# THE 1983 LANDSLIDE DAM AT THISTLE, UTAH

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ABSTRACT

The Thistle, Utah, landslide began rapid movement on April 13, 1983. The landslide, a reactivation of an estimated 22 x $10^6$ $m^3$ of old landslide debris, blocked Spanish Fork Canyon and thereby created a lake more than 50 m deep. An emergency response to this event by the Denver and Rio Grande Western Railroad and State, local, and federal agencies prevented the dam from failing by overtopping or internal erosion. Subsequently, the lake has been drained through a low-level drainage tunnel, and U.S. Highway 6/89 and tracks of the Denver and Rio Grande Western Railroad were rerouted around the landslide. Direct costs of damage have exceeded $200 million.

The landslide moved more than 150 m on a slope of about $10^o$. Post-disaster investigations revealed that the slide debris, a moderately plastic, gravelly clay, was sliding on a trough-shaped depression in bedrock. Movement has nearly stopped, but elevated pore-water pressures and extremely large lateral earth pressures still exist in the slide debris.

In the aftermath of the disaster, this paper examines the landslide event, the history of movement, geological conditions at the site, and the current situation at the landslide site. The site has apparently been involved in repeated landslide and earth-flow movement through historic and pre-historic time. However, there is good geologic evidence that the 1983 landslide movement was unprecedented in at least the past several hundred years.

Two studies, one each sponsored by the State of Utah and Utah County, have resulted in recommendations that the landslide dam can safely act as a flood-control structure for low-head, short-term storage. Long-term water retention at high reservoir levels could be hazardous. Additional investigations would be required before the landslide dam could be utilized for other purposes. Several alternatives for developing a reservoir in the area are currently being studied by Utah County.

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## INTRODUCTION

### Chronology of landsliding and damming at Thistle

In a 1952 master of science thesis Parley R. Peterson (1952) mentioned the presence of the ancient landslide near the town of Thistle, Utah, (fig. 1) and illustrated it with photographs. Coincidentally, 1952 was a year of record snowpack, but only shallow movements were observed by Peterson in the vicinity of the landslide.

Many employees of the Denver and Rio Grande Western Railroad (D&RGW) have given us verbal reports of frequent shallow movements at the landslide toe affecting trackage over recent decades, but there have been no accounts, either written or verbal, of rapid or large movements of the landslide.

Although there are reports of landslide movement as early as April 10, 1983, reports of movement prior to April 13 are speculative. On April 13, 1983, the railroad was confronted with serious misalignment of its trackage, and U. S. Highway 6/89 on the opposite (far) side of the river was also greatly disturbed. By the evening of April 14, the highway was closed and the last train traversed the slide area at 8:30 p.m. Residents of the railroad town of Thistle, immediately upstream, were evacuated thereafter as impounded waters rose about 4 m/day. All attempts to keep the Spanish Fork River channel open, using six Caterpillar 245 backhoes (fig. 2), failed. Following these attempts, track-mounted heavy equipment was employed on the landslide in an effort to compact the earth in the toe of the landslide. Efforts were concentrated on the lower 250 m of the slide because it became obvious it would act as a dam. Earthmoving activity extended as far as 650 m above the east abutment. This operation, plus construction of the emergency spillway tunnel (fig. 3), prevented failure of the landslide dam by overtopping or internal erosion.

During the first week, a technical team was convened, aerial photographic surveillance started, two survey points established, 1.2-m-diameter survey targets prepared, rock abutment mapping commenced, railroad re-routing surveys begun, pumps and pipe ordered, and plans established to construct an emergency spillway tunnel through the sandstone abutment with an inlet at 1579 m elevation. Construction of the spillway tunnel began on April 26; the railroad tunnel on April 27. The spillway tunnel was completed on May 4 and water commenced flowing on May 18 (fig. 4). In the meantime the U.S. Army Corps of Engineers had installed six 0.6-m PVC pipes over the top of the slide and had begun pumping 5 $m^3$/sec from a barge on May 17. Peak flow through the drainage tunnel occurred at the lake elevation of 1586.3 m on May 31. Trains transited the new railroad tunnel on July 4.

A lower drainage tunnel, 684 m in length, was later constructed to permit draining of the reservoir. Drainage of the lake was completed in December, 1983.

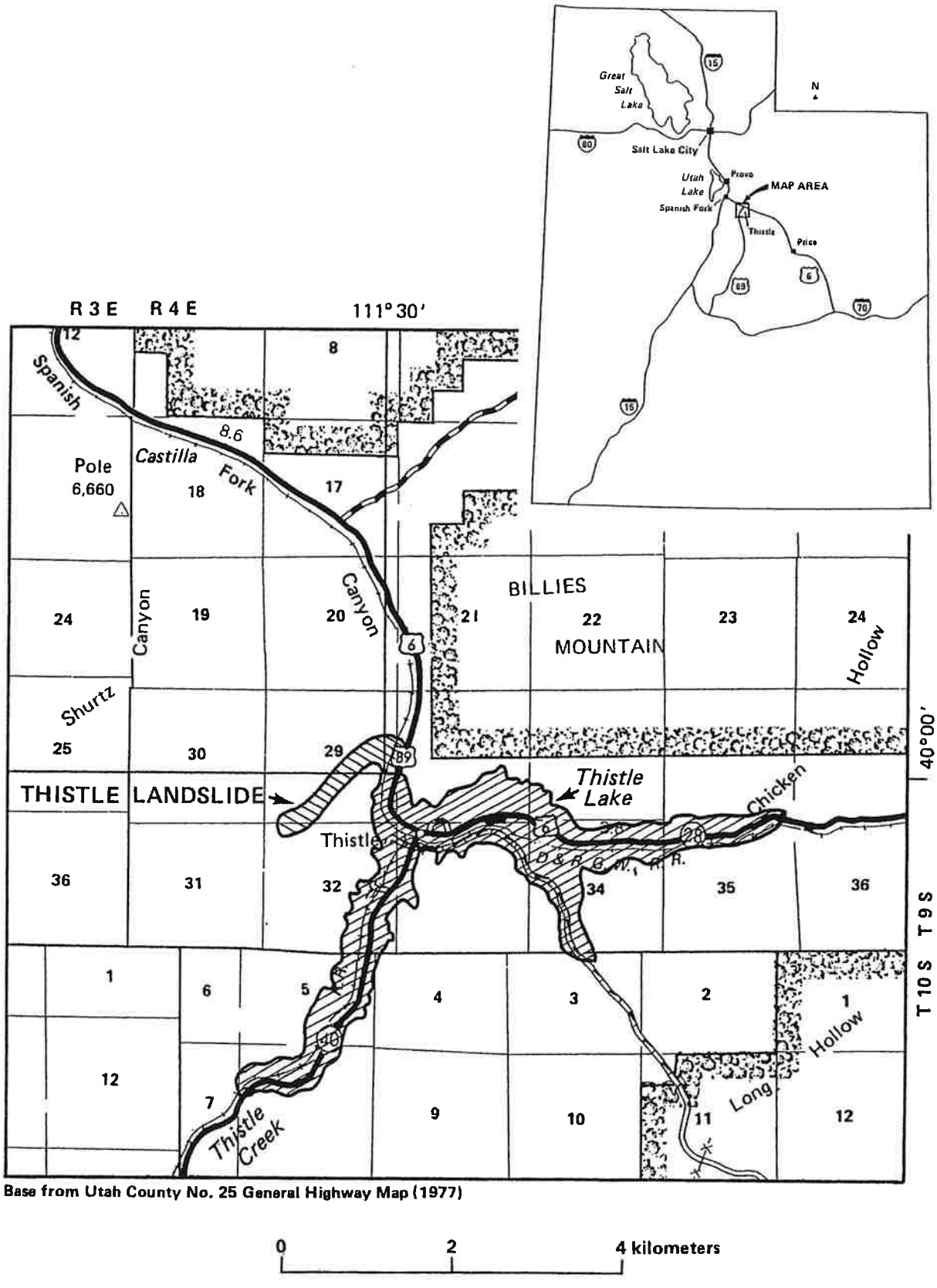
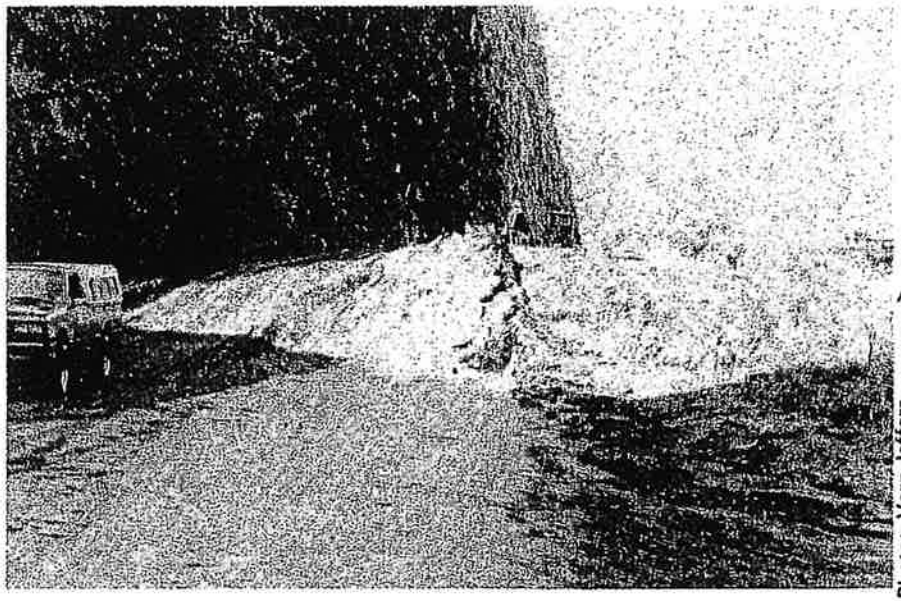



**Figure 1.** Location and vicinity maps of Thistle landslide.



A

Photo: Vern Jeffers

B

Photo: Vern Jeffers

**Figure 2.** Two views looking upstream along U.S. highway 6/89 during the early stages of landslide movement. (A) First pressure ridge and associated thrusting as it appeared on April 13, 1983. East abutment of Nugget Sandstone on left. Notice bulging of highway where it is compressed between advancing landslide debris from the right and the Nugget Sandstone. Thrust faults increased in number and surfaced farther west, up the landslide, with time. The locations of pressure ridges seemed to persist at the same locations as the height of the blockage increased. (B) View taken three days later on April 16, 1983 showing construction equipment attempting to keep the Spanish Fork River from being blocked.

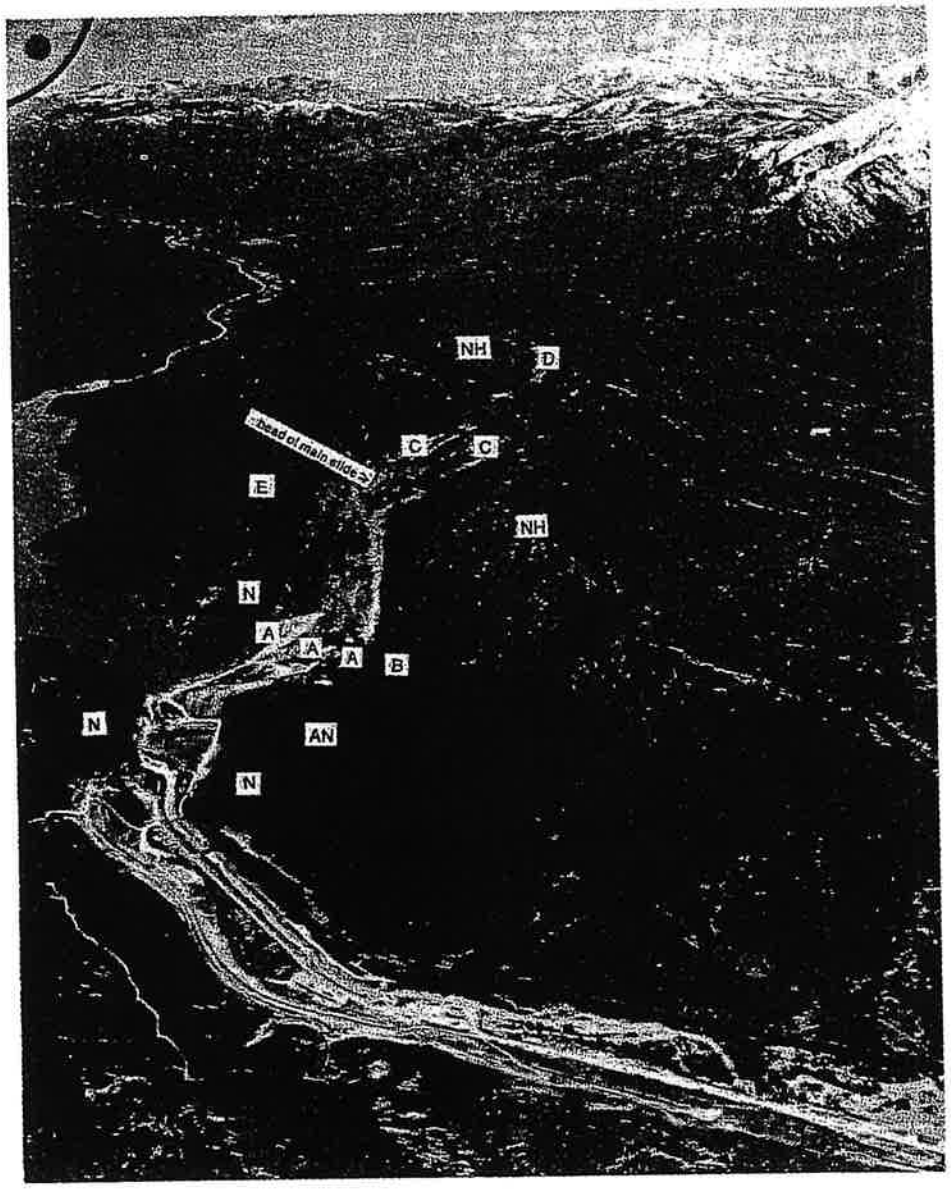



**Figure 3.** Oblique aerial view of the Thistle landslide and vicinity looking southwest (May 28, 1983). Many elements of the emergency response to the landslide hazard are visible on the photograph: note pumping barge, boom barrier, and flotsam in the lake; discharge from the upper level drainage tunnel; start of construction of the lower level drainage tunnel; northern portal of railroad tunnel and new railroad grade under construction; downstream face of blockage flattened and benched. Out of view to the left is construction activity for relocation of the highway. At the time of the photograph, the lake was at about its maximum extent.

The landslide is composed of two parts, the main landslide extending upslope from the blockage for 1783 m on a pre-failure slope angle of about $10^0$. Uphill from the main landslide is an area of peripheral landslides that are locally connected to the main landslide. The peripheral landslides are about 152 m long. Maximum thickness of the landslide is in the floor of the canyon and is about 67 m including about 6 m of added fill on top to prevent overtopping. The width of the landslide varies from about 240 to 580 m and is typically about 300 m wide.

Other features described later in this paper are annotated on the photograph as follows: (A) change in direction of the landslide from following the strike direction to following the dip direction of the underlying Ankareh Formation; (B) broad area of Ankareh-derived sandy silt that was partially incorporated into the landslide during 1983; (C) peripheral landslide area upslope from the main landslide; (D) one of several smaller landslides around the Thistle landslide that was active in 1983. Slide movement was from left to right and spilled as an earth flow over a bedrock ledge toward the Thistle landslide; (E) saddle in ridge of Nugget Sandstone, which contains ancient landslide deposits similar to those in the Thistle landslide; became partly remobilized in 1985; (AN) Ankareh Formation; (NH) North Horn Formation; and (N) Nugget Sandstone.

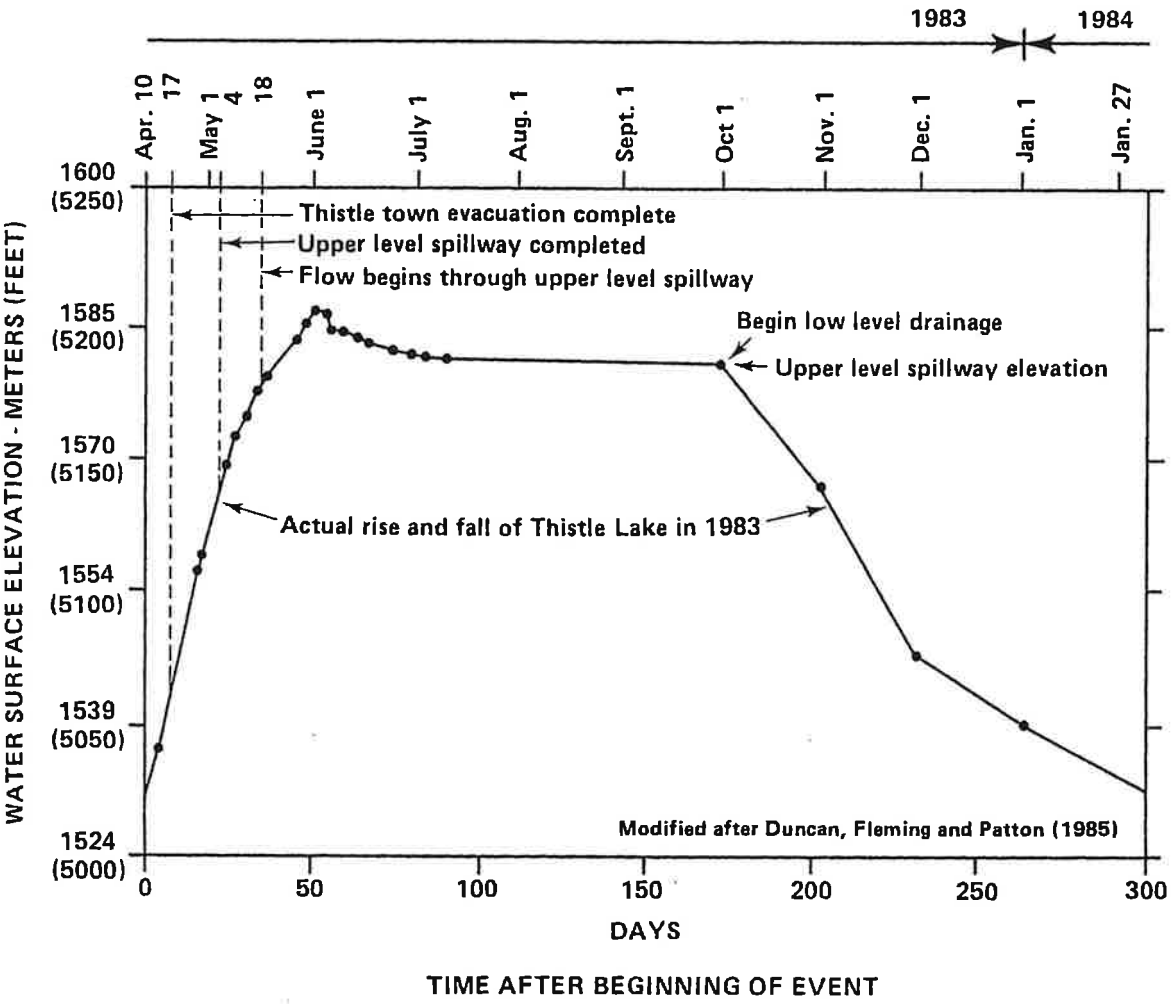



**Figure 4.** Key events in the rise and fall of Thistle Lake.

Engineering and construction were undertaken by the State Division of Water Rights and the D&RGW. The Utah Geological and Mineral Survey (UGMS) provided geological and geotechnical expertise and was assisted in the monitoring effort by the Utah County Engineer's Office. Consulting engineers were engaged and federal dam construction agency personnel were consulted by the State of Utah and the railroad at various stages during the episode of movement.

The blockage of the Spanish Fork River resulted in Utah's first Presidentially-declared disaster. It also marked the beginning of a long sequence of wet-cycle-precipitated emergencies throughout much of Utah.

The Thistle landslide has been the most costly landslide disaster in the history of the United States. Kaliser (1983) estimated the cost of damages in excess of $200 million. A comprehensive economic analysis by the University of Utah Bureau of Economic and Business Research (1984) that attempted to evaluate several of the indirect costs of damage reported that the direct costs of damages were $200 million and that indirect costs were pervasive in a broad sector of the economy of Utah.

Although the emergency situation created by the landslide in the summer and fall of 1983 has passed, costs of damage have continued to accumulate. The blockage that remains in Spanish Fork Canyon at a minimum will require maintenance. In addition, unstable road cuts across Billies Mountain have been a recurrent problem, and abandonment of the railroad spur to central Utah has caused permanent economic disturbance there.

## Location and Setting

The landslide, prior to its 1983 movement, was a complex tongue of earth of subdued topographic relief. This feature occupied a short, steep tributary to the Spanish Fork River 650 m downstream from the confluence of the drainages of Thistle and Soldier Creeks and immediately below the railroad yards in the unincorporated town of Thistle (fig. 1). The Spanish Fork Canyon is rather narrow here, with about 300 m of local relief and 600 m of regional relief. In contrast, the topography surrounding the landslide is steeper and highly dissected.

The landslide is located in Spanish Fork Canyon, a major drainage in northcentral Utah. It is only 11 km southeast of the prominent Wasatch Front, which is a major physiographic and geologic demarcation. The Wasatch Front is the western boundary of the Wasatch Range, a quite prominent expression of the Middle Rocky Mountains. To the west lies Utah Valley with its relatively high concentration of population (including the State's third most populous city, Provo). Thistle town was a railroad community established in the late 1800's with a maximum population of 600 in 1917. In 1983 the population was approximately 50.

The climate at Thistle consists of mild summers and cold winters. About 8 km downstream from the landslide, at the Spanish Fork Powerhouse, the mean annual temperature is 11°C., with the gamut recorded between -28° and 38°C. Average precipitation there is 470 mm, including 1270 mm of snowfall. Another weather station exists about 8 km upstream from Thistle at Birdseye. This station is apparently in the rain shadow of the Wasatch Mountains. Mean annual temperature there (1960-75) is 6°C, with 340 mm of precipitation.

Mean monthly discharges of the Spanish Fork River below the landslide for the 1984 water year were 11.2 $m^3$/sec, with the highest mean daily flow recorded at 68.5 $m^3$/sec in May and the lowest, 3.0 $m^3$/sec, recorded in January. The Probable Maximum Flood (PMF) has recently been calculated to be about 1240 $m^3$/sec.

## Geology

The geology of the Thistle area has been mapped and described by Witkind and Page (1983). Those aspects of the geology most directly relevant to the Thistle landslide are discussed by Duncan, Fleming and Patton (1985). The geology of the area is complex; in the immediate vicinity of the landslide, there are unconformities, folding, major faulting, tilting, and suspected diapirism. On the west the landslide borders a portion of a major thrust plate that has undergone, at one time or another, extensive erosion, diapirism (Witkind and Page, 1983), folding, and faulting.

Three geologic formations are directly associated with the landslide (fig. 5). From oldest to youngest they are the Triassic-age Ankareh Formation, the Triassic-Jurassic-age Nugget Sandstone, and the Cretaceous-Tertiary-age North Horn Formation. An angular unconformity with considerable relief occurs between the North Horn Formation and the Ankareh and Nugget Formations. The former dips northwest at from 10-20°; the older formations dip to the east and southeast at about 40-45°.

The Ankareh Formation is a reddish brown to deep reddish shaly siltstone and sandstone and may be regarded everywhere as a weak unit, especially when contrasted with the Nugget Sandstone. The Nugget Sandstone is a massive, light-colored sandstone that is a strong ridge former along the southeast side of the landslide and at the landslide toe. The North Horn Formation, partly alluvial and partly lacustrine deposits, is also a weak unit consisting of mudstone, claystone, sandstone, conglomerate and limestone.

The landslide itself is ancient, comprised largely of debris and earth flow material (fig. 6) derived mostly from the North Horn Formation, and to a lesser extent from the Ankareh and Nugget Formations. Age of the landslide is likely to be at least early Holocene (8,000 to 11,000 years). The landslide fills an ancestral tributary valley to the Spanish Fork River. Most of the valley is cut in Ankareh Formation.

Evidence for very old landslide movement is contained in a deposit of North Horn-derived material that has spilled over a saddle on the ridge of Nugget Sandstone to the south of the main landslide ("E" on fig. 3). This sliding apparently occurred at a time when the paleovalley of the Thistle landslide contained a greater volume of debris reaching to the elevation of the saddle. In the spring of 1985 this mass also began to fail; movement was in a southeasterly direction.

Figure 5 is a geologic map of the Thistle landslide showing also the approximate locations of bedrock contacts. Locations of typical topographic expressions of the different geologic formations are annotated on figure 3, an oblique aerial photograph. Note in figure 5 that the main part of the landslide is on Ankareh Formation. The landslide follows the strike direction of the Ankareh Formation downslope to the sharp bend ("A" in fig. 3) where it follows the dip direction. In Spanish Fork Canyon the landslide is on Nugget Sandstone.

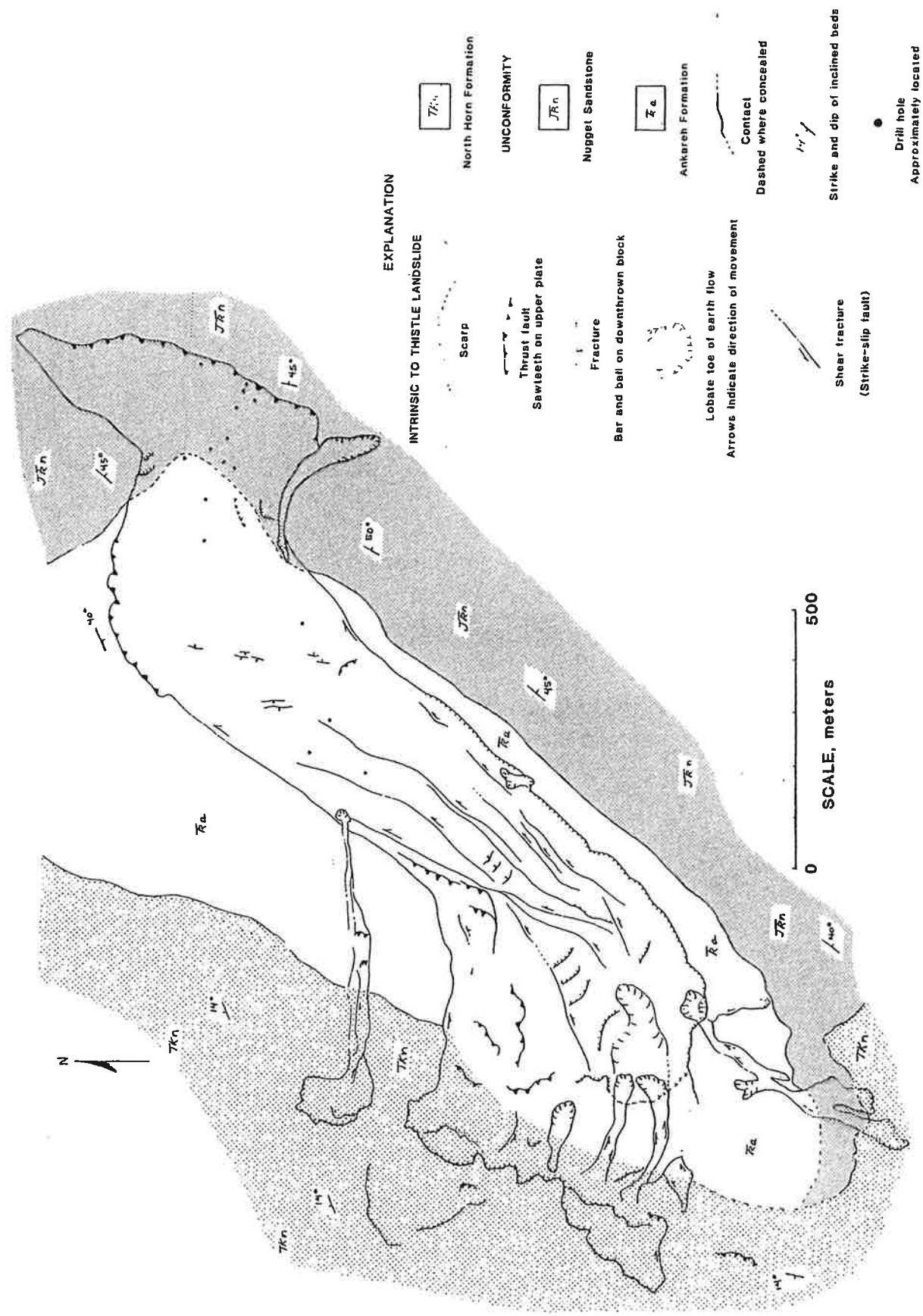



**Figure 5.** Geologic map of the Thistle landslide (modified after Fleming and others, 1985).

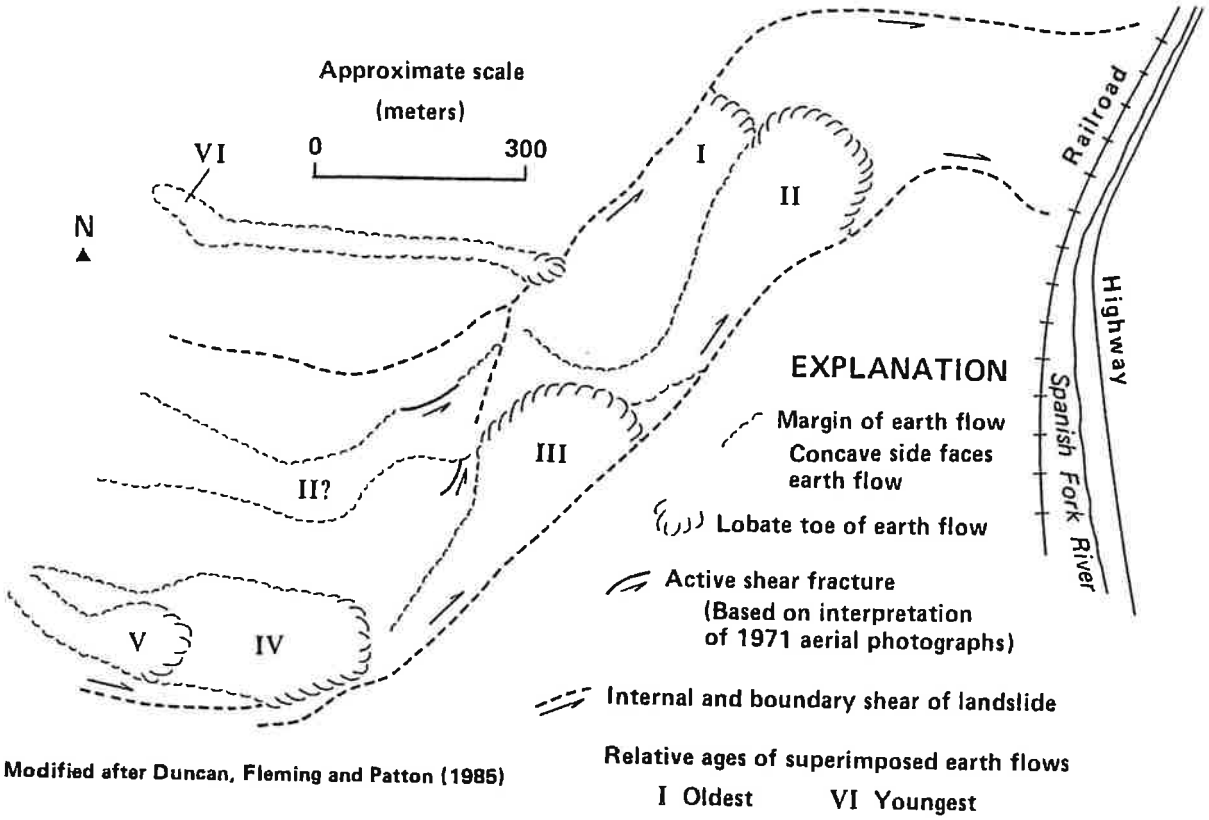



**Figure 6.** Map of pre-1983 Thistle landslide (from aerial photos).

The cross-sectional shape of the landslide is controlled by the dip of the underlying bedrock. It is thinnest on the updip or northwest flank and thickest near the southeast flank; thus, the shape is an asymetrical "U".

## 1983 EMERGENCY PHASE

At the onset of rapid movement of the toe of the landslide on April 13, 1983, the railroad responded quickly with equipment and personnel. Initially, the D&RGW attempted to keep the tracks aligned to permit passage of trains. They were joined by crews from the Department of Transportation that were attempting to keep the highway open. Both worked together to keep the Spanish Fork River flowing through the canyon. When it became apparent that the canyon would be blocked, efforts switched to preventing the blockage from failing. Failure of the blockage would produce catastrophic flooding downstream.

During the crisis period, personnel from all levels of government and the railroad met at least twice a day. Two separate committees were formed, a public safety committee chaired by State Public Safety Commissioner Larry Lunnen and a technical committee chaired by Kaliser. The technical committee provided answers for the public safety committee and made systematic observations of landslide and construction activity. Complementary expertise on earth dams, tunneling and railroad embankment was acquired from on-site personnel made available by the Utah State Engineer, the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation and the D&RGW Railroad. Questions that required immediate attention were raised during each of the two daily meetings and answers were discussed in the field prior to the next meeting. Some of these questions were as follows:

1. To what elevation would the landslide blockage likely rise across the Spanish Fork Canyon?

2. How much time would be required for the dam to rise to that elevation?

3. To what extent has the natural column of valley-fill sediments been disturbed beneath the landslide?

4. How good is the contact between the Nugget Sandstone escarpment and the landslide debris? What can or should be done to improve the abutment contact?

5. What is the probable path of seepage water appearing to issue from railroad ballast material incorporated within the landslide?

6. What problems would likely result from a tunneling operation through the adjacent Nugget Sandstone?

7. What might be done to control the landsliding by measures applied to the head of the landslide?

8. What is the worst scenario that emergency personnel might have to face? What is a more likely scenario?

9. What is the projected rate of rise of reservoir level and how does that compare to the projected height of blockage?

10. Is the peripheral sliding likely to deepen and add to the driving force of the main slide mass?

11. What would be the consequences of a catastrophic failure of this blockage? What flood levels could be expected downstream?

Not infrequently, the same question was raised on multiple occasions for refinement of answers and for consideration of additional alternatives. In response to these questions, members of the technical committee undertook specific investigations to provide information for the emergency response. The following are examples of the types of studies and the nature of information provided to the public safety committee.

An instantaneous dam-breach map was prepared for public safety officials by the UGMS in April 1983. The map was revised by the UGMS, the U.S. Bureau of Reclamation, and the River Forecast unit of the U.S. Weather Bureau, to enable 6- and 12-hour breach maps to be provided to emergency preparedness officials on May 12. The inundation zones for these two breach periods were nearly identical, so that only the water depths remained to be distinguished for each of the two scenarios. The reservoir depth of 57.9 m and a final breach width of 79.3 m were used in the preparation of these inundation maps. Maximum flood-water depths were projected to be 13.1 m at the mouth of Spanish Fork Canyon for the 6-hour breach, and 8 m for the 12-hour breach. Likewise, the figures for Spanish Fork City, southern portion, were 4 m and 2.4 m, respectively.

The authors reconnoitered the landslide vicinity in April 1983 in an attempt to determine the likelihood of additional peripheral earth masses contributing surcharge loads onto the head of the slide. This could only be done using judgment based upon ground and aerial observation.

The Nugget Sandstone, which comprised the east abutment of the dam, was of relatively great concern because in its near-vertical exposure it contained a number of joint sets in addition to seemingly random and irregular fractures and distinct shear zones (fig. 2). Erosion features resulting in large voids could also be easily observed. Photographs taken on April 18 and enlarged to a scale of approximately 1:300 were used to map rock quality of the abutment. Assessments were made with respect to the overall abutment seal and prospects for rapid and stable tunneling.

Over a distance of 378 linear meters of mapping of the near-vertical sandstone face, an average fracture frequency of 3.6 per meter was found. Fracture frequency ranged from 0.7 to 6.9 fractures per meter. Shear zones were open at the surface to widths of up to 1 m. The rock also contained cavities up to 3 m in diameter that were likely the result of wind ablation as they were not encountered subsequently in tunneling operations.

To further examine the prospects for tunneling, an abandoned tunnel, started in the early part of the century and never completed, was inspected just prior to its complete inundation by the rising waters of Thistle lake. The walls of the tunnel were standing essentially without support. This brief observation offered considerable encouragement for the concept of rapid tunneling in the Nugget Sandstone for an emergency spillway and restoration of transportation routes.

The blockage of the Spanish Fork Canyon nearly eliminated flow in the Spanish Fork River. With the dewatering of the channel downstream from the blockage, several thermal springs became evident. Prior to the blockage the closest thermal springs were believed to be those at Castilla, about 4.8 km downstream (fig. 1). Now, a line of warm springs was discovered between the blockage and Diamond Fork, about 1.6 km downstream, and concerns arose over upward seepage pressures beneath the dam and the occurrence of a fault in the canyon floor. Thermal

waters (33°C) were later found in abundance at the northern portal of the lower drainage tunnel. The source for these waters remains unknown, but several lines of evidence suggest that they may be the result of normal, deep ground-water circulation.

### Subsequent Emergency Concern

In the spring of 1984 contractor's representatives believed that earth-flow deposits resting subaqueously in the reservoir just upstream of the blockage were moving. This earth flow was the last significant event on the landslide in 1983. We were concerned that the earth flow along the south flank of the landslide could remobilize and possibly enter the channel and block the drainage tunnel intake. UGMS and the Utah County Engineer's Office embarked upon a careful monitoring program as a result of this observation. No significant additional movements were detected in 1984 or 1985.

## LANDSLIDE MOVEMENT AND HYDROLOGY

### Historical Movement

The presence of an ancient landslide at Thistle had been noted in published maps and reports of the area. In addition to remarks mentioned earlier in the thesis by Peterson (1952), the landslide was noted on a map by Hintze (1962), and sketched and described by Shroder (1971). None of these reports, however, documented any movement of the landslide in historic time.

An exhaustive search of records and interviews for any accounts of past slide movement at the site of the Thistle landslide has turned up recollections of repeated maintenance at the site over a period of several decades but no written accounts and no indications that more than several percent of the entire slide mass was ever involved in movement at one time, over historic time (about 115 years in the canyon).

In 1951 the D&RGW asked the Utah Construction Company (Vern Jeffers, oral communication, 1983) to inspect the landslide and report to them the costs for constructing mitigation measures.

Springtime maintenance of the track across the landslide appeared to have been more commonly required than not, entailing the removal of soil following regrading of local uplifted or displaced zones. A railroad cut about 90 m long, 15 m high, and with a 1:1 slope locally sloughed onto the track nearest the slide.

In January of 1983, a D&RGW official reported seeing cracks of size and depth far in excess of normal on the cut slope immediately west of the tracks. He saw no cracks upslope from the cut slope, however. Inspections ensued on a regular basis thereafter and in early March a set of cracks was reported to have advanced upslope a distance of 30 m. No material was seen on the siding (the inside or western track) at that time, however.

Over historic time, changes have been made in the width of the railroad (figs. 7 and 8) right-of-way, the alignment and width of the road up the canyon, the course of the river, drainage from the slide, grazing of cattle and sheep on the landslide and land use in the immediate vicinity. Fires are not reported to have occurred with any frequency but likely have resulted in years past from sparks from passing steam locomotives.

Photo: F. E. Anderson; from Heritage Prints Collection

**Figure 7.** View upstream (south) toward the town of Thistle, taken in about 1900. The toe of the Thistle landslide is evident as the prominent bulge in the middle right. Cuts were made in the toe of the landslide for both the railroad and the wagon road.

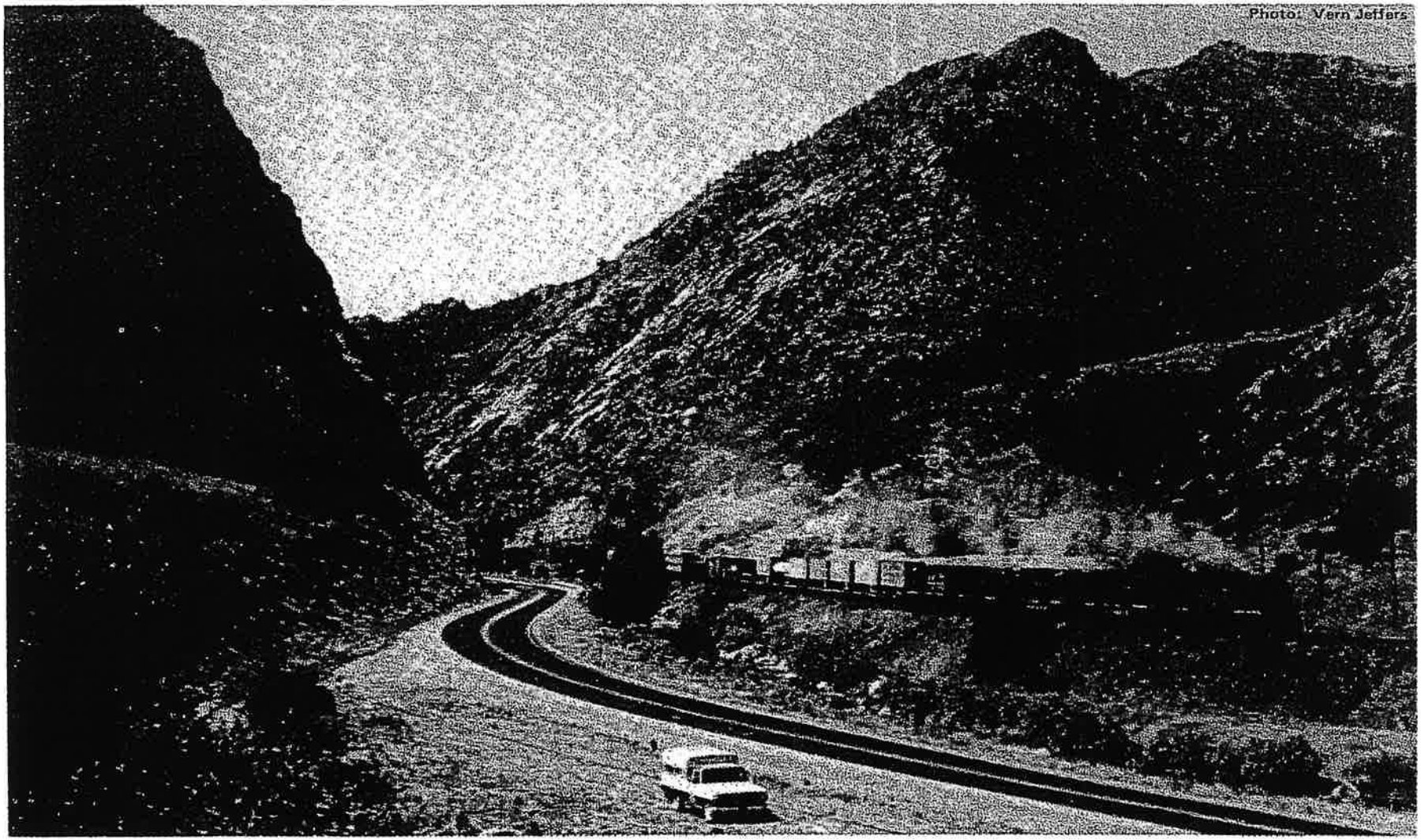



**Figure 8.** View upstream of Spanish Fork Canyon and Thistle slide taken in 1975. The toe of the landslide is in the right center of the photograph extending up the tributary valley to the west. Comparison with figure 7 shows relocation of the road to the east side of the canyon, straightening of the railroad where it crosses the landslide, and channelization of the Spanish Fork River. Note the absence of cracks or scars on the landslide, but debris slide scars are present on slopes above the landslide in the extreme upper right part of the photograph.

## Movement in 1983-84

There is ample evidence that conditions leading to a decrease in overall stability of the Thistle landslide were accumulating through historic time. The existence of an old landslide mass with a demonstrable history of slow movement presented a clear potential hazard. Earth flows and debris flows were being deposited through late Pleistocene and Holocene time in the upper part of the old landslide. Several modificatons were made at the toe of the landslide during the last 100 years that also could have been detrimental to stability. The photographs of the toe of the landslide in about 1900 and in 1975 reveal numerous changes (figs. 7 and 8). However, these negative effects of increased loading in the upper part of the landslide and modification to the lower part of the landslide did not result in immediate large-scale failure. Failure occurred many years after the major man-made and natural reductions in stability.

## Triggering mechanism

The apparent triggering mechanism for the landslide was the record-breaking precipitation in September 1982 followed by well above average precipitation through the period of initiation of rapid movement in April 1983. Three precipitation stations in the general vicinity of Thistle recorded September 1982 rainfall of 172, 205 and 237 mm, which is about 800 percent, 700 percent, and 500 percent of normal for that month, respectively. One of the stations, Spanish Fork Power House, has 77 years of record and its 205 mm September 1982 measurement exceeds its next highest September measurement (1963) by 252 percent. Furthermore, the October through April 1982 precipitation was 172 percent of normal and the October through April 1983 water year was 152 percent of normal. Antecedent moisture conditions, therefore, were clearly unprecedented in the historic weather record.

The abnormal precipitation triggered numerous local slope failures around the periphery of the Thistle landslide and elsewhere in the drainage of the Spanish Fork River. Some of these smaller landslides directly loaded the upper part of the Thistle landslide. In addition, the precipitation probably produced raised piezometric levels within the slide mass to heights that were unprecedented in historic time. Patton (1984) correlated the pattern of historic levels of the Great Salt Lake through time with inferred piezometric levels in the Thistle landslide and concluded that the excessive precipitation was a significant factor in triggering the landslide.

## Landslide movement

Rapid movement of the landslide toe began on April 13, 1983, and the rate of movement increased the next several days. Beginning on April 16, a point was surveyed by a railway survey crew 75 m west of the sandstone abutment. Average rates of lateral movement during the period of April 16 through April 21, 1983, were 0.76, 0.91, 0.76, 0.94, 0.69 and 0.55 m/hr, respectively. The range of rates measured each day for the same period were 0.24 to 1.28, 0.30 to 1.52, 0.30 to 1.22, 0.55 to 1.34, 0.46 to 0.91, and 0.37 to 0.73 m/hr. The spreads in the daily hourly velocities, then, were 1.04, 1.22, 0.92, 0.79, 0.46 and 0.36, so that it appeared that the rate of movement became more uniform within a

short period of time. More than 110 m of displacement occurred during the 6-day period of most rapid movement.

By April 25, the average rate of movement at the same location had diminished to 0.37 m/hr, and to 0.24 m/hr on the 28th of April. The range of measurements on the 28th was reduced to between 0.06 and 0.27 m/hr, or only 0.21 m/hr. By early May, movement rates greatly diminished; more than 150 m of displacement had occurred.

Movement of the slide in 1984 was quite minor and mostly occurred above the bend in the slide (about 300 m upslope from the centerline of the blockage) in late March and early April. Maximum movement recorded was 0.80 m horizontal and 0.06 m of vertical uplift.

### Thrusting

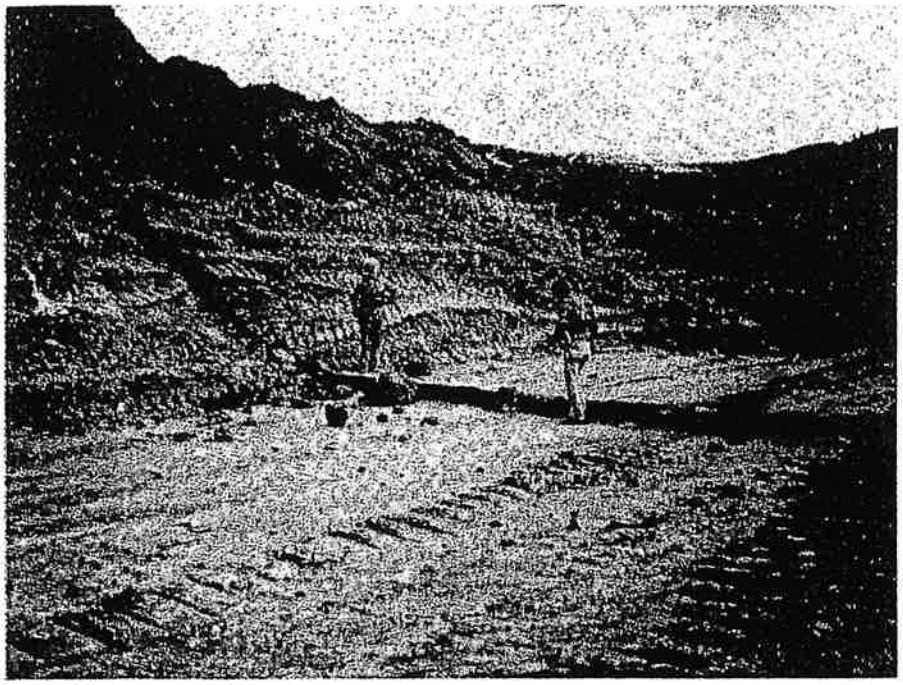
The presence of thrust faults in the blockage provides discontinuities that may be important to long-term stability of the blockage of the river. Thrusting of landslide material was common in the lower portion of the landslide (fig. 9). At any one time multiple thrust sheets were normally visible. The earthmoving operation, however, greatly obscurred this phenomenon. An attempt was made, however, on a relatively quiet earthmoving day, April 27, 1983, to acquire measurements of thrusting. Seventeen thrust faults and pressure ridges were mapped in the lower portion of the landslide. Dips varied from $30^{o}$ to $90^{o}$, with an average dip of $58^{o}$. Dip directions varied from N $70^{o}$ W to N $70^{o}$ E, with the dips averaging in direction N $40^{o}$ W, which coincides with the alignment of the lower slide. Hades were measured at between $0^{o}$ and $30^{o}$ to the south, indicating that the net thrust direction was slightly to the north, that is, the thrusting had a downcanyon component of movement.

There was also an evolutionary element to the formation of thrust faults. The first thrusts were noted in the floor of the canyon along the highway (fig. 2). As the height of the blockage increased, new thrusts formed within the landslide debris. Initially, they formed on the east side near the contact with Nugget Sandstone. Again, as the buttressing effect of the blockage became more pronounced, new thrusts appeared uphill from ones formed earlier. By late May 1983, the uppermost thrust was forming about 250 m uphill from the centerline of the blockage. Thus, there are numerous discontinuities within the blockage that are a direct result of the way the landslide commenced, moved, and finally stopped.

## Hydrology

### Reservoir siltation

Sedimentation in Thistle lake, a 4.8 km long impoundment (fig. 1), is a most interesting phenomenon of its own. The lake existed at an elevation of about 1585 m for approximately 5 months (figs. 1 and 3). Sediments up to 4.9 m thick were locally deposited in the short-lived basin. The deltas at the mouths of both Thistle and Soldier Creeks displayed typical characteristics of their environment of deposition. Recessional shoreline features were clearly in evidence, but by now have largely deteriorated; debris lines remain in evidence, however.



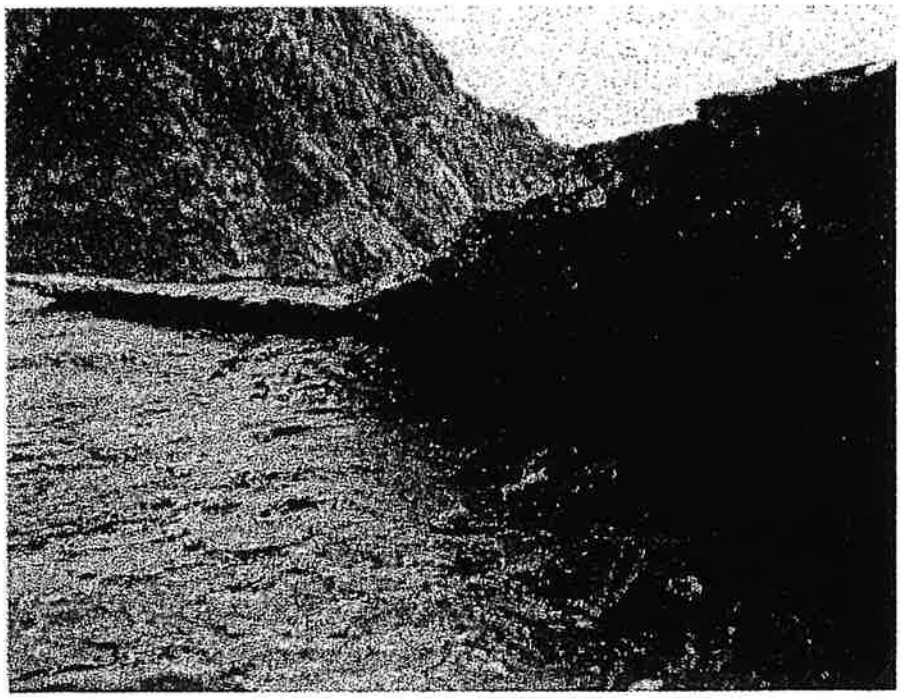




**Figure 9.** Two examples of thrust faults at the surface of the Thistle landslide. The faults emerge at a high angle, inclined upslide. With depth, the inclination of the faults presumably flatten and surfaces become parallel with the principal failure surface of the landslide. The faults are coated with a thin layer of clay, contrasting with the gravelly clay that comprises most of the landslide debris. Fault surfaces are striated and highly polished.

The reservoir drained an area of $1.24 \times 10^9$ $m^2$ with a considerable percentage of erosion-susceptible, weak rock and soil materials. Simons, Li and Associates (1985) have estimated sediment yield from the watershed at 100 $m^3$ per $km^2$. They also estimated the amount of sediment deposited in the impoundment during the 1983 runoff event as about $1.53 \times 10^6$ $m^3$. Also of importance is the fact that clear water released during drainage of the lake was freed of much of its load and therefore carried considerable erosion potential downstream.

### Paleosedimentation

A cursory field examination has been made for sediments deposited as a result of an earlier generation of canyon blockage by the Thistle landslide. The occurrence of ancient Lake Bonneville sediments, deposited about 14,000 years ago in an arm of that body while at its highest stage, can be confused with sediments dumped into an ephemeral impoundment. One new railroad cut east of Thistle and excavations for the U.S. Highway 89 bridge foundations may hold promise in shedding light on an earlier landslide episode, as a datable molluscan fauna has been observed.

### Geohydrology

The distribution of high- and low-permeability materials within the landslide mass and particularly the landslide dam remains unknown. Thus, the potential for internal erosion and piping is unknown.

However, the slide mass did impound water for 300 days; reservoir depth was 46 m or more for about 130 days. Clear-water seepage under and through the blockage amounting to only about 2.2 l/sec. was observed during that time. The water level in the impoundment rose 55 m to peak at elevation 1586.3 m within 50 days of blockage. The lake level then began to fall due to the fact that the lake inflow was less than the flow through the high-level emergency spillway tunnel (fig. 4).

No prolific groundwater discharge points on the landslide were observed at any time during 1983 or later, but numerous small discharges were observed on peripheral landslides. These probably issued from the North Horn Formation in perched bedrock aquifers. Though ponds of water were numerous on the landslide in 1983, we are unable to determine whether they were fed entirely or in part by upward seepage. Surface water from precipitation and the impervious nature of the clayey materials at the surface prevented such determination in the field. What was evident, however, was that seepage discharge points were scarce in 1985, with most emerging from peripheral landslides.

## POST-FAILURE INVESTIGATIONS

The State of Utah, Department of Natural Resources, Division of Water Rights, sponsored an investigation of the landslide and the blockage in Spanish Fork Canyon. The investigation was prompted by receipt of applications for future use of the structure for flood control, hydropower generation, water storage, and recreation. The purposes of the investigation were to evaluate the landslide and landslide dam to determine 1) current stability of the slide, 2)

suitability of the landslide dam to serve as a water retention structure, and 3) potential for further landsliding to block the portal to the low-level drainage tunnel. The Thistle Slide Committee (Duncan, Fleming, and Patton, 1985) concluded that the landslide dam could be utilized as a very low-head flood-control structure for short periods of time, but assurances of safety for longer term, larger volume storage would require a more extensive investigation. The Committee noted further that additional investigations might prove inconclusive, no matter how extensive, or might reveal problems that could not be remedied at any reasonable cost.

For that investigation and another by Utah County, 16 borings were placed at various locations in the lower part of the landslide (fig. 5), laboratory tests were conducted on selected samples from the borings, base maps were prepared of pre- and post-landslide topography, and the landslide was mapped geologically.

The geologic map (fig. 5) of the landslide (Fleming and others, 1985) revealed that the landslide is composite, containing several elements that behaved differently. The main landslide extends upslope from Spanish Fork Canyon for almost 1.8 km. Along its head and upper northwest flank, it is connected in two places to a large area of shallow, peripheral landsliding originating in the North Horn Formation (figs. 3 and 5). The principal area of peripheral landsliding is at least 150 m long; numerous other small landslides, also active in 1983, are scattered throughout the drainage basin of the main landslide and are not connected to either the main or peripheral landslides.

We have used the cross sections in the Thistle Slide Committee's Report (Duncan, Fleming, and Patton, 1985) to estimate the volume of the landslide. The main landslide consists of about $22 \times 10^6$ $m^3$. Average thickness of the entire landslide is about 40 m. The volume contained in the peripheral landslides shown on figs. 3 and 5 is about $2 \times 10^6$ $m^3$. The volume of the landslide dam itself taking the width (cross-valley dimension) equal to 200 m, is about $5 \times 10^6$ $m^3$.

Movement of the main landslide was accommodated by formation of large shear fractures within the landslide that trended downslope more or less parallel to the flanks of the landslide. The sense of shear on most fractures was left lateral, indicating a larger amount of displacement in the thicker, southeast side of the landslide.

Movement along the northwest flank of the landslide was constrained by the sharp bend ("A" in fig. 3) about 300 m upslope from the canyon floor. At the bend, the landslide was thrust over and incorporated more than 100 m of previously unfailed soil material ("B" in fig. 3).

Laboratory tests were performed on samples from nine test borings, including water content, dry density, grain size, Atterberg limits, and residual friction angles. Most samples are gravelly clays of moderate plasticity with average liquid limits of 40 and average plasticity indices of 18 (Duncan, Fleming, and Patton, 1985). Average in-situ water content was 18 percent.

Measured values of residual friction angle ranged from 7 to 10° for samples with liquid limits of more than 50, to values as high as 28° for samples with liquid limits of 33. It may be assumed that material within any of the numerous slide planes contained within the debris mass has been strained to its residual shearing resistance (Duncan, Fleming, and Patton, 1985).

In four borings drilled for Utah County by Rollins, Brown, and Gunnell, inflow permeability tests were conducted at 3 m intervals (Duncan, Fleming, and Patton, 1985). About 70 percent of the tests indicated low permeability with values ranging from zero loss of water to less than $10^{-4}$ cm/sec. The other 30 percent produced values of permeability of $10^{-4}$ to $10^{-2}$ cm/sec. In one boring there was a complete loss of water in the casing. Thus, the landslide mass appears relatively impermeable except for scattered zones of high permeability. Voids and fissures are likely to exist that can transmit substantial quantities of water under relatively low gradients.

Drilling was very difficult in all the borings and particularly on the west side of the landslide dam where the multiple thrust faults occurred during landslide movement. Apparently, lateral-earth pressures and pore-water pressures remain very large.

A topographic map of the landslide area was prepared from aerial photographs of 1971 (Duncan, Fleming, and Patton, 1985). That map was superimposed on the post-landslide topographic map and differences in elevation were contoured. The resulting map is figure 10, a map of elevation changes caused by landslide movement.

The increase in thickness of the landslide debris in the canyon floor was in excess of 50 m. A positive elevation increase occurs for a distance of 600 m upslope from the Nugget Sandstone abutment. For the next 1.2 km there is evacuation of landslide debris from a bedrock trough with more than 27 m of material depleted at the shaded areas in fig. 10.

The pre-landslide aerial photography of 1971 was also used to prepare a surficial geologic map (fig. 6) at the same scale as the post-landslide map. Most prominent of the features on the 1971 photography are earth flow deposits, the oldest of these being about 430 m upslope from the Spanish Fork River. Their lobate toes were vegetated with mature trees. The oldest flow, Stage I, had been partially over-ridden by a younger flow shown as Stage II on fig. 6. Farther upslope 550 m, Stage III had partially over-ridden Stage II. Stage IV over-rode the source area for Stage III, yet farther upslope. Stages V and VI were the youngest mapped and could possibly have been active in 1971. The pattern that emerges, then, is one where the older flows exposed farthest downslope are partially or completely buried by younger flows originating in the North Horn Formation in the uppermost part of the landslide complex.

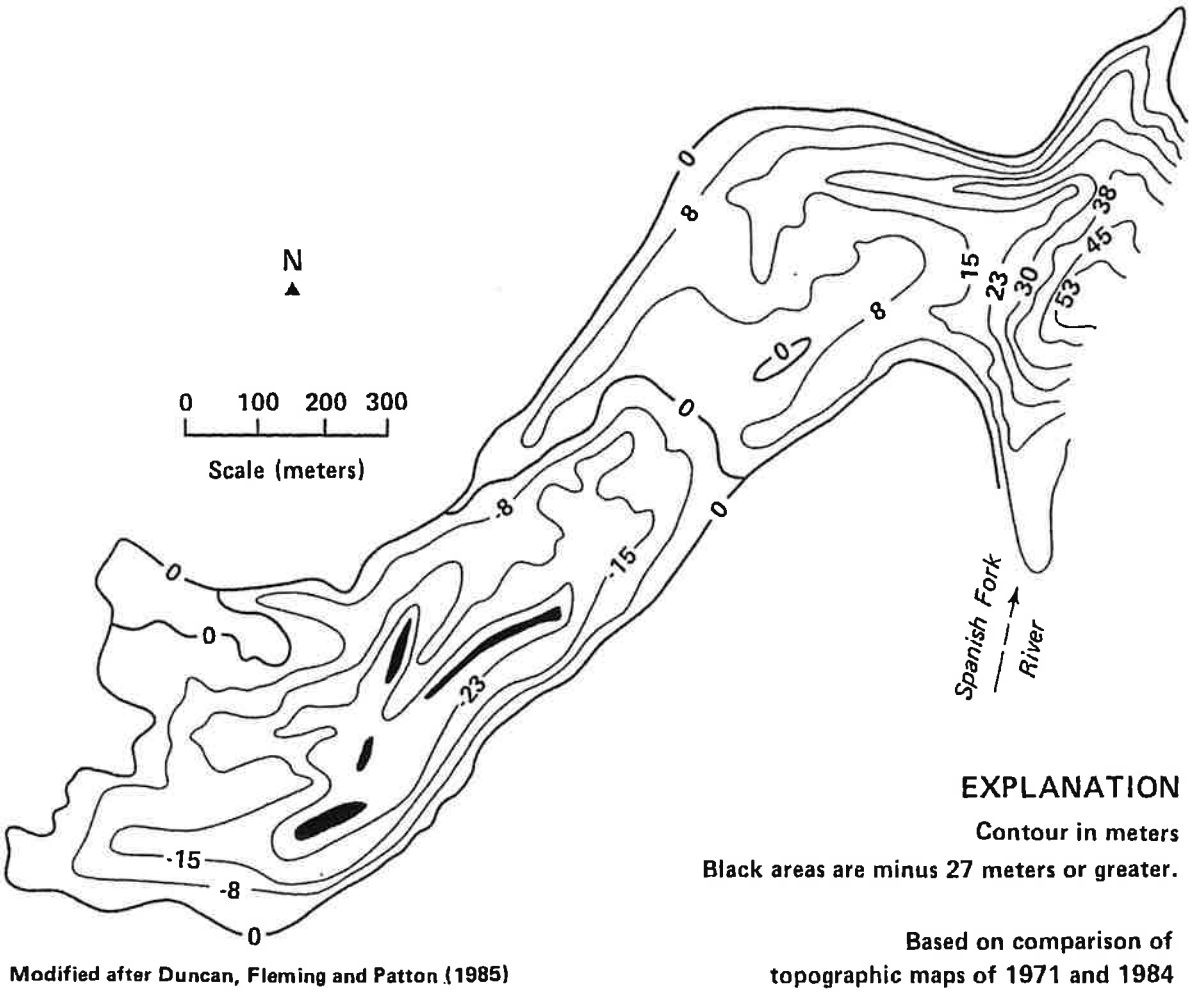



**Figure 10.** Map of elevation changes caused by landslide movement (includes peripheral landslides upslope from main one).

This evidence combined with the historical data suggests to us that movement prior to 1983 was slow and gradual. Had there been abrupt activity, as in 1983, there most assuredly would have resulted destruction of the old but well defined earth-flow lobes only 430 m upslope from the river. Preservation of at least four major episodes of earth-flow deposits probably extends the time of possible pre-1983 rapid and large displacements to very much before the age of the oldest trees on the landslide.

Essentially all of the earth-flow features were destroyed in 1983 and an extra 100 m of previously unfailed alluvial and colluvial material on the northwest flank of the landslide was incorporated in the movement. Nearly all the debris in the head region of the main landslide (in excess of 27 m) was evacuated. The radical adjustments of debris, combined with displacement rates exceeding 2 m/hr and total displacements of more than 150 m, were apparently unprecedented in the recent history of the Thistle landslide.

## SITUATION IN 1986

Geotechnical problems recognized today that make the existing landslide dam unacceptable as a permanent water-retention structure include: (1) uncertainty as to future movement of all or part of the landslide, (2) uncertainty as to composition and physical properties of the entire embankment mass and the presence of discontinuities within the mass (fig. 11), (3) the irregularity of the east sandstone abutment, including the presence of voids, (4) high piezometer levels with an erratic distribution, (5) water migration beneath the embankment, and (6) anticipated response from an hypothesized earthquake event.

### Alternatives Currently Being Addressed

In the fall of 1985, a screening process was undertaken by James M. Montgomery Engineers (1985) for the county to evaluate seven alternatives for dealing with the Thistle situation. These alternatives are briefly discussed below, with costs provided for four of them.

1. Do practically nothing; improvement of the low level tunnel intake structure only. Cost: $0.28 million

2. Take measures to improve public safety only, to comply with State of Utah dam-safety criteria. These measures include new intake structures, new bar racks, new emergency spillway and by-pass tunnel to accommodate one half of the Probable Maximum Flood (PMF). Cost: $18 million

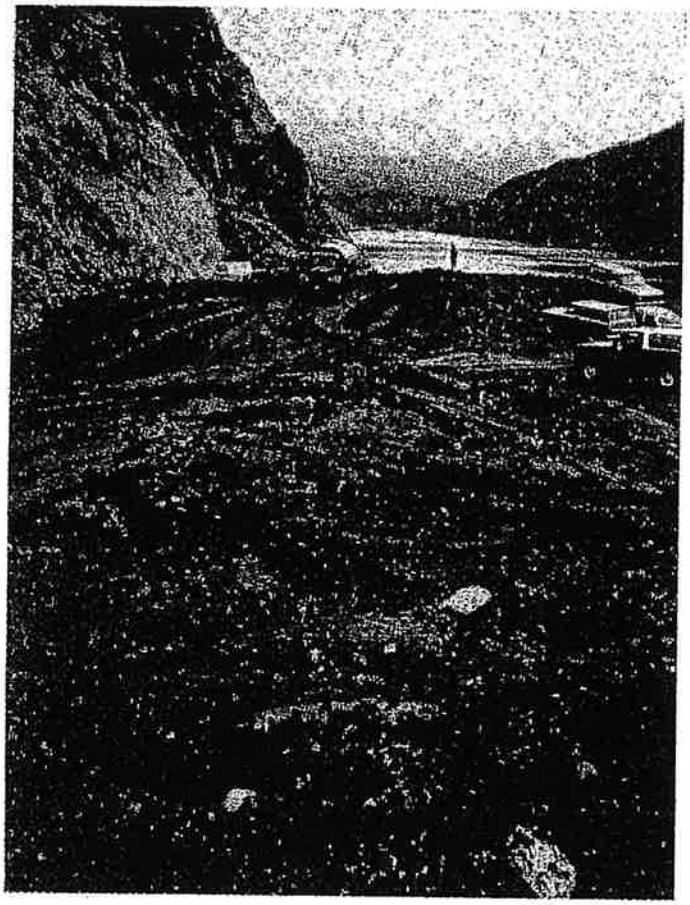
3. Reinforce the present landslide dam into a safe structure for use as a flood-control detention facility. The reservoir pool area would be cleaned of debris, upstream face improvements would be made, and a new regulatory valve added. Cost: $22.9 million

4. Construct an entirely new earthfill dam immediately upstream, completely separate from the slide mass. This new structure would serve multipurpose functions of flood control, water supply, hydropower generation, and recreation as well as providing a solution to the public safety issue with a new emergency spillway and bypass tunnel providing full PMF hydraulic capacity. Included in this proposal is extension of the existing low level drainage tunnel upstream to a new side slope intake structure, construction of a powerhouse with 1.2 MW's of installed capacity and construction of recreation facilities. Cost: $47.4 million.

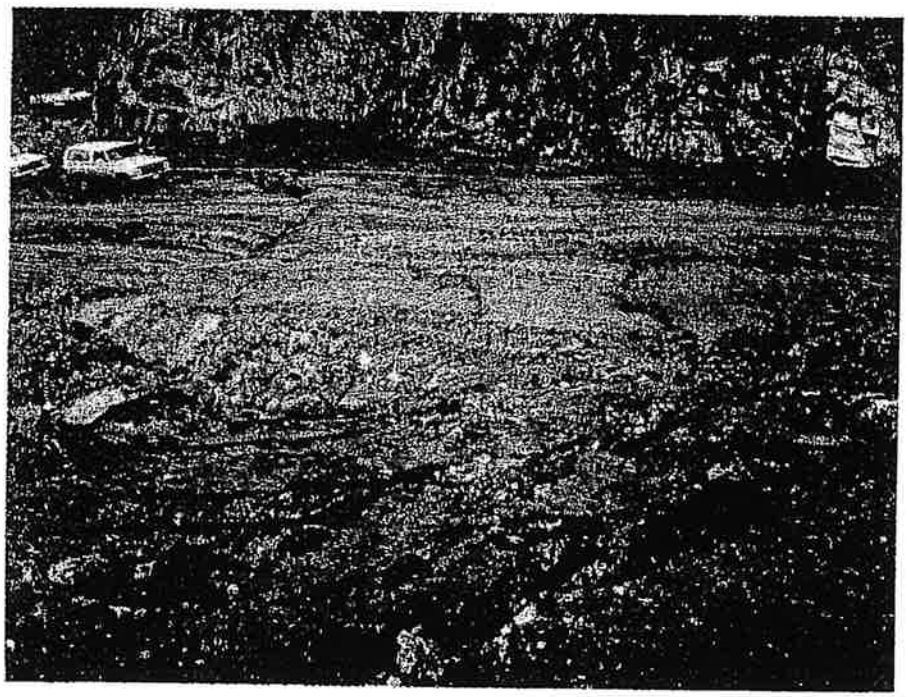
5. Complete studies on the existing landslide dam, undertake remedial measures and make it into a full service multipurpose dam.

6. Remove the landslide dam in its entirety and allow the Spanish Fork River to flow down its former channel.

7. Make use of the present landslide dam as an integral part of either a new upstream or downstream earthen structure.



A. Pressure ridge near east abutment, crest of landslide dam.



B. Longitudinal cracks extending to east abutment.

**Figure 11.** Deformation features on the Thistle landslide, April 24, 1983.

Alternative number one would store a PMF which, with snowmelt, has been determined to be $3 \times 10^8$ $m^3$, with a peak flow of 1,240 $m^3$/sec. With present facilities the PMC would cause the river flow to overtop the landslide dam as it currently exists by approximately 2.1 m for more than 72 hours, which would likely result in a breach.

Montgomery Engineers (1985) has estimated that loss of life plus damage to public and private property in excess of $90 million would result from a breach of the landslide dam. For the present there is no alternative but that the landslide dam and appurtenant drainage tunnels must continue to serve. Hopefully, a long-term solution for the problem may be achieved in the near future.

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