid construction of public facilities in landslide-prone areas and relocate obsolete public facilities in landslide-safe areas.[3]	
	Require state geologist to designate landslide areas for special studies.		
	Provide model ordinances and building codes to local governments for landslide mitigation.[3]		
	Provide information to local governments and to the public concerning landslide hazards.[2]		

TABLE 9 is from Committee on ground failure hazards (1985).
Numerical designations denote the following:
[1] Task generally performed.
[2] Task performed to some moderate extent.
[3] Task performed to slight extent.
No Action.

that both water and sewer districts, as well as flood control districts, are also eligible for the grants. Table 10 is provided to document what the relative impact was on local government in 1983. Eighty percent of costs to local government were suffered by Wasatch Front communities, which is in keeping with the population distribution in the state. Nine percent of total costs went to the three Wasatch Plateau counties of Sanpete, Sevier, and Emery.

TABLE 10. Costs to Local Government of the Events of 1983

County	Percentage of Total Cost	Costs* (in $ million)
Salt Lake[1]	38	27.137
Davis[1]	23	16.182
Utah[1]	9	6.628
Sanpete[2]	6	4.408
Weber[1]	5	3.713
Juab[1]	4	2.916
Millard	3	2.000
Daggett	1.5	1.199
Emery[2]	1.5	1.106
Sevier[2]	1.5	1.081
Tooele	1	0.661
Beaver	1	0.619
Box Elder[1]	1	0.584
Wasatch	1	0.579
Summit	1	0.484
Uintah	1	0.398
Garfield	0.5	0.345
Carbon	0.5	0.323
Duchesne	0.5	0.318
Morgan	0.5	0.317
Cache	0.4	0.268
Piute	0.2	0.170
Rich	0.1	0.037
	Total	71.473
Wasatch Front[1]	80	57.160
Wasatch Plateau[2]	9	6.598

* from Appendices I & IV, Burnett (1986)

It is apparent that these expenses affected every sector of the economy. The extent of Federal disaster relief was extensive in Utah in 1983 (CEM, 1984). Federal disaster relief administered by the Federal Emergency Management Agency (FEMA) funded 75% of certain public assistance costs, with the total equalling almost 10% of the total flood damage. Federally provided individual assistance grants amounted to 1.4%. The Federal Highway Administration was impacted to the extent that their funding alone reached 9.4% of the total flood damages, two-thirds of which was directed toward highway relocation necessitated by the Thistle Landslide. U. S. Forest Service allocations amounted to 5.2% of the total, while the U. S. Army Corps of Engineers expenditures amounted to just under 1%. In summary, Federal outlay, percentage-wise, amounted to about 27% of the total costs; the State of Utah total percentage was about 8%; local governments bore the brunt of about 10% of the total costs. The private sector accounted for 55% of the total share, with over one-half of the percentage suffered by the railroad industry and over one-quarter by agricultural interests.

Of the public assistance grants that were distributed to 23 qualifying counties in the state, 80% of the funding went to Wasatch Front communities and 9% to central Utah political subdivision (computed from figures in Burnett, 1986). These figures are likely to accurately reflect relative damage from landslides, debris flows, and debris floods. For comparison, Millard County damages, which were almost entirely due to the DMAD dam break, amounted to 3% of the public assistance total.

Impacts of Geologic Hazards on the Counties in 1983

Table 11 was prepared to compare the geologic consequences of the wet year on Utah counties (including private sector). A relative rating scale of 1 to 5 was utilized to evaluate the extent to which five types of geologic hazards caused or triggered by the wet cycle (mountainland sliding, benchland sliding, debris flow/flood, erosion/sedimentation, and high ground water) impacted each county (both incorporated and unincorporated areas). The basis for assigning ratings in table 11 are: (1) frequency of occurrence of event, (2) areal extent of hazard zones, (3) economic impact to all types of facilities, and (4) danger to population. Impacts considered both public and private facilities, including roads and streets, storm sewer systems, water and irrigation systems, residential neighborhoods, sewage disposal, utilities, and recreational facilities. This table applies to 1983 events only. For example, a wet year experiencing intense short-duration, cloudburst-type precipitation might change the picture considerably. An earthquake of only moderate magnitude anywhere in the state, occurring coincidentally with wet conditions, would also create a very different picture because of the damage caused by the effects of ground shaking.

Of the 24 counties evaluated, only three were judged to have experienced a low (none very low) level of geologic hazard activity. Of those three counties, two are very sparse in population (Rich and Daggett Counties). Forty-two percent of the counties rate high or very high; about eighty-five percent of the population of the state resides in these counties. It is interesting to note that this population figure is identical with that which has been given repeatedly for susceptibility to seismic risk in the state. Much of the population of the state, therefore, appears to be subject to more than one significant geologic hazard.

Table 11: *Relative Impact of 1983 Geologic Hazards in the Counties*

	GEOLOGIC HAZARD					
COUNTY	Mountainland Sliding	Benchland Sliding	Debris Flow/ Debris Flood	Erosion Sedimentation	High Ground Water	Rating Total
Beaver (0.31)	3	1	2	4	2	12
Box Elder (2.2)	3	1	3	4	4+	15
Cache (4.0)	1	2	2	4	3+	12
Carbon (1.5)	3	NA	3	3	3	12
Davis (10.1)	2	4	5	5	4	20^{n}
Daggett (0.05)	2	NA	1	2	2	7
Duchesne (0.88)	3	NA	1	4	3	11
Emery (0.80)	5	1	4	4	4	18^{n}
Iron (1.2)	3	1	3	2	2	11
Juab (0.37)	3	2	5	4	2	16
Millard (0.71)	3	1	4	5	3	16
Morgan (0.33)	2	3	1	3	3	12
Piute (0.09)	3	1	2	4	3	13
Rich (0.14)	1	1	1	1	3	7
Salt Lake (42)	3	2	2	5	5	17
Sanpete (1.1)	5+	1	5+	5	4	20+
Sevier (0.98)	5	1	5	5	4	20
Summit (0.74)	3	NA	2	4	3	12
Tooele (1.7)	1	1	2	3	4	11^{n}
Uintah (1.5)	3	NA	1	5	3	12
Utah (15)	5	5	4	5	5	24^{n}
Wasatch (0.56)	3	2	1	2	3	11
Washington (1.9)	2	2	1	2	2	9
Weber (9.6)	2	3	2	4	4+	15

Scale	Rating Totals	Number	Names of Counties
Very High = 5	20-24	4	Utah, Sanpete, Davis, Sevier
High = 4	15-19	6	Emery, Salt Lake, Juab, Millard, Weber, Box Elder
Moderate = 3	10-14	11	Piute, Cache, Morgan, Summit, Uintah, Carbon, Beaver, Iron, Tooele, Wasatch, Duchesne
Low = 2	7-9	3	Daggett, Rich, Washington
Very Low = 1			

NOTE: 21 of 24 counties rank as having had moderate or greater hazard exposure in 1983.
10 of 24 counties rank as having had high or very high hazard exposure in 1983.
Percent of state's total population residing in the respective county is found in parentheses. Computed from population figures for 7-1-83 (U.S. Census).
NA = not applicable

Costs associated with landslides

Costs associated with the landslides have not always been immediately apparent but some may be incurred over a long period. Listed below are some of the direct and indirect costs of the landsliding, including debris flows.

Direct Costs

1. Clearing of roads, canals, rights of way.
2. Repair to road surfacing and embankment.
3. Clearing and replacement of road culverts.
4. Repair or relocation of lifelines.
5. Damage to, or destruction of, structures.
6. Clearing of residential property.
7. Repair or relocation of dwellings and other structures.
8. Dredging of water courses.
9. Engineering, design, and construction of anti-slide measures.
10. Government services, including emergency response, inspections by officials, monitoring, overflights, consultants, overtime, travel, per diem.
11. Clearing of cropland and pastureland.
12. Cleaning of debris basins.
13. Property acquisition cost for siting of anti-slide (debris flow, debris flood facilities.
14. Emergency temporary provision of detour around the damaged area.

Indirect Costs

1. Decrease in property value.
2. Decrease in taxes generated from affected properties.
3. Value of time lost by motorists in taking detours.
4. Expenses of taking detours.
5. Revenue loss resulting from out-of-service utilities.
6. Change in spending habits of travelers, including tourists.
7. Effect on fish and wildlife population, fisherman, and hunters.
8. Effect on water courses downstream.
9. Effect on reservoir or lake storage capacity.
10. Effect of media coverage on the public's travel plans.
11. Interference with interstate freight and passenger conveyance facilities.
12. Psychological impact on adults and children.
13. Costs to commuters for reaching employment centers using alternate routes.
14. Acceptance of greater risk in future and the effect on insurance rates.
15. Loss of recreation days.
16. Loss of natural resource harvest (timber, crops, fish, etc.).
17. Delays caused by shifts in priorities by private sector.
18. Delays in providing government services where ordinarily needed.
19. Loss of business and the ultimate loss of tax revenue in a zone of the state bypassed by tourists.
20. Greater fuel consumption, perhaps aggravating a fuel shortage.
21. Increased cost per kilowatt hour of electricity generation as relatively inexpensive hydro stations are placed out of service or power lines disrupted.
22. Inability to meet peak demands by energy suppliers due to interruption of transmission facilities.
23. Placement of critical facilities farther away from a segment of the population, such as fire stations, hospitals, police stations.
24. Shut down of business or cessation of harvest of products (i.e., salt, potash, magnesium) due to loss of resource or costs exceeding reasonable expenditures, resulting in nonexistent profit margin.

25. Change in marketing patterns of a segment of the population with resulting business impact.
26. Forced acceptance of imposed charges for acquiring the right to use another firm's dedicated pipeline, rail system, etc., in order carry on with a business, albeit at higher costs.
27. Unemployment compensation for those laid off due to business closures.
28. Loss of income tax revenue to government.
29. Removal of land from tax rolls.

Debris basin costs only

Costs incurred in the removal of material from existing debris basins, and in siting, property acquisition, design, and construction of new debris basins are a clear indication of the magnitude of problems from debris flows and debris floods and the areal distribution of both phenomena in Utah in 1983.

From north to south in the state, facts relevant to debris basins are provided below (from files of the U. S. Army Corps of Engineers and the Division of Comprehensive Emergency Management, Salt Lake City):

Cache County:
1. Blacksmith Fork: two debris basins recommended.

Box Elder County:
1. Perry Creek: 30,000 cubic yard debris basin, costing $90,000. Also, cleaning of existing basin of 30,000 cubic yards, for $90,000, plus $20,000 acquisition costs.
2. Facer Creek: 40,000 cubic yards, costing $120,000 for expansion, plus $15,000 for property acquisition.
3. Willard Creek: 80,000 cubic yards cleaned from existing basin, costing $240,000 (Debris basin was completely filled from prior years of activity).

Subtotal: $485,000

Weber County:
1. Coldwater Creek: 75,000 cubic yards debris basin, costing over $203,000.

Davis County:
1. North Fork of Holmes Creek: 70,000 cubic yards debris basin, costing $243,000.
2. South Fork of Holmes Creek: debris basin, costing $300,000.
3. Baer Creek: rehabilitation of existing basin and a load acquisition, costing $5,000 to $6,000; new linear basin of 53,000 cubic yards, costing $480,000.
4. Shepard Creek: rehabilitation of existing basin costing $565,000; 97,000 to 145,000 cubic yards of material removed in 1983.
5. Rudd Creek: 100,000 cubic yard debris basin, costing $1,015,000 (includes $565,000 for property acquisition and relocation expenses).

Utah County:
1. Rock Canyon: 40 acre feet basin exists.
2. Slate Canyon: two basins exist, total 40 acre feet.
3. Hobble Creek: debris basin, costing $185,000

Subtotal: $185,000

Juab County:
1. Chicken Creek: 6,000 to 7,000 cubic yard existing basin; need 75,000 cubic yard, costing $375,000.
2. Pigeon Creek: need 45,000 cubic yard debris basin, costing $225,000.

Subtotal: $600,000

Sanpete County:
1. Pleasant Creek: rehabilitation of basin, costing $400,000.

2. **Ephraim Canyon: existing basin is adequate, but 60,000 cubic yards needs to be removed, costing $180,000.**
3. Manti Creek: two basins exist; need modification, costing $1,000,000.
4. Twelvemile Canyon: need 100,000 cubic yard, costing $300,000.

Subtotal: $1,880,000

Landslide and Debris Flow Hazard Mitigation Prior and Subsequent to 1983 Events

In Utah, in general, very little had been done to mitigate against both landslide and debris flow hazards prior to 1983. Debris basins did exist that were built in earlier decades of this century to fend off debris flows and debris floods--primarily in Box Elder, Davis, Utah and Sanpete Counties. All of these have since been determined to be undersized and some have fallen into disuse and disrepair. Attention to geologic hazards by the planning profession greatly increased in the 1970s, particularly along the Wasatch Front, resulting in some regulation of building on benchland and foothill slopes. Davis County, for example, engaged the Utah Geological and Mineral Survey to prepare a geothematic atlas (Kaliser, 1987) for them in 1976.

The urban corridor along the Wasatch Front has been under constant pressure of development in recent decades. Much of the evidence of debris flow events of the 1920s and 1930s is destroyed (Crost, 1981) by natural and/or man-made processes.

Although one of the most effective tools for mitigation is avoidance, it is no longer possible to exercise this option, for the most part, along the urban corridor of Box Elder, Weber, Davis, Salt Lake, and Utah counties.

In addition to avoidance and regulation, there exist other options: (1) relocation, (2) insurance, (3) warning, and (4) remedial mitigation measures. Relocation is most unpopular and difficult and normally cannot be achieved until damage is suffered. Twelve families were relocated following the Rudd Creek debris flow in Farmington, Davis County, in 1983. Several relocations occurred within the local area to accommodate the confines of a newly designed and constructed debris basin. With city purchase of lots for the debris basin, it became feasible for families to relocate. Even public entities are very reluctant to relocate structures.

Natural hazards insurance has been available in the Utah market prior to 1983, but there was very little public interest in the coverage prior to the storms. There was a considerable attempt to acquire it on the part of many homeowners during the spring of 1983 and some succeeded in time to file claims. Under the federal flood insurance program, debris floods and debris flows are covered, but not landslides. Approximately 2,500 individual homeowner policies were in effect, having been underwritten by Lloyds of London (Trustco, 1987). Under the private insurance program, 73 claims were filed relative to wet-year effects and $622,000 in claims paid. Seven of the claims resulted from the DMAD dam break, however. The total for claims paid for all structures under the National Flood Insurance Program was $419,000 for 272 claims (Jim Harvey, 1987). Following the worst part of the wet cycle, the number of subscribers diminished.

Warnings were provided during the crisis period based largely upon aerial observations of conditions and weather forecasts. During 1983, prior to the sliding, there were no instrumentation installations in the state. Instrumentation was pursued later in 1983 when extensometers were installed at the site of partially detached masses at Rudd Creek and at Reynolds Gulch (Big Cottonwood Canyon, Salt Lake County). The system at Rudd Creek later (in 1984) provided telemetering to the dispatcher of the Davis County Sheriff so that warnings could be facilitated.

Remedial measures are most useful in developed areas. Their selection depends upon five factors:

- Engineering feasibility: A complete engineering geologic and hydrogeologic analysis of site conditions must be made. Care must be taken to assure that the problem is not shunted elsewhere.
- Economic feasibility: Costs, including those of maintenance, must be weighed against future benefits. Also to be considered are human factors for which costs cannot be readily assigned, such as suffering.
- Legal/regulatory conformity: Liability arises if the action damages adjacent property owners.

  The measures must conform to local building and safety codes, also.
- Social acceptability: Any design must not be objected to by neighbors or the community. Aesthetics may enter into a decision.
- Environmental acceptability: The environmental impact must be within the acceptable range.

For landslides, remedial measures may include such things as: (1) buttressing to add support (resistance), (2) dewatering or control of ground water, (3) control of surface water, (4) vegetative recovery, (5) grading to improve stability, (6) removal, (7) unloading, (8) hillside benching, (9) slope reduction, and (10) retaining structures. Only in a very few instances have remedial measures been applied to landslides that moved in 1983. Benchland slides, although small, impact valuable real estate. Regrading is the most common approach along the Wasatch Front, with control of surface runoff. If a slide does not affect utilities, streets, or sidewalks, it is unlikely to be treated in Utah. Retaining structures, although in common use, have frequently been inadequately designed and constructed in the past. It is this situation that will change as a result of the 1983 storms. State legislation should be introduced requiring detailed engineering analysis for all developments and construction in hillside areas as well as where mitigation is necessary to stabilize existing developments.

Mitigation measures for debris flows differ substantially from those for landslides. With the exception of debris basins, they are rarely found in Utah. Debris basins are intended to trap material, from both debris flows and debris floods, at the canyon mouth. Following the 1983 events, engineers sized new debris basin designs upon volumes of partially detached landslide masses. An additional bulking factor might well be applied for channel accretion, however, depending upon the state of the given channel. Maintenance must be emphasized with any debris basin. There must be sufficient development or development potential below the canyon mouth to justify its costs.

Debris fences have been helpful, in some instances, in converting debris flows to debris floods. They tend to trap only large debris. Rail and timber barriers and building deflection devices, however, have not been employed in Utah to the present time. Building deflections may consist of shields for windows and doors and deflection walls to protect the upslope side of buildings. Street orientation alone may be quite effective but even more so when employed in conjunction with armoring of street sides. Slope and street carrying capacity must be adequate to handle flows. In the post-1983 era, it is likely that street orientation will receive greater attention.

Finally, as a mitigative measure, public education of the hazards should be initiated. The general public, student population, property owners, prospective homeowners, developers, real estate interests, and local zoning officials should be involved in this education process.

Crisis Period Mitigation Response

During the crisis period, in the spring of 1983, two technical teams were created to address the hazards at each of two localities. On April 15, the first multi-disciplinary team was created at the Thistle landslide. It consisted of representatives of the Utah Geological and Mineral Survey, State Engineer's Office, U. S. Army Corps of Engineers, U. S. Bureau of Reclamation, Utah County Engineer's Office, Department of Transportation, and the Rio Grande Western Railroad. The team reported daily and was intended to be responsive to the needs of the executive committee under the chairmanship of the Director of Public Safety, who was the Governor's designee. Some of the technical considerations that this team deliberated upon included: (1) likelihood of piping of the landslide materials, (2) distribution of fracture-caused voids in the landslide dam, (3) significance of seepage appearing on the downstream face, (4) grading of the landslide dam, (5) ultimate height to which the toe of the landslide could rise against the east canyon wall, (6) quality of the canyon wall sandstone acting as a satisfactory abutment, (7) effect of grading activity and new precipitation on velocity of the slide, and (8) depth of the deepest failure surface and its geologic situation under the valley of the Spanish Fork River.

On May 31, a second team was established, at Farmington, to address the hazards in Davis, Weber, and Box Elder Counties. This team consisted of representatives of the Utah Geological and Mineral Survey and the U. S. Forest Service together with the Davis County Engineers. It addressed concerns in all of the canyons of the three counties. Helicopter support was given by the U. S. Forest Service for the duration of the study.

At the conclusion of operations on June 20, 1983, the team rated the canyons for the potential for future problems. Judgement was made by the multi-disciplinary team based on the following factors:

- likelihood of enlargement of unstable areas
- volume and number of unstable soil masses
- Catchment area for precipitation collection above the unstable slope
- travel distance for debris flows to reach the main drainage channel and the distances therefrom to the canyon mouth
- watershed area above the confluence of the debris flow path with the main channel
- material remaining in the channel available for future scour

The ratings, as assigned, were:

Very High: Rudd
High: Baer, Shepard, Farmington, Hornet, Ward, Holbrook
Medium: Steed, Barnard, Parrish, Mueller, Coldwater

Canyons that were not listed were not construed to be hazard-free, but they were judged to be rated relatively low. At the same time, a warning was given that high-intensity summer cloudbursts could trigger additional events.

Following the crisis period in northern Utah, the senior author recommended that a small consulting team be mobilized in order to address debris flow remedial measures at the earliest opportunity. The concept was sold to the State and to the Federal Emergency Management Agency based upon the following points:

1. Additional information would be immediately provided to all concerned parties in both the public and private sectors.
2. Elected officials would be provided with data necessary to forestall imprudent actions on the part of its citizens, businesses, et cetera.

3. Expertise would demonstrate that the problem is not one of hopelessness, but rather one that can be rationally dealt with.
4. Land managers (U. S. Forest Service, et cetera) would be provided with a full range of ideas for coping with the hazards on their property.
5. Uniformity would be provided in the approaches used by multiple entities.
6. The state of knowledge for communities to act upon would be rapidly advanced.
7. Smaller communities could be placed in a posture to benefit equally with the larger areas in progressing toward feasible solutions.
8. Discussion would be fostered as to the most suitable alternative solutions for use on the Wasatch Front.
9. Communities would be alerted to a better definition of the hazards they were to face at the present and in the future.
10. Recommended remedial measures would be documented at an early date so that necessary funding could be sought without delay.
11. The role of technical advisors would be further reinforced in a national disaster situation.
12. An example of its utility would be provided for communities elsewhere faced with like hazards.

This recommendation led to the engagement of the U. S. Geological Survey to see that the canyon assessment was accomplished. Four USGS geologists and an engineer from the Los Angeles County Flood Control District performed the work and released their report (Wieczorik, 1983).

Predictive Capability

Given the information contained in this paper, the debris flow/debris flood events of 1983 could have been predicted. Many factors govern the debris flow/debris flood transition. One cannot predict which exact canyon wall or slope will fail but it is possible, with current knowledge and technology, to establish the physical parameters and general location of failures. We do know that the short mountain front drainages which flow only intermittently with runoff and which are high and relatively uniform in gradient are most likely to yield debris flows on their alluvial fans. We know the geologic units which are most apt to fail and/or supply materials for slope failures, and we know the general climatic conditions that provide the moisture that produces the failures.

Much research is being done in an attempt to more specifically answer the questions. Some scientists obviously look upon the probability of fruitful results with greater optimism than others. From what was observed in 1983, the authors believe it likely that locations of future events can be predicted with fair reliability. In 1983, most of the small, shallow debris slides were on virgin slopes (i.e., new events). Now that the 1983 season is over, we find a different situation. Greater or lesser portions of slides have detached completely from the slopes, leaving partially detached earth masses remaining on gentle to very steep slopes. These masses may have moved very little in some instances; in others, they may have slid noticeably but have not completed their ultimate transport down the slope. Where this is the case, we may be able to make a reasonable determination for future instability. However, there is a large number of such masses and, unless a very specific local risk situation requires analysis, it is most unlikely that a thorough treatment will be given.

Planning implications and slope hazard scenarios

It will be necessary during future wet years and cycles to monitor weather conditions and canyon slopes, as was done in 1983. In an attempt to provide some prediction capability of short time frame, clues can be gathered from emerging weather patterns and aerial reconnaissance during the snow melt period. A list of scenarios for this purpose follows:

Low potential for slope movement:

1. Below normal or normal soil moisture regimes existed during the fall and winter.
2. Low to intermediate elevation snowpacks (below 7,000 feet) are melted by May 1.
3. The April 1 snowpack is 100% of normal, and soil moisture conditions are saturated.
4. A weather trend of gradual warming for a few days followed by a cooling for the entire melt period.
5. Little storage capacity exists for the spring runoff period. Discharge will be capable of diluting any debris flow that may occur.

Moderate Potential for slope movement:

1. Low to intermediate elevation (below 7,000 feet) snowpack remains in May.
2. The April snowpack is 100% to 200% of normal and is sitting on frost-free, saturated soil moisture conditions.
3. Constant warming occurs during the snowmelt with no cool days forecast for the melt period.
4. Reservoir runoff storage capacity exists.

High Potential for slope movement:

1. High ground-water levels in normal and perched aquifers and saturated soils in the fall, without ground frost.
2. Snow pack remains on low to intermediate elevations (5,500 feet to 7,000 feet) on May 15.
3. The April 1 snowpack is about 200% of normal.
4. Below normal May temperatures are forecast.
5. Reservoirs above capacity going into the melt period.
6. Above normal runoff occurs at the start of the peak melt season.
7. High-intensity rainfall is forecast.

For those slide areas that may pose a relatively significant risk, instrumentation may be considered in the future for early detection of warning signs; however, it must be understood that such systems are still in the experimental phase. Most important, it must be recognized that there may be surprises that will occur on virgin slopes in the future. This knowledge should, then, caution all public entities to exert the greatest vigilance in the citing of public facilities in the future. In other words, just being on an alluvial fan in proximity to a distributory channel or near the apex of the fan must be regarded as a location with risk, regardless of whether or not slides have been identified within the canyon confines. Obviously, some greater knowledge of slide potential will enhance the ability to assess the risk factor.

It may actually be desirable in planning and zoning to consider the citing of higher capital projects on alluvial fans so that engineered debris basins and runoff channels can be afforded to accommodate all or much of the hazard. Special landslide abatement districts could then be established with sufficient tax base to be able to address the problem. The districts would consider: (1) landslide treatment for hazard reduction, (2) watershed protection measures, (3) channel obstruction removal, (4) channel setback recommendations, (5) run-out zone management, (6) cost-benefit measures, and (7) engineered diversion structures, et cetera.

SUMMARY: 1983 EVENTS

Extensive debris flow damage also referred to as "extraordinary" geologic events occurred in Utah as a result of "extraordinary" meteorologic conditions. Even though generally classified "extraordinary," similar periods of high precipitation and associated debris flows have happened in the past and should be anticipated to happen in the future. Snow/water contents in the state during the spring of 1983 ranged from two and one-half to eighty times normal. The late peak in snow accumulation occurred in May, some six weeks later than normal. Finally, a sustained melt, caused by a warming trend and warm rainfall, yielded water at rates averaging over one inch per day for a period of 24 days at intermediate mountain elevations. In a two-week period, a sustained rate of snowmelt 1.6 inches per day occurred; for six days, as much as three inches per day occurred at the 7500-foot elevation. Utah's 140-year climatic records are too short with respect to providing a reliable statistical basis for identifying climatologic cycles that recur infrequently. Although a recurrence interval for the meteorologic conditions and associated geologic phenomena which occurred in the spring of 1983 is not within the realm of prediction, the future occurrence of similar phenomena is inevitable. The knowledge of the inherent weaknesses of the slopes and the record of slope failures and debris flows initiated in 1983 should, therefore, alert government to exercise caution in subsequent land-use planning. A great deal has been learned from the events of 1983. Engineering geologic analysis of all proposed construction sites within the Wasatch range and terrain at the base of the slopes and beyond (benchland and valley floors) should be a requirement.

Antecedent rainfall and snowmelt are important factors in bringing the soil moisture to saturation or field capacity prior to the peak rainfall and/or snowmelt. Although Utah generally had twenty-eight years of negative curve on the cumulative departure graph, the record precipitation months of October of 1981, July and September of 1982, and March of 1983 were adequate to bring conditions to field capacity and to surcharge the shallow but important hydrogeologic regimes. September of 1982, alone, sustained eight to ten inches of precipitation. Proof of the effect upon the ground water system was manifested by flows 128% greater than the next highest year.

The orographic effect of both the Wasatch Mountains and the Wasatch Plateau is such that, over short geographic distances, the normal difference in magnitude of precipitation is on the order of four times. At elevations between 6,000 feet and 8,000 feet where the critical melt fluctuations occurred, there were greater quantities of snowwater to be released than normal . As the snow line receded to higher elevations, additional moisture was available via snowmelt.

The very abundant debris flow events appear to have been initiated or triggered by slope failures, with slumps occurring within saturated surficial materials rapidly converting to debris slides and eventually to debris flows. Upon failure, the material commonly incorporated increasing quantities of debris by erosion from swales and channels until up to twenty times the initial volume was produced and, in turn, transported as debris flows down canyon or slope. These materials were eventually deposited on or near the apex of alluvial fans located at the canyon mouths.

The debris slides were most commonly of the translational type. Also common were slides with both translational and rotational components. Purely rotational debris slides were less common. Perched ground water or zones of increased pore-water pressures were frequently responsible for the saturation that initiated the failures. Generally, the initial failures developed in the zone of active snowmelt. They, therefore, generally occurred at higher elevations and more distant from the urban areas with time. It was noted that, in some cases, however, failures occurred even though the soil or geologic section was not within the zone of saturation. It is evident that, in certain instances, there were paths of subsurface flow perhaps controlled by joints, animal burrows, decomposed roots or other types of voids that allowed ground water to flow to subjacent sites.

The resulting debris flows were not simple phenomena. Normally, there was a succession of surges, varying considerably in viscosity and in volume. Fluctuations of the melt rates with periods of additional precipitation in the form of warm rain, bank sloughing, instantaneous blockage and breaching, contributions from tributary channels and previous local channel deposition are all factors of relevance to the production, quantity, and timing of the surges of the debris flows. Factors that controlled run-out capability are numerous and not easily quantified. More research is necessary to develop methodology and predictability; nevertheless, sufficient scientific knowledge and current engineering technology are available to allow immediate implementation of procedures to mitigate. The consequences of debris flows can be significant upon the natural and man-made environments; the consequences in populated areas can be destruction of property and loss of life if not mitigated.

Other types of earth movements were less frequent in 1983. Earth slumps were next in order of abundance, generally occurring below 5,000 feet on the Wasatch Front but occurring at all elevations on the Wasatch Plateau. Block slides were rare and rock slides were scarce.

Lithology of rock units, degree of fracturing and/or weathering, and texture of surficial units were major contributing factors in determining locality and frequency of slumps and other modes of slope failure. Significant in causing slope failures were terrain modifications by man, even decades old in age, and existence of old recognizable landslides. Natural processes, such as erosion and tectonic displacement (fault scarps) were less important factors contributing to slope failures.

Data concerning both direct and indirect costs of slope movements is still seldom collected and recorded. Even in the case of the Thistle landslide there is not a comprehensive knowledge of the indirect costs. In fact, some of these costs are continuing to be recognized and/or assigned to the winter-spring of 1983.

Items of interest derived from this study:

- The high antecedent moisture available, coupled with the abnormal storm events of 1983, saturated surficial earth materials and often caused debris flows rather than the more typical clear-water flow.
- Historic or previous years of somewhat similar climate sequences lack the scientific recordation of slope failure cause and effect.
- Damage and economic losses appear to be unprecedented. Some of this can be attributed to the high antecedent moisture in conjunction with the abnormally high precipitation, though it must be remembered that records show similar but lesser events during the past 140 years or so.
- Monetary losses were in the excess of $650,000,000 and are still being recorded.
- Debris flows extended to the apex of at least three alluvial fans, inundating and/or burying residential structures.

- Accelerated erosion was evident.
- Ground-water levels reached historically high levels.
- Previous flood danger mapping depicted clear-water flow scenarios and did not show location or elevation of debris flow; thus few anticipated the extent of damage and losses.
- There is a need for more research as to cause and effect of similar climatic conditions.
- There has been inadequate use of available geologic and geotechnic engineering data and knowledge for slope failure and debris flow mitigation.
- Knowledge and expertise to recognize and mitigate landslide and debris flow hazards have been available for more than three decades but are essentially unused.
- An abnormal "El Niño" effect may have contributed to the abnormal climatic event of 1983.
- Efficient and effective land-use planning, coupled with use of geologic expertise, has proven very effective for mitigation in other geographic areas.
- Reaction and emergency response to the disaster were very good; proaction and pre-planning to prevent were poor.
- The most desirable scenario is to take action before the disaster rather than to react to the disaster.
- Knowledge about the recurrence of debris flows along the Wasatch Front and elsewhere might be gained by excavating and logging exploration trenches and/or drilling and logging, (including electric logging), exploratory borings in the alluvial fans that form at the mouths of canyons along the mountain fronts. Some thought would have to be given to selection of sites most likely to yield the best data. Carbon isotope dating of fragments derived from the work could be used for age dating the events.

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