DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Report of the Thistle Slide Committee
to State of Utah
Department of Natural Resources
Division of Water Rights

by

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BRIEF DESCRIPTION OF SLIDE AND ITS CURRENT CONDITION

Beginning on April 10, 1983, and continuing through May of that year, a massive landslide occurred on the west side of the Spanish Fork Canyon. The landslide is located about 3,000 ft north of the site of the town of Thistle, in Utah County, Utah. The landslide mass is about 6,000 ft long. There is 1,000 ft elevation difference from the canyon floor to the head. The landslide moved from west to east on a slope of about 10°. At the east wall of the canyon, the slide thrust against a steep bluff of sandstone resulting in a 200-ft-high blockage of Spanish Fork Canyon. The blockage caused disastrous flooding upstream in the Soldier Creek and Thistle Creek valleys (see fig. 1). A high-level emergency spillway was excavated to prevent the reservoir waters from overtopping the slide mass. Later, a low-level diversion tunnel was constructed to drain the reservoir created by the landslide blockage. This low-level tunnel currently carries the river flows. The flooding caused by the landslide necessitated relocation of a highway and a railroad that had passed through the canyon, and caused direct costs estimated to exceed $200 million (Kaliser, 1983).

The landslide still blocks the canyon. Above the blockage, more slide debris fills the trough-shaped tributary valley on the west side of the canyon. Currently the slide appears to have stabilized, although some small movements are still taking place. Measurements of surface displacements indicate 0.1 ft to 0.3 ft of downslope movement from March, 1984, through August, 1985. Piezometric measurements suggest the presence of high pore pressures within much of the landslide, with piezometric levels above the ground surface at many locations.

The blockage within Spanish Fork Canyon supports the slide debris in the tributary valley above it. For this reason, the lower portion of the slide is subjected to a large lateral thrust. This thrust has produced a squeezing action that results in high lateral pressures acting within the lower portions of the slide. Drilling was extremely difficult, particularly in the west side of the blockage. Drill holes tended to be squeezed shut by the high earth pressures, and the drill casings became stuck.

The shape of the landslide was modified somewhat by earth-moving activities. Landslide debris was moved onto the blockage to raise the crest elevation and to provide a buttress on the downstream face. The risk of overtopping was reduced, and drainage improved stability. Some 16 borings were drilled to explore the slide, and numerous samples were obtained for observation and testing. Although these have provided considerable information on conditions within the slide mass, some important questions remain unanswered. These questions include: the location of the alluvium that occupied the valley bottom before the slide, the location and continuity of the railroad ballast and highway base course, and the conditions along the east abutment contact between the cliff of Nugget Sandstone and the slide. These questions have an important bearing on seepage through the slide under conditions of high reservoir, and on the potential for internal erosion and piping of the blockage.

Figure 1 -- Oblique photograph of the 1983-Thistle landslide.
(Numbers are locations of recent boreholes)

PURPOSE OF THE COMMITTEE'S STUDIES

The main purpose of the Committee's studies was to determine whether, from a geotechnical point of view, it would be feasible to use the landslide mass blocking Spanish Fork Canyon as a dam for flood control, irrigation storage, recreation, or power generation. The Committee was also charged with recommending an investigative program to develop the information needed to address these questions.

COMMITTEE'S ACTIVITIES

The Committee met three times in Utah during the course of their studies. They examined information provided by the Division of Water Rights, examined and mapped the landslide, planned an exploration and field measurement program, examined cores obtained from the test borings, planned and evaluated laboratory test and field measurements, and prepared this report. The results of our initial review and proposed exploration program were summarized in a report dated April 9, 1984. In addition, Committee member Fleming spent approximately one week mapping the slide area. He prepared a topographic map of the slide and the surrounding area showing conditions after the 1983 slide. A preslide geologic map was also prepared.

SUMMARY OF MAIN POINTS

The mass of earth that moved during the 1983 Thistle landslide consisted of landslide and earthflow deposits that had been accumulating in the tributary valley to the west above Spanish Fork Canyon for a considerable time, perhaps thousands of years. The landslide may have been moving at very slow rates prior to the rapid movements that occurred in 1983.

Most of the materials in the landslide were silty, sandy, or gravelly clays derived from the North Horn Formation. These materials had medium plasticity, with an average liquid limit of 40 and an average plasticity index of 18. Silty and clayey sands were encountered at some locations within the slide. The landslide enveloped: the ballast of the railroad, portions of the alluvium that filled the lower part of the canyon before the slide, and the base course of the highway. The deepest portions of the alluvium probably remain in place beneath the slide mass in the canyon.

The triggering mechanisms for the 1983 landslide are believed to have been the near record precipitation in the fall of 1982 and the substantial snowmelt in the spring of 1983. Once in motion, the landslide continued to move until a buttress was formed by the accumulated slide debris in Spanish Fork Canyon, and until the debris from the tributary valley to the west above the canyon was nearly depleted. The landslide is squeezed between the sandstone cliff on the east side of the canyon and the portion tending to move down from the west. Thus, the mass in Spanish Fork Canyon contains high horizontal earth pressures that contribute to difficult drilling conditions. The high pressures would seriously affect construction activities within the mass.

Small movements of the landslide are still occurring, although major movements have stopped at the present. There appear to be high pore pressures within the mass. These may or may not dissipate with time. Any such dissipation would be accompanied by additional settlement and horizontal movement. Renewed sliding does not appear to be imminent, although it could be triggered by extremely heavy precipitation or snowmelt, or by renewed surcharging at the top by landsliding at higher elevations than those involved in the 1983 event. Surficial slides and erosion in the mass blocking Spanish Fork Canyon are continuing possibilities.

The landslide debris within Spanish Fork Canyon functioned as a dam for a considerable period in 1983 until the lake was drained. Based on this experience, the Committee believes that it would be safe to use this blockage as a flood control dam without permanent reservoir, if water levels were held below elevation 5,055 (the low point on U.S. Highway 89) and retention lasted no more than three months. The Committee believes that impoundment to higher elevations or for longer periods would be unsafe. Inspection and care of the outlet facilities will be required, whether the blockage is used for flood control purposes or allowed to remain in its present condition.

To incorporate this blockage into a dam for irrigation, recreation, or hydropower uses that would require storage at elevations above 5,055 or for periods longer than three months would require extensive further exploration of the landslide. The Committee believes that further exploration could prove inconclusive no matter how extensive the program, or it could reveal deficiencies that could not be remedied at any reasonable cost. It is likely that a more reliable, multiple-use reservoir could be developed at lower cost by constructing a dam upstream from the blockage rather than incorporating the blockage into a dam.

GEOLOGY

BEDROCK GEOLOGY

The broad geologic setting for the Thistle landslide is depicted on a map prepared by Witkind and Page (1983). The Thistle landslide is along the east flank of a major thrust plate that has undergone, at one time or another, extensive erosion, diapirism, folding, and faulting. The complex sedimentary and structural history of the area probably played a major role in producing some enigmatic features that are associated with the landslide. For example, several warm springs are along the floor of Spanish Fork Canyon, as well as in the floor of the diversion tunnel, and along the northwest flank of the Thistle landslide (Genevieve Atwood, Utah Geol. and Min. Survey, oral commun., 1984). These springs may reflect concealed faults or may be the result of normal, deep groundwater circulation.

This report concentrates on the geology of the slide and adjacent areas. Readers interested in the regional geology should refer to the map by Witkind and Page (1983).

Three geologic formations underlie or crop out adjacent to the landslide; in ascending order, these are, the Ankareh Formation, the Nugget (also known as the Navajo) Sandstone, and the North Horn Formation. The distribution of the three formations is shown on the geologic map (plate 2, Appendix C). A columnar section and general description of each formation is given in plate 7 in Appendix C.

ANKAREH FORMATION

The oldest formation, the Ankareh Formation of Triassic age, is a reddish-brown to deep-reddish, almost maroon, shaly siltstone and sandstone. A weak unit, it commonly forms strike valleys, one of which underlies the Thistle landslide. The Ankareh is exposed in contact with the overlying Nugget Sandstone on the low hill that forms the north boundary of the landslide. There, the Ankareh beds strike about N. 30° E. and dips 40° SE toward the floor of Spanish Fork Canyon. The Ankareh was penetrated in all the borings requested by the Committee that reached bedrock, except for DH-1, which did not extend deep enough to reach it (see geologic map, plate 2, and cross section A-A', plate 3, in Appendix C). In the upper part of the landslide, above the 5,300-ft contour line, the landslide trends generally parallel to the strike of the Ankareh Formation. At the 5,300-ft contour, the landslide changes direction abruptly from northeast to southeast, and in this sector parallels the direction of dip of the Ankareh. This conspicuous change in direction is referred to as "the bend" in the remainder of this report.

NUGGET SANDSTONE

The Nugget Sandstone, of Jurassic and Triassic age, conformably overlies the Ankareh Formation. The Nugget is a tan to reddish-brown sandstone that not only forms the prominent ridge that delineates the southeast flank of the landslide but also underlies the landslide in Spanish Fork Canyon. Bore holes DH-1, DH-2, DH-4, and DH-5 all encountered Nugget Sandstone below landslide debris. Some core samples of the Nugget were fractured, with smooth, rounded gravel in the fractures. The gravel represents an alluvial fill formed on the floor of the Spanish Fork Canyon, which was cut in the Nugget Sandstone. All movement of the Thistle landslide apparently was above this bedrock unit (see discussion in Appendix E).

The Nugget Sandstone is present in the source areas for most of the rockfalls and debris flows that are exposed in the scarp along the southeast flank of the landslide. These deposits have contributed a small amount of debris to the Thistle landslide.

The attitude of the Nugget conforms to that of the underlying Ankareh Formation; both formations strike northeast and dip 30° to 40° SE.

NORTH HORN FORMATION

The North Horn Formation, of Cretaceous and Paleocene age, unconformably overlies these two older formations. The North Horn dips northwest at 10° to 30° (see geologic map, plate 2). The surface of this unconformity is marked by considerable relief; thus, it is difficult to determine the subsurface position of the contact between the North Horn and the underlying formations. The contact between the Ankareh and the North Horn is based largely on a color difference between the colluvium overlying the North Horn, which tends to be various light-colored shades of orange, tan, greenish brown, and gray, and the colluvium on the Ankareh, which tends to be deep red to reddish brown (I. J. Witkind, U.S. Geol. Survey, oral commun., 1985).

The lithology of the North Horn Formation is extremely variable. Uncemented mudstone and claystone containing weak clay minerals make up the bulk of the formation; as a result, the formation is extremely unstable. Interlayered in this mudstone-claystone sequence are discontinuous seams and beds of well-cemented sandstone, conglomerate, and light-gray limestone. These fresh-water limestone beds are similar to the limestones that make up the overlying Flagstaff Limestone. The debris that forms the Thistle landslide has nearly all been derived from landslides and earthflows originating in and on the North Horn Formation (Appendix E).

One prominent limestone bed in the North Horn Formation, exposed along the ridge southeast of the landslide, (coordinates N604000 and E1995200; see plate 2), is visible from most places on the landslide and is strikingly like the Flagstaff Limestone. This North Horn limestone bed can be traced about 200 ft northwest from about coordinate N604000 and E1995200 (just off the mapped area on plate 2), where it is sharply offset. The attitudes of both the in-place and displaced limestone beds are similar, but the displaced bed is at least 50 ft below its projected in-place position. Another small patch of the displaced limestone bed crops out at coordinates N605200 and E1995300.

Another prominent light-gray, ledge-forming bed in the North Horn Formation that may be correlative with the limestone bed so well exposed southeast of the slide, crops out northwest of the slide. This bed differs lithologically, consisting primarily of calcareous sandstone with a few, interlayed, apparently discontinuous, seams of limestone up to about 1 ft thick. This calcareous sandstone bed can be traced northeastward more than 2,500 ft from N609400 and E1997400 to a small earthflow at about N606800 and E1996300. Beyond that point, the bed is absent, possibly displaced by deep-seated landslide movement, salt collapse, or tectonic processes.

These two prominent light-gray beds, presumably correlative, and exposed above and on both flanks of the landslide, appear to provide limits on the extent of any past, deep-seated landsliding in the crown and head areas of the Thistle landslide. We found no evidence that these older, deep-seated landslides, should they be present, were active during 1983 or later. In 1983, all slide movement in this extreme upslope part of the old landslide complex was shallow. The shallow landslides outside the map area were not connected to the main Thistle landslide. The presence of older, deep-seated landsliding well above the Thistle landslide would be a matter of concern if confirming evidence were obtained (see Landslide Geometry, p. 17).

THISTLE LANDSLIDE BEFORE 1983

An old ancestral landslide existed at the site of the 1983 Thistle landslide prior to 1983. A brief description and map of this older slide was published by Shroder (1971), who cited several other published references to the old landslide. D. J. Varnes noted the presence of the landslide in a reconnaissance of landslides in the area in 1947 (U.S. Geological Survey, oral commun., 1983).

In order to understand the pre-1983 history of the Thistle landslide, it is instructive to make a distinction between earthflow and landslide. A landslide moves predominantly by sliding on one or more thin, relatively continuous surfaces of slip. An earthflow, by contrast, moves as a slow, downslope movement of poorly consolidated materials that commonly overrides the pre-existing topography. The materials in an earthflow move by a combination of sliding along a base and flowing by distributed shear. The movement in 1983 was predominantly by sliding, whereas the form of the deposits suggests that earlier movements were both by sliding and flowing. Apparently, much of the material in the old landslide represents successive earthflows derived from that part of the North Horn Formation exposed near the head of the landslide. The landslide debris, thus, is a stacked sequence of earthflow deposits that has partly filled a pre-existing valley that was cut in the Ankareh Formation.

Geologic maps were prepared of both the old landslide and the reactivated Thistle landslide of 1983. The map of the old landslide, shown as figure 2 and plate 7, Appendix C, was based on photointerpretation of the 1971 aerial photographs. The old landslide was clearly visible on the photographs, and it is interesting to compare plate 2 with 8. The southeast flank of the old landslide corresponds very closely to the boundary formed along the younger reactivated slide.

When the northwest flanks of the old and young landslides are compared, a more complex pattern appears. In 1971, a well-expressed shear zone extended from near the railroad tracks upslope almost to the prominent light-gray limestone bed in the North Horn Formation. During the rapid movement of 1983, the landslide followed that zone only for short segments. More impressively, the 1983 movement enlarged the width of the landslide below the 5,600-ft contour line by causing previously unbroken materials along the northwest flank to fail. The landslide increased in width during 1983 by 100 to 450 ft.

Only two shear fractures were visible on the 1971 aerial photographs that seemed to be active. One, at coordinates N605700 and E1997500 (plate 8), appears to be the same fracture and has the same orientation as one of the very active shear fractures apparent during rapid movement of the landslide in 1983. The other shear fracture, at N606000 and E1997300 (plate 8), coincides with the boundary of an earthflow and may not indicate deep-seated sliding.

Earthflows are the most prominent features on the 1971 aerial photographs. Only those that were clearly defined on the aerial photographs were mapped. However, a detailed examination of the photos probably would find more.

As younger earthflows tend to override older ones, it is possible to assign them relative ages. The oldest well-defined earthflows were about 1,200 ft upslope from Spanish Fork River, and their lobate toes were marked by mature trees. The oldest flow, shown as I on figure 2 and plate 8, was partially overridden by flow II. About 1,600 ft upslope from the terminus of flow II, flow III had partially overridden flow II. Still farther upslope, flow IV had overridden the source area for flow III. Flows V and VI are the youngest flows mapped and may have been active in 1971. Thus, the pattern that emerges is of older flows, exposed farthest downslope, being partly or completely buried by younger flows originating in that part of the North Horn Formation exposed at the uppermost part of the earthflow complex.

Some evidence suggests that, coincident with these discrete, localized movements of the earthflows, the entire earthflow complex adjusted to the newly imposed loading by sliding. According to unpublished reports, downslope movement of the landslide's toe required realignment of the Denver & Rio

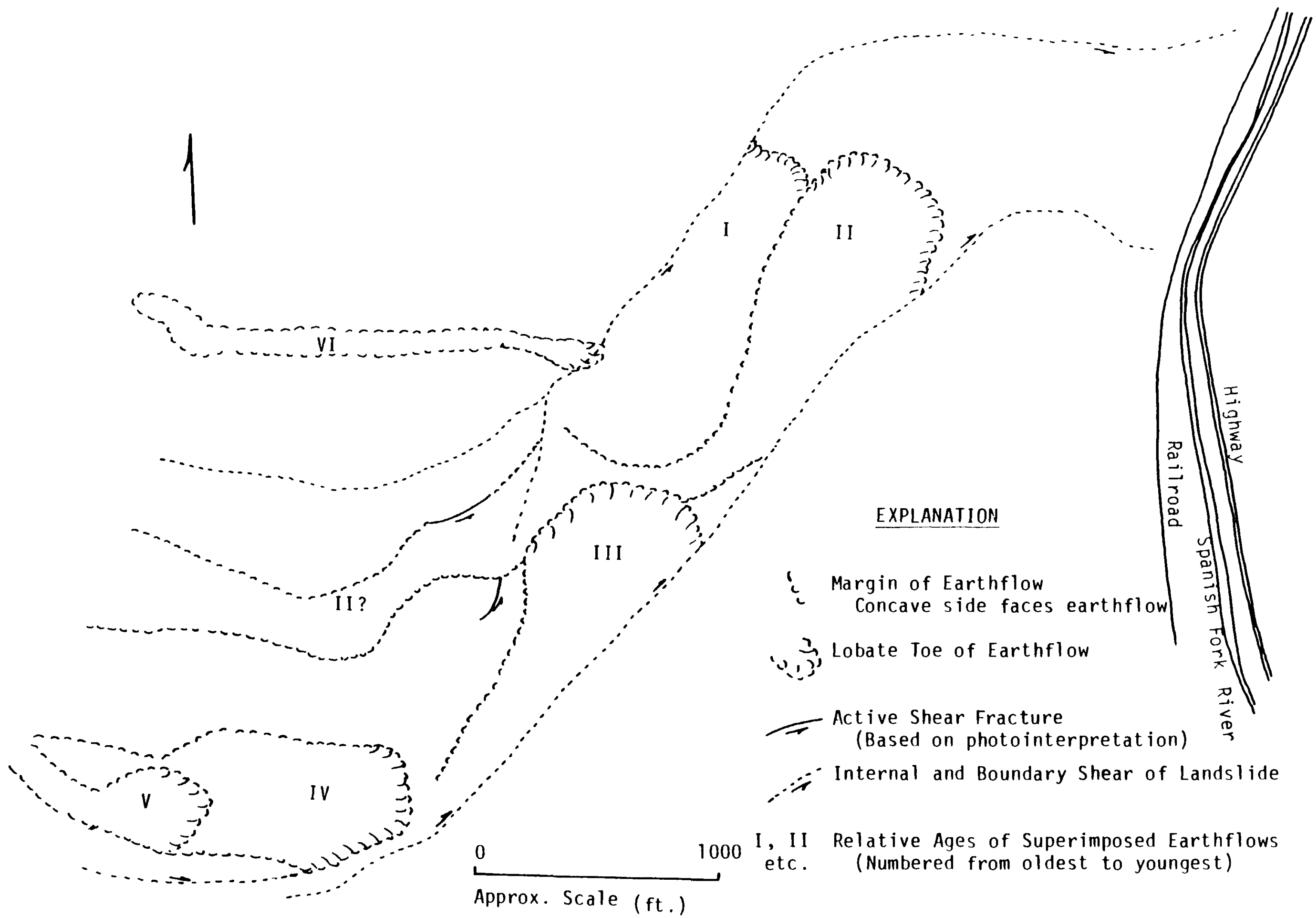


Figure 2 -- Map of the Pre-1983 outline of the Thistle landslide

Grande Western (D&RGW) railroad tracks several times during the past 50 years. Old photographs of the site reveal sedimentation and flooding problems in the switching yards at Thistle that might have been caused by gradual uplift of Spanish Fork River by slow, landslide movement (see photographs and page 15 in Sumsion (1983)). The Committee believes, however, that sliding has been slow and gradual during the past hundreds to perhaps thousands of years. If abrupt movement comparable to the 1983 landslide had occurred, such large displacements would certainly have destroyed the old, but well-defined earthflow lobes that were only 1,200 ft upslope from Spanish Fork River. Furthermore, the destruction of the mature trees on the oldest earthflow lobes are evidence that rapid and large displacement of the landslide had not occurred within the lifetime of the trees. Preservation of at least four major episodes of earthflow deposits probably extends the time of possible rapid and large displacements to well before the lifetimes of the oldest trees on the landslide.

The scale and rate of landslide movement in 1983 appears to have been unprecedented in the history of the landslide as recorded by the deposits present. In addition to destroying all the earthflow features on the landslide, the landslide incorporated an additional 450 ft of previously unfailed material on the northwest flank near coordinates N608300 and E199200 (plate 8). The landslide depleted nearly all its source material in the head region, at coordinates N604800 and E1996800 (plate 2), and added about 200 ft of debris in the floor of Spanish Fork Canyon.

In summary, it appears that the debris in the Thistle landslide accumulated as a result of recurrent earthflows, with younger flows partly overriding older ones. This earthflow complex was probably sliding intermittently as an entity prior to 1983, but any displacements would have been small and the rate of movement slow. The movement of the landslide in 1983 contrasted sharply with the movements before 1983. In 1983, movement rates of more than 6 ft/hr, displacements of several hundred feet, and incorporation of previously unfailed material were unprecedented in the history of the Thistle landslide over the past several hundred years.

DESCRIPTION OF THE 1983 THISTLE LANDSLIDE

In this section, the 1983 landslide event is described and inferences are made regarding the kinematics of sliding, the geometry of the failure surface, and the current condition of the landslide.

CHRONOLOGY OF LANDSLIDE EVENTS

The exact day in April, 1983, when the Thistle landslide began to move is uncertain. Dates and times reported here are mostly taken from Sumsion (1983) who prepared a popularized account of the landslide. Most sources list the date as April 10, 1983. Sumsion showed a photograph (1983, p. 10) taken on April 2, 1983, of an active slump on the surface of the railroad cut at the toe of the landslide. Whether there was any connection between this relatively small slump and the later movement of the large Thistle landslide is unknown. The first report that the tracks of the Denver & Rio Grande Western Railroad were out of alignment was at 7:30 a.m. on April 13. About 12 hours later, heave was noted along the road surface of U.S. Highway 6 and 89, which was about 200 ft east of the railroad tracks and across the Spanish Fork

River. Despite continuing minor displacement of the tracks, the railroad attempted to keep the route open. The last train used the tracks on the evening of April 14. The advancing toe of the landslide prohibited further use after that time.

Considerable effort was made to keep the canyon open and Spanish Fork River from being blocked. By April 17, it was clear that the landslide would block the canyon and dam the river, and the residents of Thistle were evacuated.

An effort was then made to keep the blockage from being overtopped by the rapidly rising, newly formed lake. The effort was successful due to the help of earthmoving equipment and excavation of the high-level spillway tunnel by contractors working in behalf of the Denver & Rio Grande Western Railroad, and by pumps mobilized by the U.S. Army Corps of Engineers. The resulting lake, known locally as Thistle Lake, was ultimately drained by a low-level tunnel, and the blockage remains across the floor of Spanish Fork Canyon.

The earthmoving equipment transported a large volume of debris from the lower part of the landslide to the downstream toe of the blockage in the floor of Spanish Fork Canyon. The blockage was also growing as a result of slide displacement such that the precise amounts and locations of material emplaced by construction equipment are difficult to establish. Some of the debris was compacted and a drainage blanket was placed along part of the downstream face of the blockage. This earthmoving activity undoubtedly improved the stability of the blockage, particularly on the downstream face. Unfortunately, the emergency situation did not permit the level of engineering design and field control on construction that is required for modern earthfill dams.

We have been unable to establish unequivocally the part of the landslide that began to move first. However, it appears that movement began somewhere in the upper part. Photographs taken on April 15, 1983, by Mr. Paul Sjoblom, Division of Oil, Gas, and Mining, State of Utah, and on file with the Department of Emergency Services, show extensive cracking in the snowpack throughout the upper portion of the landslide and extending downslope to the lobes of old earthflows (fig. 2 and plate 8). Aerial photographs of the lower part of the landslide were taken on April 15 by Intermountain Aerial Surveys. In part, the snowpack upslope from the lobes was broken by polygonal cracks, but a series of well-developed longitudinal fractures also developed within the boundaries of the landslide. These fractures trended downslope, and, during the subsequent weeks, would accommodate much of the internal displacement within the landslide. The shear fracture on the northwest flank of the landslide appeared to coincide with the boundary identifiable on the pre-1983 aerial photographs. On the southeast flank, however, the most active shear fracture was inside the boundary of the pre-1983 landslide. However, the location of this fracture was not well expressed on pre-1983 aerial photographs. In the upper reaches of the southeast flank, the active scarp appeared to be 20 ft or more in height.

In contrast to the upper part of the landslide on April 15, there were only a few cracks in the landslide toe. With the assistance of several backhoes, the river continued to flow in its channel although water was backed up to the switching yards of the railroad, about 1,000 ft upstream. At this stage, the landslide appears to have undergone more displacement in its upper part than in its lower part.

The landslide is sharply constricted below the downslope limits of the earthflow lobes in the vicinity of the bend. Before reactivation, the landslide was about 1,000 ft wide at the earthflow lobes and about 700 ft wide farther downslope, below the bend. Below the bend, the landslide passed between two bedrock-supported hills. Within this constricted area, the landslide was deformed into a series of low amplitude folds oriented at right angles to the direction of movement. The folds had amplitudes of a few feet and wave lengths of 100 to 200 ft. Long, relatively straight tension cracks parallel the folds.

By the time of the next aerial photography on April 17, the landslide had blocked the canyon. Most of the movement on the lower southeast flank was still within the boundary of the older well-established shear zone on the flank, but elsewhere new features had developed that were later to become major structural elements within the landslide.

Surveyed rates of movement for two points in the lower part of the landslide were provided by the Denver & Rio Grande Western Railroad, and Utah County. We were unable to establish the locations of the surveyed points except that both apparently were in the lower part of the landslide. Data furnished by the railroad begin on April 14, when the landslide was moving about 0.75 ft/hr. The rate of movement increased to a maximum of 2.5 to 2.8 ft/hr during the period April 17 to 19. The rate declined to 0.80 ft/hr by April 25, which is the last day of the available record. During the 12-day period of record, the lower part of the landslide moved about 500 ft. The data from Utah County are for the period from April 18 through April 22. Displacement rates were computed for one hour intervals ten times during the period. Rates were of slope displacement and are slightly larger (about 3 percent) than the horizontal displacement. Rates varied from 6.6 ft/hr on April 19 to 1.5 ft/hr on April 22, and the overall average displacement rate during the period was 5 ft/hr. Total displacement of this point during the 5-day period was 465 ft.

By the first of May, the large slide movements of the previous two weeks had nearly ended. In part, the reduction of movements was due to the buttressing effect of the landslide debris piled up in Spanish Fork Canyon. Large areas marked by small thrust faults were visible on the downstream side of the blockage in Spanish Fork Canyon on aerial photography of April 19. At the same time, a broad zone of tension cracks developed along the upstream side of the blockage where the uncompacted debris was sloughing into the lake.

The areas containing thrust faults apparently migrated upslope as the elevation of the blockage increased. Thrusting apparently began in the canyon floor at the onset of rapid movement. Later, the thrust planes were visible well above the canyon floor on the downstream side of the blockage. By April 26, thrust planes were noted on the crest of the blockage by Committee member Patton. The thrusting propagated upslope as the buttressing effect of the blockage became more pronounced. Perhaps the last major thrust, photographed in late May, 1983 (fig. 3), was in the area of the bend.

(A)

(B)

Figure 3 -- Photographs of thrust plane intersecting surface of Thistle landslide. Large thrust formed in landslide debris in the area of the bend. (A) View looking toward the northwest flank. (B) View toward southeast showing detail on the thrust surface (Photograph taken in late May, 1983 by I. J. Witkind, USGS).

Another factor in the marked reduction in rate of displacement by early May was the loss of driving force at the upper part of the landslide. Displacements in excess of 500 ft resulted in a major redistribution of the landslide debris. For this study a map was prepared of the elevation changes of the ground surface that resulted from landslide movement. This map was made by subtracting the contours from the post-slide topography from the pre-slide topography. Figure 4 is the resulting contour map of the elevation changes. It shows an increase in the thickness of the landslide debris in the floor of the canyon in excess of 175 ft. There is an elevation increase for more than 2,000 ft up the slope from Spanish Fork River to a neutral line (zero contour). For about 4,000 ft above the neutral line, the landslide was depleted by the slide movements. More than 90 ft of material is missing in the areas shaded on figure 4.

SURFICIAL FEATURES

The Thistle landslide is part of a much larger landslide complex. Previously failed materials cover much of the surface of the watershed containing the landslide. These failed materials in the upper part of the watershed, however, are mostly colluvium derived from the North Horn Formation and, for the most part, are thin.

Upslope from the main part of the active landslide are numerous small landslides and earthflows that are not part of the Thistle landslide. Most are beyond the limits of the mapped area, but several were traced in the field. In all cases, the full perimeter of the small landslide or earthflow on the slope could be traced.

Overall, the surface of the landslide contrasts sharply with the adjacent, unfailed slopes. The blockage in Spanish Fork Canyon is more than 175 ft high, the result of both landslide movement and construction activity (see fig. 1). Extending upslope from the excavated surfaces, the ground is visibly disturbed with only a few trees standing upright. Hummocks and furrows of bare ground alternate irregularly with areas of strongly tilted trees and shrubs.

Prior to 1983 the surface averaged about 10° for the main part of the landslide. If subordinate small landslides that are connected to the main landslide are included, the average slope angle is about 11°. Currently, post-failure, the slope angle of the main part of the landslide is 7.7° (fig. 5 and plate 2). The length of the main landslide is about 5,700 ft. If one includes the small landslides, the total length is about 6,500 ft. The width gradually increases from about 850 ft at the head of the landslide to about 1,200 ft near the bend where the landslide turns to the southeast. Below the bend, where the landslide is constricted between two hills, the slide narrows abruptly to slightly less than 1,000 ft. By contrast, before the 1983 movement, the landslide was only about 700 ft wide at the constriction between the two bedrock-supported hills.

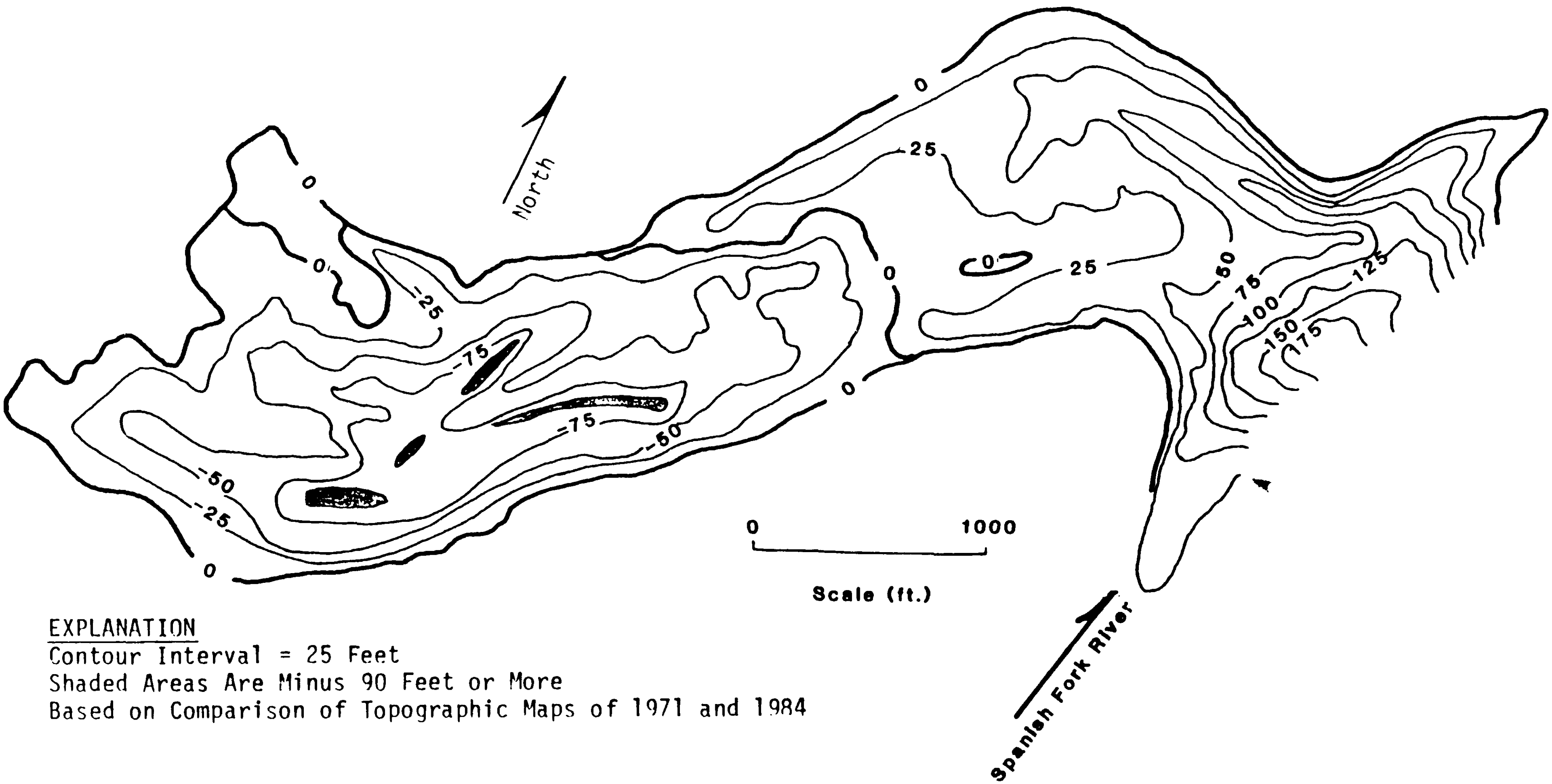


Figure 4 -- Map of elevation changes caused by landslide movement

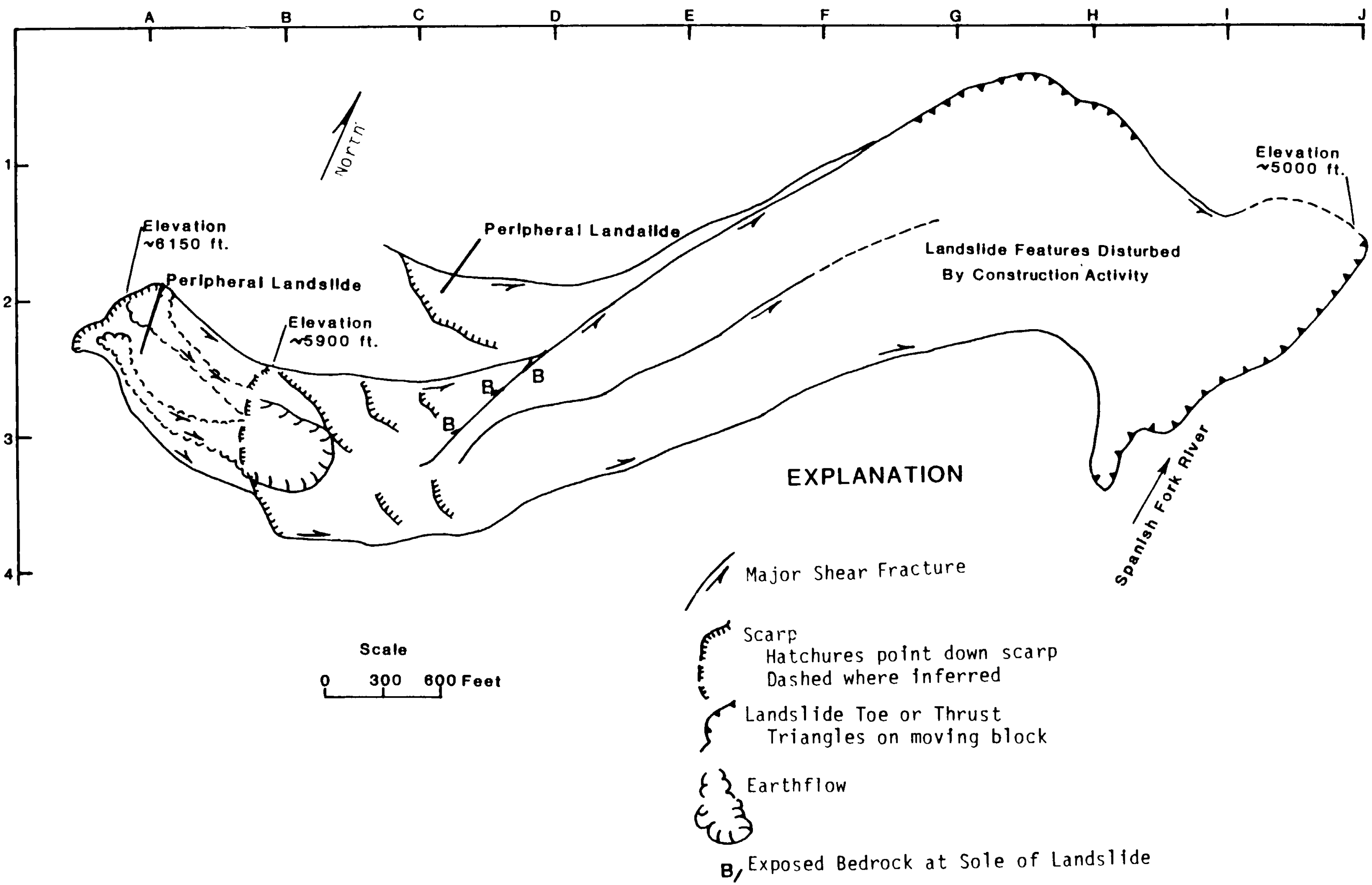


Figure 5 -- Simplified geologic map of the Thistle landslide

Rapid movement produced a myriad of structures within the landslide boundaries. The structures can be used to infer how the landslide moved and the shape of the failure surface. Some of the cracks and other structures evolved and changed as the landslide moved downslope.

Other structures were formed as the landslide began to move and persisted for the duration of that movement. Among these were longitudinal shear fractures that formed early and are still clearly visible on 1985 aerial photographs. The most prominent of these shear fractures is shown on figure 5 trending down the middle of the landslide. Several other comparable shear fractures, mapped on the larger scale geologic map (plate 2), trend almost parallel to the strike of the underlying Ankareh Formation.

Two small areas, shown at A-2 to A-3, and C-2 (fig. 5), marked by landslides and earthflows, are coupled with the main landslide. Several of these slides have partly obscured the headscarp of the main landslide, particularly in the area depleted of debris by landslide movement.

The shear fracture along the southeast flank is relatively smooth and straight and corresponds closely to the position of the flank identifiable on pre-1983 aerial photography. In contrast, the other fracture has a compound structure. It extends downslope from the earthflow complex at A-2 (fig. 5) as a clean, sharp boundary. At D-2, the shear fracture on the upper part of the flank meets a major shear fracture that curves out across the middle of the landslide to join the northwest flank. Displacement along the two major shear fractures was complicated by movement of the second peripheral landslide attached to the main landslide. Movement of the peripheral landslide at C-2 to D-2 produced a complex array of cracks within the body of the main landslide. The main shear fracture, farther downslope on the northwest flank, is a sharp break extending to the bend (G-1 to H-1). Here, the landslide overrode and incorporated previously unfailed material. Both the sharp bend and the previously described constriction farther downslope severely confined the lower part of the landslide. A photograph of the northwest flank near I-1, at the upper part of the constriction (Sumsion, 1983, p. 27), shows open cracks that formed in the adjacent, unfailed bedrock as a result of landslide movement.

Movement along the southeast flank of the slide was less constrained by the sharp bend. Displacement occurred relatively unimpeded along several subparallel internal shear fractures. A few poorly defined scarps formed in the upslope terminations of those shear fractures in the central part of the landslide (plate 2, coordinates N605200 and E1997400).

Along the northwest flank, near the head scarp at B-3 to C-3 (fig. 5), landslide debris was confined between the curving shear fracture in the center of the landslide, and the northwest flank of the landslide. There, the landslide moved as large slump blocks with both uphill- and downhill-facing scarps; some blocks were rotated slightly upslope. Displacements in this part of the landslide were apparently smaller than the rest of the main landslide.

FAILURE SURFACE

The sole or failure surface of the landslide is exposed at three locations in the upper part of the landslide. Observations here tended to confirm that the attitude of the underlying Ankareh Formation has controlled the movement of the landslide, and that the upper part of the landslide is depleted of material. The locations are shown as "B" on figure 5. At these locations, thin landslide debris rests on undisturbed Ankareh Formation, and the contact zone is slickensided and striated, and associated with soft, plastic clay layers. Locally, the failure zone appears as a clayey gouge about 1/4 to 2 in. thick. The slickensided surface plunged about 15° toward Spanish Fork Canyon.

LANDSLIDE GEOMETRY

The geometry of the failure surface in the upper part of the landslide is apparently controlled by the attitude of the underlying Ankareh Formation. Throughout the upper part, the landslide trends about parallel to the strike of the Ankareh. As the Ankareh dips toward the southeast flank of the landslide we suspect that the cross-sectional shape of the upper part of the slide is asymmetric, with thinner debris on the northwest flank increasing in thickness toward the southeast flank. The axis of the thickest debris is probably near the southeast flank more or less parallel to the flank, and passing through bore hole DH-8 (see plate 5 and Appendix E). Our interpretation is supported by the depths to the failure surface in bore holes DH-6, DH-7, and DH-8. Furthermore, the failure surface is exposed (fig. 5) near the northwest flank, in an area where one would expect the landslide to be thinner.

Near the bend the direction of landslide movement changes from following the strike of the Ankareh to following the dip direction. Subsurface information suggests that the failure surface in the canyon floor dips about 2° to the east. The relief on the failure surface, as shown on the cross sections (Appendix C), could reflect the positions of buried stream channels under both the Thistle landslide and alluvium of the Spanish Fork River.

There has been discussion that the failure surface beneath Spanish Fork Canyon may be concave upward and perhaps deeper than the depth of drilling. This interpretation is based on the observation that U.S. Highway 6 and 89, adjacent to the bluff of Nugget Sandstone, was rising vertically as much as 3 ft/hr. In our opinion, this vertical movement of the highway could be a consequence of the landslide pushing debris, almost horizontally, toward the highway at a rate of 3-6 ft/hr. A photograph taken on or about April 19, 1983, of the upstream face of the toe of the landslide (Sumsion, 1983, p. 29), shows broken railroad tracks inclined only slightly upward toward the Nugget bluff as if the tracks were pushed rather than lifted. The boring logs do not appear to support a deep failure surface.

GEOLOGIC EVIDENCE OF CURRENT STABILITY OF THE THISTLE LANDSLIDE

Although the Thistle landslide has stopped moving as an entity, some movement and readjustment of the debris appear to be occurring internally. A few active cracks within the main part of the landslide appear to reflect deeper movement. One group of cracks extends across the landslide from D-2 and E-2 to E-3 (fig. 5). These cracks appear to have been caused by continuing displacement of the peripheral landslide at C-2 to D-2 (fig. 5). Both peripheral landslides shown on figure 5 were actively moving during 1985. In addition, many of the smaller slumps and earthflows upslope from, but not part of, the main landslide continue to move several feet per year. Much of this debris will ultimately reach the Thistle landslide and replenish the head area now depleted of debris. This process is likely to continue for perhaps hundreds of years, before conditions are re-established that would compare to those that existed before the 1983 landslide.

The large basin near the head of the landslide that has displaced bedrock ribs between the basin and the head of the slide (see Bedrock Geology, p. 4) would appear to pose the most serious threat to a reactivation. Abrupt sliding of that entire basin could produce a return to pre-1983 conditions or worse. Explanations other than deep-seated sliding could have produced the offsets observed. Seemingly, the offset bedrock was not displaced during 1983 or later. It is possible that careful mapping of the area coupled with measured stratigraphic sections and further drilling could resolve the issue.

In summary, the geologic evidence suggests that the lower portion of the Thistle landslide has virtually stopped moving except for minor internal adjustments, particularly at relatively shallow depths. This condition should continue for some time. The large basin that contains displaced bedrock upslope from the head of the main landslide would appear to pose the principal threat for any large-scale reactivation of the Thistle landslide.

SOIL PROPERTIES AND IN-SITU CONDITIONS

A number of laboratory tests were performed on samples obtained from the nine test borings (DH-1 through DH-9) that were drilled by Northern Engineering and Testing at the request of the Committee. These included measurements of natural water content and dry density, grain size, Atterberg limits, and residual friction angles. Visual descriptions of the materials in the slide mass, and the results of the laboratory tests, are summarized in tables 1 and 2. Summary logs of the borings are in Appendix D.

Most of the materials encountered in the borings were clayey and had moderate plasticity. Most were silty or sandy clays, with average liquid limits of 40 and average plasticity indices of 18. The average in-situ water content of these materials was 18 percent, somewhat below the plastic limit.

Silty and clayey sands and gravels were also encountered, but less commonly. The minus 40 fraction of these materials had moderate plasticity, with an average liquid limit of 32, and an average plasticity index of 12. The average water content in situ was 12 percent.

Several of the more highly plastic samples were selected for direct shear testing, to determine the residual angle of shearing resistance. The test results summarized in table 2 were performed by Northern Engineering and Testing, and by the USGS Engineering Geology laboratory in Denver. Figures 9 through 15, Appendix F, contain the results of the direct shear tests used by Northern Engineering and Testing; the procedure used in the USGS tests was similar.

The measured values of residual friction angle (ϕ'_r) ranged from approximately 7^o to 10^o for samples with liquid limits over 50, to values as high as 28^o for the samples from DH-6, which had a liquid limit equal to 33. These residual friction angles are deemed of interest because the slide mass

TABLE 1.--Descriptions and physical properties of materials sampled in test borings DH-1 through DH-9

Descriptions

Most commonly encountered soils were silty and sandy clays of medium to high plasticity, containing some gravel particles. These soils were red, brown, gray, and green.

Less commonly encountered were silty and clayey sands and gravels, non-plastic to highly plastic. These soils were red, brown, and gray.

Atterberg Limits

Silty and sandy clays	LL = 25 to 57, Average = 40
	PI = 6 to 25, Average = 18
Silty and clayey sands and gravels	LL = 24 to 40, Average = 32
	PI = 7 to 21, Average = 12

Natural Water Contents and Dry Densities

Silty and sandy clays	w = 10 to 25, Average = 17 percent
	γ_d = 105 to 133, Average = 118 pcf
Silty and clayey sands and gravels	w = 11 to 14, Average = 12 percent
	γ_d = 124 pcf (one measurement)

Unconfined Compressive Strengths

Silty and sandy clays	q_u = 2.3 to 6.3 ksf

TABLE 2.--Summary of measured residual friction angles

Test Boring	Depth (ft)	LL (%)	PI (%)	ϕ_r' (degrees)	Type of Test	Performed by
DH-2	105	58	23	8.4	DS(-40)	NET
DH-3	39	53	19	7.1	DS(-40)	NET
DH-4	234	50	22	15.0	DS(-40)	NET
DH-8	12	52	23	10.2	DS(-40)	NET
DH-8	115	57	25	7.1	DS(-40)	NET
DH-8A	21	54	26	9.5	DS(-40)	NET
DH-3	251	47	26	19.3	DS(-10)	USGS
DH-3	251	47	26	18.7	DS(-40)	USGS
DH-3	251	47	26	18.2	RS(-10)	USGS
DH-3	251	47	26	15.8	RS(-40)	USGS
DH-6	57	33	16	28.6	DS(-10)	USGS
DH-6	57	33	16	28.7	DS(-40)	USGS
DH-6	57	33	16	27.4	RS(-10)	USGS
DH-6	57	33	16	25.0	RS(-40)	USGS
DH-8	174	51	22	11.0	DS(-10)	USGS
DH-8	174	51	22	9.5	DS(-40)	USGS*
DH-8	174	51	22	9.9	RS(-10)	USGS
DH-8	174	51	22	6.7	RS(-40)	USGS
DH-8	174	51	22	8.4	DS(-40)	NET*
Failure Surface	0	45	30	21	DS(-40)	USGS
Failure Surface	0	45	30	19.5	RS(-40)	USGS

LL = liquid limit
PI = plasticity index
ϕ_r' = effective residual stress friction angle
DS = direct shear
(-10) = portion of sample passing No. 10 sieve
(-40) = portion of sample passing No. 40 sieve
NET = Northern Engineering and Testing, Inc., Salt Lake City
USGS = U.S. Geological Survey Engineering Geology Laboratory, Denver

* These tests were run on the same sample

has undergone such extremely large shearing deformations. The material along any of the numerous slide planes contained in the debris has probably been strained to its residual shearing resistance. Evaluations of stability of the blockage in Spanish Fork Canyon, or the higher portions of the slide within the tributary valley to the west, should assume that the residual friction angles of the materials will control further movements on existing sliding planes.

A number of inflow permeability tests were performed by Rollins, Brown and Gunnell, Inc., (RB&G) at 10-ft intervals in their test borings. They placed four borings in the blockage in the canyon at the locations shown on plate 2; logs of the borings are in Appendix D. Values of permeability were calculated assuming that the head loss was equal to the difference in elevation from the test interval to the water level in the casing. Because the actual head losses were probably smaller than those used in calculating the permeability values, the actual permeabilities are likely to be higher than the reported values.

Seventy percent of the tests (37 of 54 tests) indicated low permeability values, with results ranging from no measurable loss of water, to values of permeability less than 10^{-4} cm/sec. The remaining 30 percent of the tests indicated permeability values ranging from 10^{-4} cm/sec to 10^{-2} cm/sec, and, in boring RB&G-1, complete loss of all the water in the casing. A 4.5-ft void was encountered in that boring at 109 ft, which was 7 ft below the open-tube piezometer.

The results of these tests thus indicate that the matrix permeability of much of the landslide is fairly low, and that the clayey materials making up most of the slide are fairly impermeable. Scattered through the landslide, however, are zones of higher permeability materials, voids, and fissures capable of transmitting large amounts of water under relatively low gradients.

Another important aspect of the slide mass within Spanish Fork Canyon is the existence of high horizontal earth pressures within the mass. An indication of the existence of these high earth pressures comes from the difficulties experienced during drilling. Boreholes tended to squeeze shut quickly, and drill casings were bound tightly by the squeezing ground. These high earth pressures are important in several respects: First, excavation within the slide may initiate further sliding quickly, as material squeezes into the excavation. Second, structures built within or appurtenant to the landslide would be subject to high earth pressure loads. Third, as the pore pressures within the landslide dissipate, consolidation may result in lateral movements as well as settlements. Furthermore, these high horizontal stresses may have a significant influence on the stability of the blockage with respect to sliding upstream and downstream. High horizontal pressures are not common, and the geotechnical profession has limited experience with them. Thus, it is difficult to anticipate their possible effects on upstream and downstream slide movements.

HYDROLOGIC CONSIDERATIONS

LAKE LEVELS AND DISCHARGE RATES

The use of the blockage in Spanish Fork Canyon as a dam requires consideration of seepage through the blockage and the potential for internal erosion and piping. The possibility of internal erosion and piping depends on the grain size, composition, and distribution of high-permeability and low-permeability materials within the slide mass. These characteristics are largely unknown. The possibility of internal erosion also depends on the depth of water ponded behind the blockage and the length of time the water would be retained. Some indication of the ability of the blockage to retain water can be obtained from the 1983 experience, when Thistle Lake formed and was drained.

Figure 6 shows the rise and fall of the lake during the 1983 flood. Within about 50 days after the landslide blocked Spanish Fork Canyon, the lake level had risen about 180 ft to peak at elevation 5,204.5. Shortly after that time the lake level began to fall, owing to the fact that flow through the high-level emergency spillway tunnel was larger than the inflow to the lake. The lake level dropped to elevation 5,185 during the following 120 days, and, on October 1, 1983, about 170 days after the slide, drainage of the lake through the low-level outlet tunnel began. By means of the low-level tunnel, the lake was drained within a period of 130 days.

As figure 6 indicates, the blockage retained water for a period of 300 days, and it retained water at a depth of 150 ft or more for about 130 days. During this period some clear water was reported to be seeping under or through the mass, but no dirty flows indicative of internal erosion were reported. One piezometer (near the upstream edge of the blockage, see plate 2) was observed to fall with the reservoir, suggesting a relatively direct connection between the reservoir and the buried gravelly alluvium in which the piezometer tip was completed.

This temporary service as a dam does not indicate that the blockage could have retained water at a high level for longer than 130 days. The longer the period of retention, the greater the chance that seepage would lead to internal erosion followed by piping and failure. The 1983 experience does indicate, however, that the blockage can retain some water safely provided the levels are kept low and the retention period is not long. The risks in such low-level impoundments do not appear to be significant.

A calculated rise and fall of the lake is also shown in figure 6 for the condition that would exist if the 1983 inflow to the lake was experienced under the present conditions; that is, with the low-level tunnel open and no regulating valves in place. In this case, the lake level would rise to elevation 5,045, 10 ft below the low point on Highway 89, and would return to normal after 90 days.

Other hypothetical events are summarized in table 3. Note in table 3 that the 1983 inflow to the reservoir has an expected return period of about 300 years and would produce a peak flow of about 2,900 cfs through the outlet tunnel. The maximum inflow possible without flooding the low point on Highway 89 (elevation 5,055) has a return period of about 3,000 yrs and would result

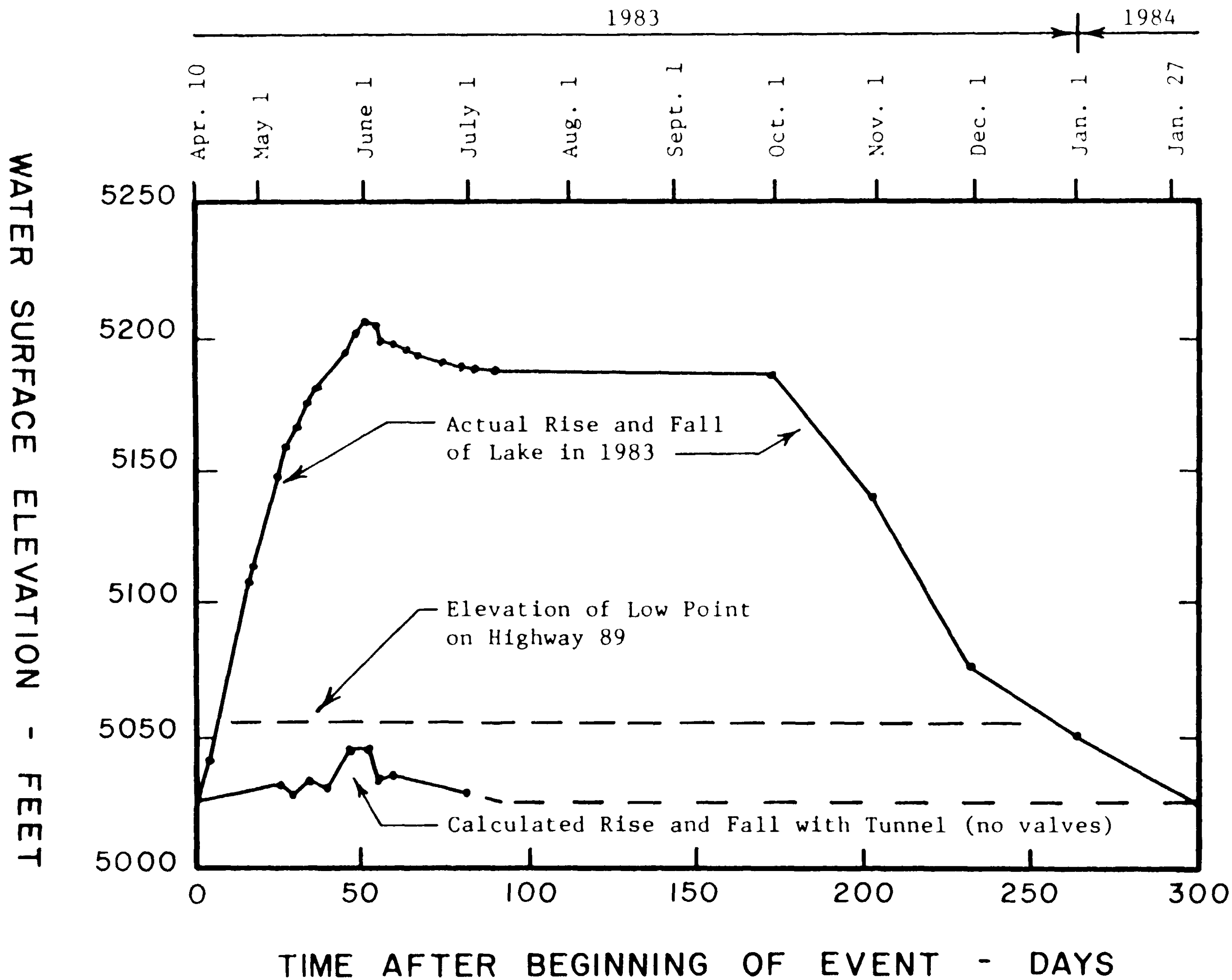


Figure 6 -- Rise and fall of Thistle lake

TABLE 3.--Calculated water surface elevations, peak flows, and return periods

[Drainage tunnel open, no valves]

Water Surface Elevation (ft)	Tunnel Discharge (cfs)	Approximate Return Period (yrs)
5025	5	--
5030	449	2
5035	1270	20
5040	2190	100
5045	2940	300
5050	3410	500
5055	5342	3000

Data from the Utah Division of Water Rights in peak flows in excess of 5,300 cfs through the outlet tunnel. Such a flood is reported to represent approximately 10 percent of the probable maximum flood.

GROUNDWATER CONDITIONS

Piezometers were placed at eight of the nine drill-hole sites completed in 1984. Measurements of the pressure head were made just after the drill holes were completed and at nine intervals between December 16, 1984, and August 12, 1985. The individual water pressure readings are shown in tables 5 and 6 in Appendix G and the data are plotted on figures 16 to 24 in Appendix G. The results are plotted in terms of equivalent piezometric level relative to the ground surface vs. depth. On these plots a hydrostatic pressure distribution would be indicated by a vertical line.

The results appear to indicate that the fluid pressures within the slide mass are relatively high. The piezometric levels frequently approach or exceed the level of the ground surface in the middle to lower portion of the slide mass. There appears to be a pronounced decrease in fluid pressures directly below the failure surface in the majority of the drill holes (DH-1, 2, 4, and 5) located within the Spanish Fork Canyon and DH-7 higher in the landslide. However, in other drill holes (DH-6, 8, and 9) located in the upper portion of the slide, evidence for such a decline in fluid pressures was not observed.

Exceptionally high fluid pressures were recorded in DH-4 at depths of 92, 115, and 230 ft. Fluid pressures measured are approximately 34, 52, and 120 ft above the ground surface. The standpipe piezometer completed at a depth of 225 ft in boring RB&G-3 (see plate 2) was observed to be flowing in September, 1985. These indications of high fluid pressures occur near the key areas of the bend and the constriction below the bend (see boring logs for DH-3 and SH-3). High fluid pressures here would be significant to the stability of the slide.

It is unfortunate that the measurements from all the piezometers installed in 1984 must be considered somewhat doubtful and perhaps unreliable. This is because pressure-response tests could not be performed to check the operation of the pneumatic transducers installed.

There are other reasons to question the piezometric data. These include the remarkable constancy of most of the 34 piezometric readings over the period from February, 1985, through August, 1985. This period included a spring snowmelt followed by a relatively dry summer. Piezometers placed in other landslides in similar situations of climate and topography typically show significant seasonal fluctuations in piezometric levels. Changes of 10 to 30 ft or more would be expected for the Thistle Slide. However, only three piezometers showed changes of 10 ft or more and two of these show no significant fluctuations between March, 1985, and August, 1985. Only six piezometers showed fluctuations, of 5 ft to 9 ft, between February and August, 1985. Of these, three piezometers exhibited indications of unreliable behavior. Of the remainder, none showed more than a 4-ft variation in pressure head between March, 1985, and August, 1985. Twenty-two piezometers showed maximum variations of 0 to 2 ft between February, 1985, and August, 1985. The non-zero changes are sufficiently small so that all 22 piezometers could possibly be inoperative. While it is possible that most of the piezometers are located within uniform zones of low permeability that are relatively isolated from seasonal effects, such locations and behaviors seem unlikely for so many of the piezometers, and the results of the measurements are, therefore, somewhat suspect.

Exceptionally high fluid pressures associated with an exceptionally heavy precipitation event are described later in this report as the simplest and most obvious explanation for the timing of the 1983 slide. However, the piezometer measurements do not appear to support this hypothesis as they do not show significant evidence of even modest seasonal fluctuations. Therefore, either the hypothesis is incorrect or the piezometric data are incorrect, or perhaps misleading. An alternate explanation is that the fluid pressures measured after the 1983 slide bear little or no relationship to those present when the slide was triggered. Therefore, both the pressures and fluctuations measured during 1984-85 could be quite different from those in April, 1983. Since it is not possible to subject the piezometers to field quality control tests, it does not seem reasonable to challenge the above hypothesis on the basis of the available piezometric data.

Most of the water levels from piezometers placed in the four RB&G drill holes (see figures 28 to 31, Appendix G) and from piezometers installed in the three State drill holes (SH-1, 2, 3) completed in 1983 (see figures 25 to 27, Appendix G) were not available to the Committee. However, results from the standpipe piezometer placed in the bottom of RB&G-2 were recorded for several weeks in October, 1983. Data from RB&G-2 covered a period when the lake level was declining. This piezometer was completed in a deep gravel channel located below the blockage and probably below the general level of alluvium covering the Spanish Fork Valley floor. The water levels in this piezometer declined relatively directly with declining levels of the reservoir. This drill hole is located on top of the blockage, about one-third of the distance from the upstream toe of the slide to the downstream toe (see plate 2). The head loss recorded by this piezometer varied from about one-half the maximum head difference (reservoir level minus stream level downstream of the slide) during the initial readings to two-thirds the maximum head difference when the final readings were taken. The change in response suggests either that an increase in permeability occurred downstream of RB&G-2 in October, 1983, or that a decrease in permeability occurred upstream of RB&G-2 during that period.

Few groundwater data are available for the bedrock and alluvium below the toe of the slide. However, data are available that confirm that the Spanish Fork Valley serves as a regional groundwater discharge. There are numerous occurrences of warm to hot water in springs and wells along the valley floor in the vicinity of the slide as well as warm waters encountered during construction of the low-level diversion tunnel for the slide lake. The temperature of this water varies from 45^{0} to 120^{0} F. These data are summarized in figure 32, Appendix G, prepared by W. F. Case of the Utah Geological and Mineral Survey and on tables 7 and 8, Appendix G, prepared by the State Division of Water Rights (DWR). The warm water spring (near F-1, figure 5) reported by Atwood adjacent to the small temporary pond at approximately elevation 5,300 ft on the left flank of the slide could also be a significant element of the hydrogeology of the slide.

A well drilled about one-quarter mile downstream from the slide encountered 35 gpm of warm sulfurous water at 98^{o} F at a depth of 60 ft. At a depth of 85 ft, 88^{o} F water came from white sandstone. Reports of groundwater from shallow wells (8 to 15 ft deep) dug in the townsite of Thistle indicated 47^{o} F to 50^{o} F water from alluvium. The log of a deeper bedrock well drilled in Thistle showed 0-23 ft of gravel and small flows of 0.15 gpm of 49^{o} F water from a depth of 43 to 53 ft. These data suggest that the normal temperature of the near-surface groundwater in the alluvium in the valley is 45^{o} to 50^{o} F. The flows recorded also provide an indication of the hydraulic conductivity of the alluvium and underlying bedrock units.

INFLUENCE OF CLIMATIC FACTORS

No groundwater measurements are available from the Thistle slide in the period prior to the slide of April 1983. Therefore, any discussion of groundwater levels at that time is speculative. However, the reactivation of the slide was closely related in time to what was very likely a period of high groundwater levels. The evidence to support this statement is provided by the railway history and regional climatic data.

The railway was constructed along the Spanish Fork River in 1881. No movements equivalent to the 1983 event occurred in the interval between 1881 and 1983.

An insight into the long-term nature of the groundwater fluctuations in the Wasatch Mountain region can be obtained by examining the record of water levels of Great Salt Lake from 1848 to 1983. These fluctuations are shown in figure 33, Appendix G. It is apparent from this record that the runoff from the entire Great Salt Lake basin was appreciably greater in 1982 and 1983 than for any other period in the 138-year record. Since most of the runoff for the Great Salt Lake basin comes from the surrounding mountains, the lake level probably reflects precipitation and runoff from the vicinity of the Thistle slide. A study of cumulative departures of the average annual precipitation for Salt Lake City showed that the wet cycle that reached a climax in 1983 began around 1968.

It would be considered normal for such long-term precipitation cycles to be directly reflected in higher groundwater tables and higher piezometric levels at depth within the mountain slopes. Thus, we would expect record piezometric levels within the Thistle slide before and during the spring snowmelt of late March and early April, 1983.

CAUSES OF SLIDING

The Thistle landslide occurred in April, 1983, when the gravity-induced shearing forces tending to cause downslope movement exceeded the available shearing resistance of the slide mass. The shearing resistance was already low at the base and sides of the pre-existing landslide, which had undergone significant previous movements. These antecedent movements had probably reduced the strength along the sides and base of the slide to residual frictional values, leaving the remaining slide debris susceptible to further movements when particularly adverse conditions developed again. The material forming the old landslide consists largely of plastic clay with low shear resistance (see table 2).

Since the last episode of movement involving a major displacement of the toe of the slide, numerous lobes of earthflow deposits had accumulated on the sides and head of the old landslide. Typically, these lobes have thicknesses of 10 to 40 ft or more. These lobes served to increase the weight of the main slide mass and increase the surface slope of the slide debris. The remnant upper portions of these lobes also significantly increased the driving forces acting on the perimeter of the main slide mass. The volume of materials added at the top of the slide through the accumulation of these lobes exceeded by many times the volume of materials removed at the toe of the slide by excavation. An examination of the airphotos taken in 1971 and 1981 suggests that significant movements had occurred between these dates in the upper portion of the slide.

Processes detrimental to the stability of the landslide were occurring at the toe of the slide from time to time. These included: (1) dredging or other events that deepened the river channel, (2) excavation and slope steepening related to railroad construction and maintenance, and (3) natural erosion occurring along the gullies formed by intermittent streams on either side of the toe of the slide.

Evidence observed on air photographs taken in 1971 and 1981 indicates that stream erosion was active in the steep gulley located along the north flank between the slide and the hill just north of the toe of the slide (I-1, figure 5). This gulley coincided with the shear zone on the left flank (north side) of the slide. The hill noted above forced the slide to turn almost 70^{o} before it reached the railroad. Any change of the shearing resistance in this area is likely to have had a significant effect on the overall stability of the slide. A photo taken April 17, 1983 (see Sumsion, pg. 37, lower photograph), during the early stages of the slide activity shows erosion along this shear zone, as well as new cracks in the rocks on the north side of the gulley. These cracks apparently resulted from the shearing forces applied to the rock abutment by the slide. The cracking and any of the resulting enlargement of the narrow neck of the slide would have increased the forces acting on the toe of the slide and would also have removed some support from the upper slide mass. Another event occurring at the toe of the slide during early April 1983 was the sloughing and/or sliding of the railroad cut slope. This is shown in a photo in Sumsion (pg. 12) taken April 2, 1985.

The Committee's study did not determine conclusively whether the 1983 movements of the Thistle slide began at the bottom or the top. However, the Committee believes that further study of the available data might throw light on this aspect of the behavior of the slide.

Superimposed on this background of long- and short-term but persistent detrimental effects on the stability of the slide are the fluctuating effects of the annual spring snowmelt and any other exceptionally heavy precipitation events. These could decrease the factor of safety of the overall slide mass on the order of 2 percent to 20 percent. Thus, if the factor of safety were 1.10 before the snowmelt period and the effect of the snowmelt was to decrease the factor of safety by 5 percent, then the remaining factor of safety could be about 1.05 and the slope should be relatively stable (although in local areas the factor of safety may go below 1.0 and local deformation might result).

Figure 7 is a sketch which shows schematically the variation of the factor of safety of a slide with time. This figure shows the seasonal effects of snowmelt or other precipitation events, such as the 8 to 13 in. of rain that fell in late September, 1982. Figure 7 also illustrates the long term reduction in factor of safety due to small slides or debris flows advancing from time-to-time onto the upper portion of the slide.

Snowmelt and rainfall have the direct effect of increasing horizontal forces in water-filled cracks in the slide. Water also has the indirect or delayed effect of increasing the water pressures acting on slip surfaces on the sides and bottom of the slide. By this means the maximum shearing resistance along the internal planes or zones of shearing within the landslide are also decreased as the water pressures within the mass increase. This decrease in shearing resistance can be significant at key blocks where appreciable internal deformation of the slide mass is required for a general movement to occur.

The remote possibility that slide movements were indirectly related to local deformation of the near-surface bedrock units cannot be completely eliminated. This is because the slide is adjacent to a major regional thrust fault (Witkind and Page, 1983). Also, Witkind and Page indicated that evaporite rocks may occur at depth below the slide. Therefore, collapse due to solution or deformation because of the relative mobility of these underlying rocks might be possible. However, unless direct evidence were obtained for the timely involvement of these geologic factors, it would appear to be more reasonable to attribute the cause of the slide to more immediate geologic and environmental factors.

The period of slide movement in April 1983 was perhaps extended due to a relationship between the rising lake levels and increasing fluid pressures on the failure surfaces at the toe of the slide mass. As the lake level increased, so would the water pressures acting on and within the slide. This behavior would tend to decrease the stability of the slide at the same time as the increased volume of debris, which was being deposited at the toe of the slide, was tending to increase its stability. Hence, the stability of the slide mass would remain low until such time as the reservoir level was lowered.

In summary, the Thistle landslide has existed in a meta-stable condition for many years as an old slide comprised of clay-rich debris. A significant long-term detrimental effect was the periodic addition of earthflows and shallow landslides to the upper portions of the main slide mass. Probably less significant were events at the toe of the slide. These include erosion, dredging, and railroad construction and maintenance. The triggering action was most likely the direct and indirect effects of the spring snowmelt of 1983 superimposed on the remnant effects of the exceptionally heavy rainfall of late September, 1982. The result was that the overall factor of safety of the slide reached a low value (on the order of 1.0), which had not been achieved for hundreds or more years. The rising lake level behind the slide probably contributed to the duration of the period of pronounced slide instability in April and May, 1983.

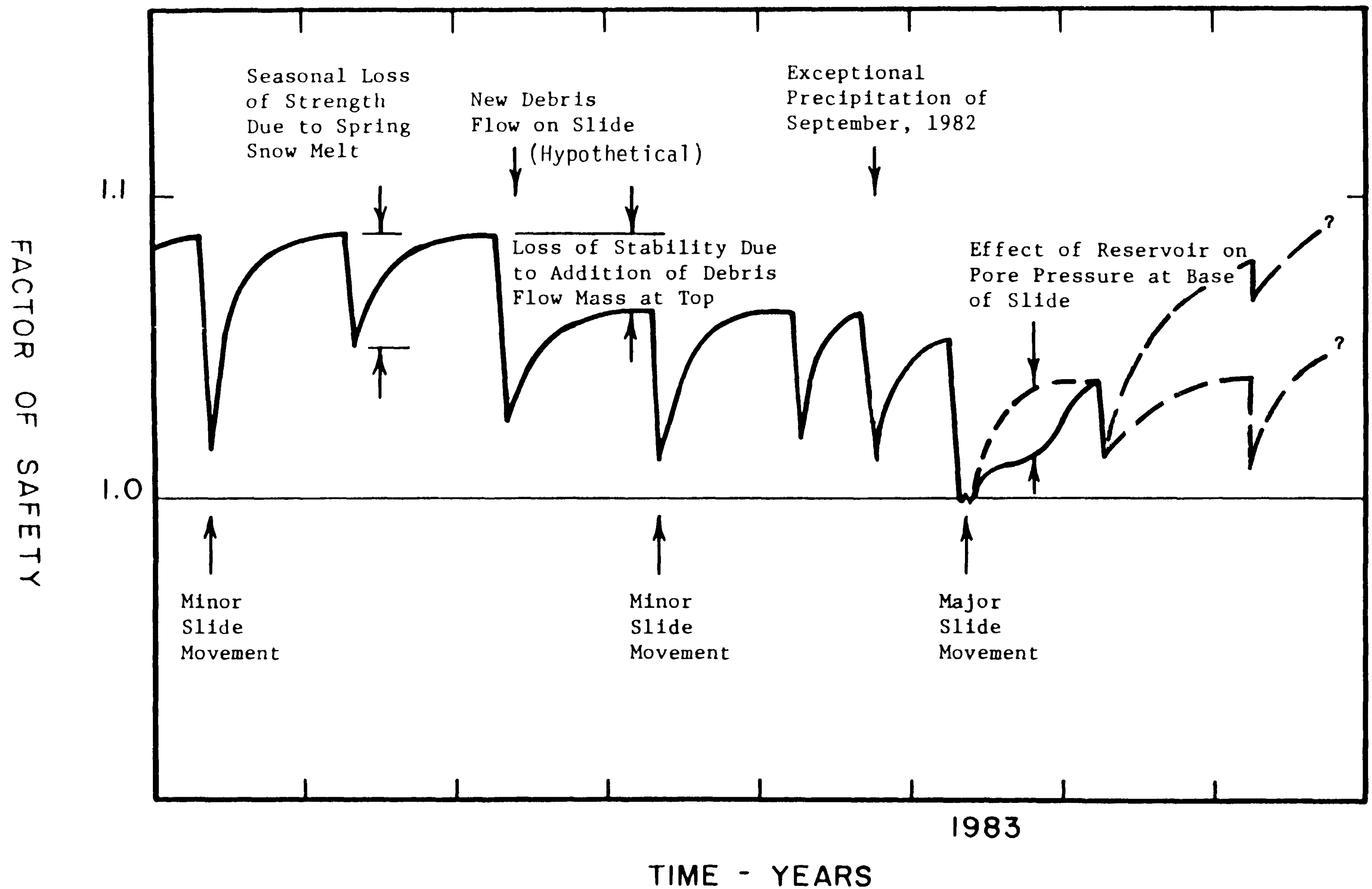


Figure 7 -- Schematic representation of variation of factor of safety with time

CURRENT CONDITION OF LANDSLIDE

SURFACE MOVEMENTS

Surveys of the locations of points on the surface of the slide were made between March 19, 1984, and August 14, 1985. These surveys have been undertaken by the Utah State Division of Water Rights. Figure 8 shows a plan view of the toe of the slide with the changes in horizontal positions of these points shown by movement vectors. The movements between March 19, 1984, and August 14, 1985, range from 0.06 ft to 2.78 ft and average 0.48 ft. If the largest value is ignored, the average of the remaining 10 points is 0.25 ft.

The rigidity and stability of many of the survey points employed in these measurements may not be commensurate with the small differences in position determined. For example, the differences could be due to animals disturbing the stakes supporting the reflectors. Thus, without fully reliable reference points on the slide and quality control checks on the survey results, the possibility of survey error cannot be excluded. However, the available evidence suggests that small downhill movements are continuing at the ground surface.

SUBSURFACE MOVEMENTS

Grooved plastic inclinometer casing to permit borehole deformation measurements was installed in drill holes DH-1, DH-2, DH-4, DH-5, DH-6, DH-7, DH-8, and DH-9 by Northern Engineering and Testing, Inc. A summary of the results of measurements through May 9, 1985, is given in table 4. Out of the eight inclinometer casings placed in the drill holes, indications of displacements or blocked casings were noted in four drill holes at depths of 158 to 314 ft, and some indication of displacements was noted in all eight drill holes at depths of 10 to 265 ft. In most of the drill holes there was evidence of displacements or incomplete coupling of the casing to the drill-hole walls in the upper 10 to 35 ft. The magnitude of movements required to deform the inclinometer casing to prevent advance of the inclinometer probe is in general agreement with the magnitudes of surface movements shown on figure 8, assuming that the shearing displacements were concentrated along relatively thin shear zones. Thus, the possibility of displacement in these zones cannot be dismissed.

OTHER ASPECTS

Other aspects of the current conditions of the slide mass are discussed in Description of the 1983 Thistle Landslide, p. 9, on the geology of the slide mass and in Groundwater Conditions, p. 25, on the water pressures within the slide. Specific data relating to the borings are in Appendices C and E. The movement record (surface and subsurface) should be the definitive record of the current condition of the slide with respect to its stability. Unfortunately, the instrumentation results of movements do not stand up well to a rigorous analysis.

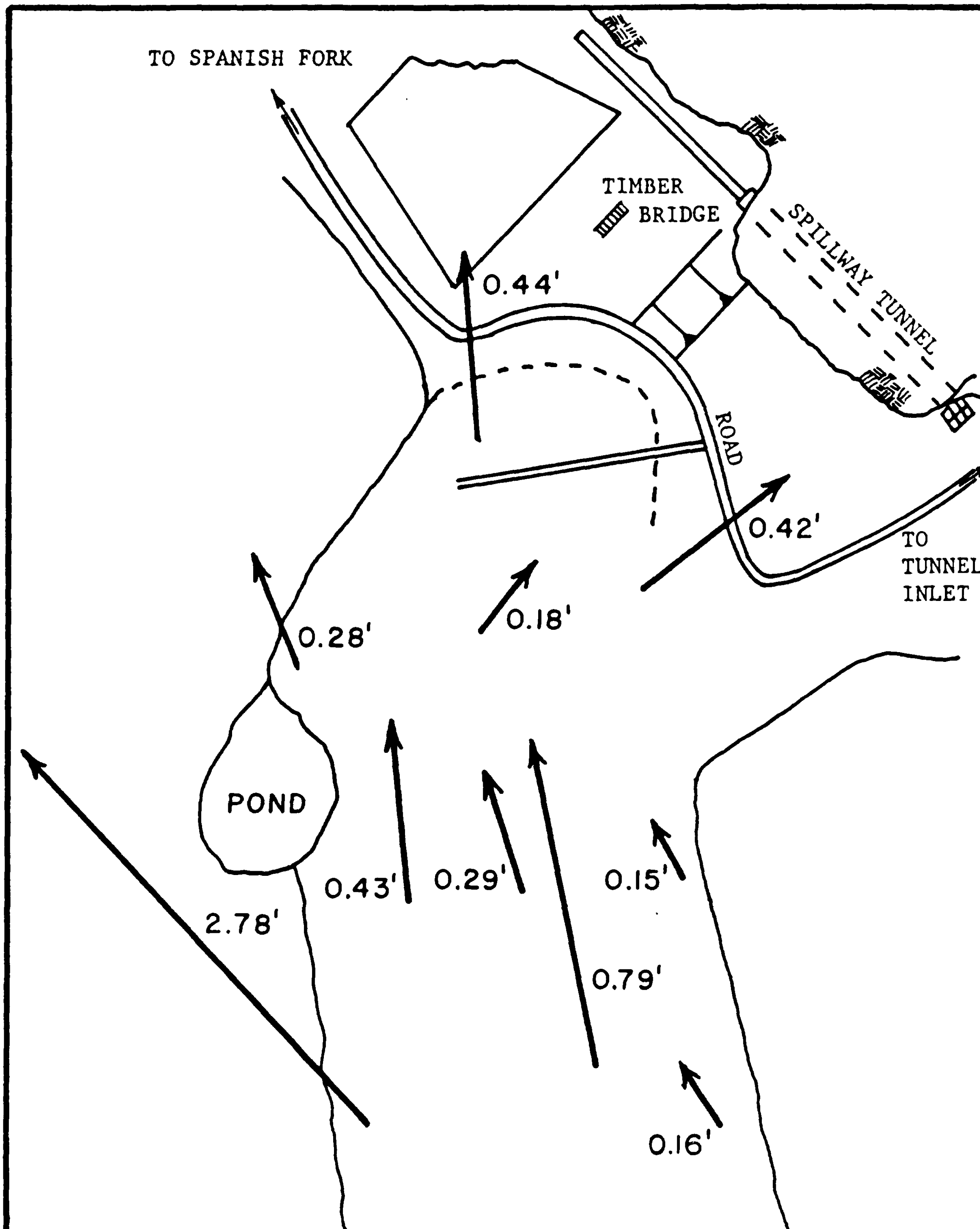


Figure 8 -- Map of measured surface movements from March 19, 1984 to August 14, 1985

TABLE 4.--Summary of inclinometer results

Drill hole	Depth (ft)	Inclinometer Depth (ft)	Comments
DH-1	270.5	273	Readings to 270 ft
			Displacements noted at 10-15 ft depth
DH-2	349	338	Unable to read below 314 ft (possible shear zone)
			Also suggestions of displacements at 265 ft, 205 ft, 145 to 150 ft, and 10 to 15 ft
			Mud noted in base of casing May 9, 1985, and resistance to probe passing @ 200 ft
			On May 9, 1985, lowest reading was 284 ft
DH-5	335	328	Casing reported "sheared off" at 214 ft
			Significant displacement at 25 to 35 ft
			Very small flow of water reported from inclinometer casing
			Possible displacement at 125 to 185 ft
DH-6	178.5	180	No reading recorded below 158 ft (possible shear zone)
			Possible displacement at 50 to 55 ft
DH-7	209	210	No readings below 206 ft
			Inclinometer casing is reported to be loose and flops inside surface casing in upper 35 ft of hole
DH-8	349.6	350	No readings below 348 ft
			Possible displacements in upper 75 ft
DH-9	178	180	No readings below 172 ft (possible shear zone)
			Otherwise no significant displacement apparent

LIKELIHOOD OF RENEWED SLIDING

WITHOUT A RESERVOIR

The overall stability of the slide is likely to be appreciably better under current conditions than when the lake was ponded behind the slide mass. This is because any reservoir-induced influence on the fluid pressures on the base of the slide and within the blockage should have been reduced by draining the lake. These decreases in fluid pressures should result in correponding increases in the external and internal shearing resistance of the slide mass.

Offsetting these stabilizing factors are a number of destabilizing or at least potentially destabilizing factors. These include: (1) removal of the substantial water load from the lake acting on the upstream face of the blockage, thus decreasing the stability of its upstream face, (2) removal of material at the toes of contributing slides at the top of the main Thistle slide, thus decreasing the stability of these slides and adjacent slopes, (3) erosion and deterioration of the material at the toe of the slide, (4) a possible increase in fluid pressures acting on the toe of the slide mass caused by blockage of the local or regional groundwater flow systems due to a blanketing effect of the relatively low permeability slide debris covering a portion of a groundwater discharge area, and (5) increases in fluid pressures within the landslide due to precipitation and snowmelt. The detrimental influences of items (2) to (5) above would be effective whether or not the lake was present.

For many landslides, the relative magnitude of such favorable and unfavorable factors on their stability can often be quantitatively determined, and a quantitative estimate can be made of the resulting net increase or decrease in stability. However, when evaluating the stability of the Thistle slide, the Committee is reluctant to make such quantitative estimates of the stability. This is because so many of the important parameters are still largely unknown (for example, geometry of key planes) or suspect (for example, movements and fluid pressures). In particular, the magnitude of current seasonal fluctuations in water pressures throughout the landslide remains largely unknown.

Some minor downhill movements of the landslide appear to be continuing, and it does not appear to be possible to establish whether these are due to readjustments of the slide following the major events of 1983 or to continued activity of the overall slide that could lead to a new movement. However, the Committee favors the first possibility.

Local landslides in the downstream and particularly the upstream slopes of the blockage in the Spanish Fork Canyon are a distinct possibility. These slopes are presently steeper than the natural slope of most of the slide debris (8^{o} to 12^{o}) prior to the 1983 event, and steeper than the natural slopes of the toe of the slide (approximately 18^{o} to 20^{o}) prior to the post-1900 excavations by the railroad (see Sumsion, 1983, photo, pg. 4). Hence, with time and without remedial support, one would expect that the current slopes of the blockage would deteriorate until the slopes noted above would prevail.

Renewed activity of the Thistle slide due to an earthquake is a possibility. However, the risk is believed to be relatively small because the earthquake would probably have to occur at the same time that a peak rainfall or snowmelt was affecting the slide.

WITH A RESERVOIR

If water is allowed to pond against the upstream face of the slide mass, four out of five of the detrimental factors noted above would be operative. In addition, there would be an increase in fluid pressures within and beneath the debris in the blockage. The only apparent beneficial effect is that increased water pressures would be applied to the upstream face of the blockage.

If the reservoir is used for flood control, the fluctuating water levels will result in additional detrimental effects. These include the adverse stability conditions associated with slow and rapid drawdowns of the reservoir and any deterioration and erosion due to alternating wetting and drying of the landslide. Such effects can accelerate when the clay has the dispersive nature that is reported to be associated with clays derived from the North Horn Formation.

With a reservoir, the possibility of renewed landslide activity exists and is quite likely. The Committee felt that the extent of such renewed sliding would be difficult to predict but would be highly dependent upon the nature of the new reservoir, its level and fluctuations during usage, and the nature and extent of any remedial measures taken. Thus, with the current information, a quantitative evaluation of the likelihood of renewed sliding does not appear to be warranted. Furthermore, there can be no assurance that additional exploration of the slide would appreciably improve one's ability to predict the future behavior of the Thistle landslide.

LIKELIHOOD OF INTERNAL EROSION AND PIPING

There is a possibility of internal erosion and piping if the slide blocking Spanish Fork Canyon is used as a dam. The likelihood of these processes occurring depends on the depth of water retained in the lake, the length of time the water is impounded, and the nature and distribution of materials forming the blockage and its foundation. Although the distribution of low-permeability and high-permeability materials within the landslide is largely unknown, the experience in 1983 of filling and draining the lake shows that the landslide has some ability to impound water safely.

If the water level in the lake is kept below elevation 5,055 (the elevation of the low point on U.S. Highway 89), the average hydraulic gradient across the blockage would be about 0.02. It seems unlikely that this level of impoundment would produce catastrophic internal erosion or piping, even if it persisted for a period of months.

Significantly higher levels of impoundment, and longer periods of retention, would entail greater risks of internal erosion and piping within and beneath the blockage. It is not possible to quantify the risks associated with deeper and longer impoundments, because the distribution of materials within the slide is not well known. It is known, however, that the material forming much of the landslide is easily erodible, and that the distribution of high-permeability and low-permeability materials within the slide mass may be extremely adverse. Thus, maximum hydraulic gradients within the slide might be much higher than the average value calculable from a knowledge of external water levels.

The consequences of a piping failure of the landslide could be a rapid loss of the reservoir with possible downstream flow rates in excess of those attainable through the ungated tunnel. Thus, impoundments above elevation 5,055 would involve both greater probability of failure, and greater chance of disastrous consequences should failure occur.

RESPONSE TO SPECIFIC QUESTIONS

Specific questions addressed to the Committee by letter of March 7, 1984, from Mr. Dee Hansen to the Committee are listed below.

Question 1 Should the Thistle slide be investigated to estimate its stability and suitability for potential use as a dam?

Response Yes

Question 2 If the slide should be investigated, what program should be followed to gather the necessary information?

Response The Committee recommended a program of borings, laboratory tests, instrumentation, and field mapping that was begun in 1984 and has continued to the present. These recommendations are detailed in the April 19, 1984, Committee Report.

Question 3 Are the upstream portal and channel susceptible to a blockage by additional sliding?

Response Yes. There is some remaining risk for such an occurrence. Although the likelihood of plugging by rockfalls has been reduced by covering the inlet channel, the possibility of blockage by renewed slide movement remains. The likelihood of such an occurrence would increase with the frequency and depth of retained flood waters against the upstream face of the landslide mass, as well as with the amount of precipitation.

Question 4 If susceptible, what type of preventive measures can be taken to protect the portal?

Response Possible preventive measures can be separated into four categories: (1) Stabilization of the surface and the upstream slope of the landslide mass blocking Spanish Fork Canyon. Stabilization measures should consider the relative ease with which the material is eroded, as well as its stability against slope failure. (2) Construction of an embankment or a wall to divert earth flows and slides away from the intake. (3) Replacement of the present intake with a new structure in a different location. (4) Installation of a warning system for detecting blockages of the low-level intake portal and a contingency plan for their removal.

Question 5 Can the slide be utilized for any of the following purposes:

(a) Flood control (low heads for short period of time),
(b) Irrigation storage (moderate heads for 3 to 4 months), or
(c) Multi-purpose, that is, recreation, irrigation, flood control, and hydroelectric power (high heads with permanent storage)?

Response It is the Committee's opinion that the landslide can safely be used as a flood control dam, storing water up to elevation 5,055 for periods of 3 months or so. The Committee believes it would be unsafe to store water to higher elevations, unless very extensive further exploration of the landslide was undertaken to assess its stability. The Committee further believes that there is a very significant possibility that further exploration might prove inconclusive no matter how extensive the program, or that it might reveal deficiencies that could not be remedied at any reasonable cost. It seems likely that a multiple-use reservoir can be developed at lower cost, and with much greater reliability, by constructing a dam upstream from the landslide blockage rather than modifying the blockage so that it can be used as a dam.

The continued ability to route flows around the landslide depends on the successful operation of the low-level outlet tunnel. Thus, periodic inspections of the tunnel, intake shaft, rock slopes, and outlet are imperative. The inspections should be preceded by a review of the stability of these features under earthquake loading and the potential for long-term deterioration. Deficiencies should be promptly corrected.

ACKNOWLEDGMENTS

The Committee appreciates the technical and logistical support received from a number of organizations and people. In particular, Dr. Irving J. Witkind of the U.S. Geological Survey examined core samples, prepared boring logs, provided mapping, drew cross sections, and provided much information on the regional geology of the area. Ms. Diana Fair of GRG, Inc., Denver, CO, prepared the topographic base maps. Mr. Robert L. Morgan, Utah State Engineer, was of great help throughout our investigation. He provided our reference information and assisted the activities of the committee. We also appreciate the help received from Walter V. Jones, Northern Engineering and Testing, Inc., and several individuals from the Utah Geological and Mineral Survey, the Division of Water Rights, and Utah County. To all those who contributed to our investigation, we express our sincere thanks.

REFERENCES

Kaliser, B. N. (1983), Geologic Hazards of 1983: Survey Notes, Utah Geological and Mineral Survey, v. 17, no. 2, p. 3-8, 14.

Shroder, J. F., Jr., 1971, Landslides of Utah: Utah Geological and Mineral Survey Bulletin 90, p. 26-28.

Sumsion, O. B., 1983, Thistle--focus on disaster: Springville, Utah, Art City Publishing Company, p. 173.

Witkind, I. J., and Page, W. R., (1983) Geologic Map of the Thistle Area, Utah County, Utah: Utah Geological and Mineral Survey Map 69.

APPENDIX A

DOCUMENTS FURNISHED TO THE COMMITTEE

Articles

Thistle Landslide: Utah's First Presidential Disaster Declaration, Survey Notes: Utah Geological and Mineral Survey, v. 17, no. 2, Summer, 1983.

Emergency Drainage for Massive Utah Landslide: Woodward-Clyde Consultants Newsletter.

Progress Reports

Rollins, Brown, and Gunnell, Inc. to Utah County Engineering Department
October 11, 1983
November 1, 1983
December 16, 1983
(Reports include logs for borings RB&G-1, 2, 3, and 4)

Core Logs

Borings for State of Utah by Woodward-Clyde Consultants includes SH-1, 2, and 3.

Miscellaneous Water Quality Tests

Submitted to State Engineer's office by Utah County and Utah Geological and Mineral Survey. Samples collected 9/29/83.

Proposal to Perform an Investigation

Rollins, Brown, and Gunnell, Inc. to Engineering Department of Utah County, July 28, 1983.

Geologic Map of the Thistle Area, Utah County, Utah, by Irving J. Witkind and William R. Page, published by Utah Geological and Mineral Survey, June, 1983.

Thistle Dam Preliminary Contour Lines

Utah County Surveyor, 9/16/83.

Thistle Slide Cross Section

By R. L. Morgan, Utah Division of Water Rights, 3/84.

Hydrology and Hydraulics

Plots prepared by Utah Division of Water Rights

1. Lake Thistle elevations, 1983, with and without valves.
2. Lake Thistle water level projections, average, 150 percent of average, 250 percent of average.
3. Lake Thistle elevations - water year 1952, with valves, without valves, outflow limited to 1,300 cfs.
4. Lake Thistle water level projections, 250 percent normal, with 1952 flow pattern, without valves.
5. Lake Thistle water level projections, 250 percent normal, with 1983 flow pattern, without valves.
6. Spanish Fork River at Thistle hydrograph, 1952 flow regime at 250 percent of normal.
7. Spanish Fork River at Thistle hydrograph, 1983 flow regime at 250 percent of normal.
8. Lake Thistle hydrograph, water year 1952.
9. Lake Thistle hydrograph, estimated inflow 1983.

Stream Flow Records

1. Spanish Fork at Thistle, Utah. Water year October 1972 to September 1973, U.S. Geological Survey.
2. Spanish Fork at Thistle, Utah. Water year October 1951 to September 1952, Spanish Fork River Commissioner Report.

Letter from Leedshill-Herkenhoff, Inc. to Robert L. Morgan, August 15, 1983.

Nine well logs of water wells in the Thistle area, records from the Utah Division of Water Rights.

Photograph of Thistle landslide with drill hole locations noted.

Inclinometer data through January 16, 1985, for drilling locations numbered 1, 2, 4B, 5, 6, 7, 8, and 9. From Utah Division of Water Rights.

Piezometer data: Initial; December 16, 17, and 18, 1984; January 15, 1985, for piezometers located at drilling locations numbered 1A, 2A, 4A, 5A, 6A, 7A, 8A, and 9A. From Utah Division of Water Rights.

Surface monument movement net changes; March 19, 1984, through November 1, 1984. Survey by Utah Division of Water Rights.

Map illustrating drilling locations on the Thistle slide, Utah Division of Water Rights, February, 1985.

Report of Thistle landslide instrumentation, Thistle, Utah: Report by Northern Engineering and Testing, Inc., December 18, 1984.

Photographs of all core recovered from boring DH-1 through DH-9 including auxiliary borings for piezometers. Taken by Utah Division of Water Rights.

Thistle landslide laboratory test results, grain size and Atterberg limit tests: Report by Northern Engineering and Testing, Inc., March 14, 1985.

Thistle landslide direct shear test results: Report by Northern Engineering and Testing Inc., July 10, 1985.

Laboratory tests on samples from the Thistle landslide: Report by U.S. Geological Survey, July 18, 1985.

Thistle slide investigation, additional tests from DH-8, 176.3-176.8 ft: Report by Northern Engineering and Testing, Inc., August 19, 1985.

Thistle, a study of problems and potential, Section 3 in Hydrology and flooding along the Spanish Fork River, Utah County, February, 1985.

Two shear-test diagrams: GeoSoils, Inc., July 1985.

Piezometer data, borings DH-1A through DH-9A, initial readings through August 8 and 12, 1985.

Cumulative surface monument movement, March 19, 1984, through August 14, 1985. Data obtained by Utah Division of Water Rights.

Twenty photographs taken during early part of Thistle landslide movement by Utah Department of Transportation.

Drawing of "as constructed" toe of Thistle slide, plan and cross section views. Prepared by Utah Division of Water Rights.

Logs of borings at drill sites DH-1 through DH-9 in the Thistle slide, Thistle, Utah. Logged by Dr. Irving J. Witkind and Kathleen Murphy, March 11-14, 1985.

APPENDIX B

POST-SLIDE TOPOGRAPHIC MAP

This appendix contains a topographic map prepared by Ms. Diana Fair, GRG Associates, Denver, Colorado. The map used topographic control supplied by Utah County. Many survey control points were established in the landslide area by different organizations. Locations and elevations of some of the survey control points in the project area are incorrect. The Utah County topographic control was set as a single survey job and the traverse was closed and adjusted. Our aerial photographs are not optimally oriented with respect to the Utah County topographic control, and it was necessary to use photographs from two flights taken at different times to produce the map. The ground below elevation 5,670 ft was contoured using photography of August 1984. Above elevation 5,670, aerial photography of May 1983 was used. The resulting composite map (plate 1) is better controlled and more accurate in the lower part of the landslide.

Plate 1 was used as the base for the geologic map and cross sections given in Appendix C.

APPENDIX C

GEOLOGIC MAPS, CROSS SECTIONS, AND COLUMNAR SECTIONS

This appendix contains a geologic map of the landslide (plate 2), four cross sections (plates 3 through 6), a stratigraphic column (plate 7), and a photogeologic map of the landslide as of July 28, 1971 (plate 8). The maps and sections are at a scale of 1 in. equals 200 ft. The base map (plate 1) has a contour interval of 20 ft. The geologic map was prepared during one week of field work by Committee member Fleming and Bruce N. Kaliser of the Utah Geological and Mineral Survey. Some landslide features were added by Fleming using aerial photographs and a stereoplotter. Contacts of the bedrock formations were drawn by Dr. Irving J. Witkind of the U.S. Geological Survey.

Plate 8, the photogeologic map, was prepared by Committee member Fleming using a photogrammetric stereoplotter. A separate topographic map was not prepared from the 1971 aerial photography. Spot elevations were obtained from the 1971 aerial photographs for use on the cross sections.

On the cross sections (plates 3 through 6), we have shown the 1971 topographic profile and the post-landslide profile. Geologic information on the cross sections was obtained from field reconnaissance and boring logs. Not all the borings are shown on the cross sections. Cross sections based on information from these unused borings would be similar to the cross sections prepared.

In general, there is reasonably good control on the depth to the failure surface in the area upslope from Spanish Fork River (plates 3 through 5, sections A-A', B-B', and C-C'). The principal uncertainty is the depth to the failure surface on the extreme western end of the landslide where subsurface information is lacking. Farther downslope near Spanish Fork Canyon, the failure surface appears to be defined by several borings. There, the failure surface dips at about 2^{o} toward the Spanish Fork River.

Beginning at a point about 300 ft west of the bluff of Nugget Sandstone on the east side of Spanish Fork Canyon, there is appreciable uncertainty about the shape and position of the failure surface. In cross section A-A', the uncertainty stems from information in boring RB&G-2. No failure surface could be identified from the log of boring RB&G-2. The boring penetrated landslide debris, mostly a stiff, red, gravelly clay, to a depth of 245 ft. At that point, it encountered what was described as alluvium, and the hole terminated in alluvium at a depth of 284 ft.

Whether the failure surface in boring RB&G-2 is on top of or below the alluvium (above 245 ft or below 284 ft) is unclear from the boring log. However, there are two lines of evidence that suggest the alluvium is below the failure surface. First, the top of the alluvium is almost 45 ft lower than the projected top of the alluvium before failure (see cross sections A-A' and D-D', plates 3 and 5). It seems likely that the upper 45 ft of alluvium was displaced to the east by the landslide and is missing. Second, an open-tube or standpipe piezometer was installed at the bottom of the boring. When the lake was drained, the water level in this piezometer closely followed the drawdown of the lake. If the alluvium had been involved in the landslide, it seems likely that there would have been a more significant lag between the piezometer reading and the lake level due to the disruption in the continuity of the alluvium.

A good hydraulic connection between the lake and the alluvium in RB&G-2 appeared to exist. However, it is probable that the continuity of the alluvial channel was disturbed somewhere along its length. The amount of seepage emerging in Spanish Fork River downstream from the blockage is reported to have remained relatively constant at about 35 gpm regardless of the height of the reservoir. If the alluvium in the channel was continuous throughout the length of the landslide, the seepage rate below the slide mass would have been expected to increase with the water level in the lake.

Cross section D-D' (plate 6) is based on less information than cross section A-A' and is somewhat speculative. The interpretation shown on cross section D-D' is based in part on an inspection of aerial photographs taken during April 1983. Where the landslide passed between the two bedrock-supported hills downslope from the bend, it was about 700 ft wide. The width tapered in a parabolic fashion to a blunt toe no wider than about 300 ft at Spanish Fork River. As movement progressed, the width of the toe increased as the landslide spread laterally upstream and downstream. Thus, the deeper movement, which may have broken the continuity of the alluvium under the landslide, is shown as a 400-ft-wide zone on cross section D-D'.

The major uncertainties in the cross sections presented cannot be resolved by information from any of the existing borings. Critical information on the thickness of alluvium and shape of the valley under the landslide is provided only in boring RB&G-2. If the interpretation of the log of boring RB&G-2 is correct, there is a deep, alluvium-filled valley in the floor of the canyon. The thickness of that alluvium apparently was at least 70 ft before landsliding, and it probably had continuity along the canyon floor.

The information provided by the log of boring RB&G-2 is enigmatic. We find no evidence of a deep, buried valley in logs of water wells upstream in the Town of Thistle; alluvial thicknesses are generally 25 ft or less. Also, when the Spanish Fork River was blocked by the landslide, numerous small thermal springs became apparent downstream from the blockage. If a thick alluvial valley were present in the floor of the canyon, it is unlikely that the springs would have appeared as they did. The springs probably would have been less evident because a greater quantity of cooler reservoir water would have obscured them.

If further exploration is conducted on the landslide, the area around boring RB&G-2 should be carefully investigated. Note that a section through SH-2, DH-1, DH-2, and DH-3 (see plate 2) would show a consistent trend of the failure surface sloping toward the east at about 2^{o}. The information from RB&G-2 thus complicates an otherwise simple picture.

APPENDIX D

SUMMARY BORING LOGS

Sixteen sites were drilled as part of three separate jobs on the Thistle landslide. Approximate locations of the borings are shown on plate 2. This appendix contains summary boring logs of the drilling. The logs were prepared by the Thistle Slide Committee from information supplied by the Utah State Engineer.

Nine sites were drilled under the supervision of Northern Engineering and Testing, Inc., in response to recommendations by the Thistle Slide Committee. At least two holes were drilled at each boring site; piezometers were installed in one of the borings and an inclinometer casing in the other. Extremely difficult drilling conditions prevented installation of piezometers or an inclinometer casing at site DH-3. All nine of the borings apparently penetrated through the landslide debris and into bedrock. The Committee inspected core samples from the borings and prepared summary logs of the holes. The logs are shown as DH-1 through DH-9 on the following pages.

Four borings were drilled under the supervision of Rollins, Brown, and Gunnell for Utah County. Two of the four borings apparently penetrated into bedrock. The Committee did not inspect samples from these borings. Our interpretations of the information obtained are based on the drilling logs supplied by Rollins, Brown, and Gunnell. One boring was placed at each site and an open-tube (standpipe) piezometer was installed in each completed boring. Our summary logs are shown as RB&G-1 through RB&G-4.

Three borings were drilled under the supervision of Woodward-Clyde Consultants for the State of Utah. The Committee did not inspect samples from these borings. Two of the three borings apparently penetrated into bedrock. The third boring did not penetrate into bedrock because of extremely difficult drilling conditions. Piezometers were installed in each of the borings. Logs of the borings are shown as SH-1 through SH-3.

The quality of information obtained from all the borings is variable. In addition to the normal problems of bad weather and difficult access, squeezing ground, lost circulation, and weak geologic materials all contributed to poor sample recovery.

Most of the landslide debris is a gravelly clay derived from the North Horn Formation. This material would be difficult to sample under ideal conditions. As a result of poor sample recovery, the principal failure surface could not be identified in any of the borings. The locations of the failure surface as shown on the cross sections in Appendix C are based on the inference that bedrock was not involved in the landsliding. The evidence for selecting the depth to the failure surface is discussed in Appendix E.

Measurements of selected physical properties on the core samples are discussed in Soil Properties and In-Situ Conditions, p. 18.

DH-1.

Depth, ft	Description
0	Landslide debris, gravelly clay, gray, gravel fragments are predominantly claystone, sandstone, and limestone. Some fragments are cobble to boulder size. Gravel fragments appear to be derived from North Horn Formation. Contains scattered zones of red and reddish-brown gravelly clay. Contacts of different color zones are generally sharp
95	Zone of discontinuous small slickensides
130	Distinct color change from predominantly gray to predominantly reddish brown
210	Gravelly sandy clay, reddish brown, rounded gravel of quartzite and limestone in a matrix of sandy clay
219	Nugget Sandstone, tan to light gray with a few yellowish (oxidized) bands, well cemented, fine grained. Contains rounded fragments of quartzite and limestone in fractures near contact with overlying landslide debris
235	Highly fractured zone
239	Well-cemented and massive sandstone, color becomes white below 241 ft
270.5	Bottom of hole

DH-1A.--Instrumentation Hole

0	Landslide debris, gravelly clay No core to depth of 183 ft. Below 183 ft, landslide debris similar to that in DH-1
211	Mixture of landslide debris, alluvium, and fragments of Nugget Sandstone. Alluvium is rounded gravel and cobble-size quartzite and limestone. Appears to be a transitional contact to Nugget Sandstone
216.5	Nugget Sandstone, reddish brown at top and becomes lighter colored with depth, well cemented, fine grained. Lost drill fluid circulation at 231 ft --not regained
248	Bottom of hole Piezometers installed at 46, 85, 125, 162, 200, and 245 ft

DH-2.

Depth, ft	Description
0	Landslide debris, gravelly clay, reddish brown, gravel-size and larger fragments of claystone, sandstone, and limestone. Material predominantly derived from the North Horn Formation
60	Drilled through tree in landslide debris
95	Color changes to gray green, very stiff, mostly remolded claystone
98	Lost circulation for three minutes, regained circulation when casing advanced to 100 ft
106	Color change to reddish brown
140	Driller noted hole squeezing, large percentage of coarse fragments at 140 to 150 ft. Drill bit snagged at about 140 ft when it was brought up from 180 ft
220	Predominantly cobble-size fragments in clay matrix
256	Driller noted top of rock
259	Nugget Sandstone, tan to light gray, well cemented, fine grained. Began coring at 259 ft and already in sandstone. Bedding inclined about 50 ft
275	Lost circulation
289.5	Sandstone, blue gray, fine grained. Alternating gray and bluish-gray sandstone are a transitional zone to underlying Ankareh Formation
290	Regained about 10 percent of circulation
302	Ankareh Formation, dark red to maroon sandstone with scattered layers of gray to blue-gray sandstone, fine grained. Contains minor amounts of siltstone
	Contains soft claystone seams up to 1 ft thick at 321.5, 326.5, 329.5, and 332.7 ft. The seams dip at 40^{0} to 50^{0} and some are slickensided
335	3-ft zone that has slaked to fine sand
349	Bottom of hole

DH-2A.--Instrumentation Hole

Depth, ft	Description
0	Landslide debris, gravelly clay, brown to reddish brown, similar to materials from DH-2, no core obtained in landslide debris
180	Hole caved between 180 and 265 ft
243	Lost circulation
244	Basalt, black, fine grained. Identified by thin section of a sample. It is not known whether the basalt is part of a dike in Nugget Sandstone or a rock fragment resting on top of the Nugget Sandstone. Began coring at 244 ft
245	Nugget Sandstone, tan to light gray, well cemented, fine grained
277	Mudstone, blue gray, beginning of transition zone to underlying Ankareh Formation. Alternates with tan, fine-grained sandstone
292	Ankareh Formation, sandstone, dark red, fine grained
300	Bottom of hole. Piezometers installed at 23, 68, 153, and 295 ft

DH-3.

Depth, ft	Description
0	Landslide debris, gravelly clay, reddish brown, gravel fragments are mostly claystone and sandstone with minor limestone derived from North Horn Formation. A few slickensides present; debris is generally soft
28	Gravelly clay becomes very stiff
34	Difficult drilling, hole caving
60	Slickensides present here and at scattered locations deeper in the boring. Material is generally very stiff with scattered soft zones
174	Gravelly clay is soft to very soft. Locally drill could be advanced by pushing without rotation
217	Mixed very stiff and very soft zones, hole caving badly and squeezing casing. Drilling becomes more difficult with depth
240	Water flows out of casing at a rate of about 1 qt/min
249	Debris contains a smooth, water-worn pebble. Assumed that it was derived from a conglomerate in the North Horn Formation
250	Ankareh Formation, sandstone, light green, fine grained. Depth uncertain, core recovery was poor, but sample contained a fragment of bedrock
254	Bottom of hole. Drilling stopped because of difficult drilling conditions

DH-3A.--Instrumentation Hole

0	Landslide debris, gravelly clay, reddish-brown to gray and gray-green gravel fragments are sandstone, claystone, and limestone derived from North Horn Formation
185	Difficult drilling, hole squeezing
215	Lost circulation
230	Rods stuck in hole. Bottom of hole No piezometers placed in this hole

DH-4.

Depth, ft	Description
0	Landslide debris, gravelly clay, gray to brown, firm to stiff, gravel fragments are of claystone, limestone, and sandstone that were primarily derived from the North Horn Formation
70	Debris is somewhat softer below 70 ft
148	Sandy clay, reddish brown, apparently derived fro Ankareh Formation
163	Gravelly clay, gray to brown, derived from North Horn Formation. Severe caving of hole near contact with overlying debris derived from Ankareh Formation. Small amount of water flows from hole
168	Sheared zone, slickensides dip 47°. Abundant slickensides at 172 ft. Entire zone between 160 and 180 ft apparently has been sheared
190	Set casing to 190 ft to reduce caving. Hole squeezing, set casing to 238 ft
249	Base of landslide. Contact of gravelly clay with highly disturbed Ankareh Formation. Ankareh is highly weathered, bedding is near vertical below contact
254	Ankareh Formation, claystone and sandstone, dark red with gray inclusions
275	Lost circulation, regained about 30 percent of circulation at 278 ft
305	Bottom of hole

DH-4A.--Instrumentation Hole

0	Landslide debris, gravelly clay, similar to material from DH-4. Set casing to 230 ft
254	Ankareh Formation, claystone and sandstone, contact is approximate
273	Temporarily lost circulation
275	Bottom of hole. Piezometers set at 92, 115, 230, and 272 ft

DH-4B.--Inclinometer Hole

Depth, ft	Description
0	Landslide debris, gravelly clay, same as DH-4, started coring at 275 ft in Ankareh Formation
254	Ankareh Formation, position of contact approximate
298	Numerous slickensides on bedding planes in Ankareh Formation
303	Lost 80 percent of circulation
305	Bottom of hole

DH-5.

Depth, ft	Description
0	Landslide debris, gravelly clay, color is notably different than that in most other borings. Color is mostly tan, blue gray, and brown with minor amounts of dark red. Gravel fragments are claystone, limestone, and minor sandstone. Debris is firm to stiff
35	Lost circulation, set casing, began coring. Circulation return is poor when boring is advanced more than a few feet beyond casing
130	Boring squeezing drill string, slickensides in core at 130, 145, 150, and 155 to 164 ft. Water losses, squeezing, and caving ground result in poor core recovery to 187 ft
187	Drilling remains very difficult. Drilled to 249 ft with rock bit and set casing
245	Nugget Sandstone, tan to light gray, fine grained, highly jointed and fractured. Position of contact estimated from driller notes
277	Claystone, greenish gray, interbedded with sandstone, sheared, transitional zone between Nugget and Ankareh Formation. Fine-grained units are highly disturbed with scattered slickensides and gouge
283	Ankareh Formation, sandstone, fine grained, reddish brown to dark red. Contains scattered layers of claystone that typically contain slickensides
335.5	Bottom of hole

DH-5A.--Instrumentation Hole

0	Landslide debris, gravelly clay, same as in DH-5. Coring began in Nugget Sandstone. Location of contact uncertain because of recording error of depth
245	Nugget Sandstone
280	Bottom of hole. Piezometers set at 40, 90, 182, and 275 ft

DH-6.

Depth, ft	Description
0	Landslide debris, gravelly clay, mostly dark red to brown, gravel-size and larger fragments are claystone and sandstone. Based on color and partly on texture, much of the landslide debris was derived from the Ankareh Formation
59	17-ft zone of badly caving hole. Boring flowed water for 2 minutes at a rate of 1 gal/min
110	Began core samples. Silty clay, dark reddish brown, primarily derived from Ankareh Formation
128	Transitional zone from landslide debris and colluvium derived from Ankareh Formation to disturbed, but in-place Ankareh Formation
132	Ankareh Formation, sandstone, fine grained, dark red, well cemented. Contains a few soft seams of claystone
178	Bottom of hole

DH-6A.--Instrumentation Hole

0	Landslide debris, similar to DH-6, not cored
36	Thin, permeable layer in landslide debris, boring flowed water. Hole caved
90	Driller reported no gravel-size fragments in boring, drilling was noticably smoother
	After boring completed, it flowed between one and two pints of water per minute. Casing was broken at 70 ft, left uncased below 80 ft
130	Bottom of hole. Piezometers set at 25, 55, 85, and 120 ft

DH-7.

Depth, ft	Description
0	Landslide debris, gravelly clay, dark reddish brown to brown, firm to stiff. Gravel fragments are predominantly claystone and sandstone. Debris appears to be derived from North Horn Formation
32	Softer than above with very soft zones at 39 and 47 ft
49	Hole squeezing, drill fluid emerges about 10 ft west of bore hole. Hole cased but circulation lost as boring is advanced beyond casing
85	Slickensides in landslide debris. Casing advanced with drilling to reduce circulation losses. Drilling fluid emerges at ground surface near drill
111	Ankareh Formation, mudstone, claystone, and sandstone, dark red, disturbed and weathered in upper part and more massive with depth. Bedding dips about 20^{o} and contains several zones of slickensides.
157	Mudstone in Ankareh Formation, variegated reddish brown and purple. Highly fractured with many shear zones
188	Sandstone in Ankareh Formation, gray, red, and purple, massive, well cemented
209	Bottom of hole

DH-7A.--Instrumentation Hole

0	Landslide debris, gravelly clay, similar to material in DH-7, no core
31	Small amount of clear water flowed from hole. Drilling fluid surfaced near drill
109	Hole squeezing
111	Ankareh Formation, claystone, dark red to brown
140	Bottom of hole. Piezometers installed at 18, 32, 85, and 125 ft

DH-8.

Depth, ft	Description
0	Landslide debris, silty clay, stiff, color varies dramatically. Log of color changes prepared to illustrate extreme variation in color of debris with depth. Began coring at 10 ft

10-14 ft	purple
14-29	gray green
29-57	light gray green
57-62	brownish gray green
62-73	light greenish gray
73-92	dark green
92-98	reddish brown
98-101	green
101-112	tan
112-116	green
116-120	gray sandstone boulder
120-125	brown
132-186	reddish brown with pebbles of gray limestone and claystone
186-204	yellowish brown
204	dark red to maroon, transitional to bedrock

17	Lost circulation briefly
77	Squeezing ground, drilling fluid surfaces near drill
100	Prominent slickenside in core
186	Clayey sand, bright yellow brown, hole collapsing and squeezing, cased hole to 200 ft. Numerous slickensides below 175 ft
204	Siltstone, dark red to maroon with scattered small gray spots. Appears in part to be landslide debris but is entirely derived from Ankareh Formation. Material is transitional to Ankareh Formation
224	Ankareh Formation, siltstone, light red with scattered thin gray layers and blebs, steeply dipping, contains scattered slickensides
257	Sandstone and mudstone, fine grained, brownish red, contains small gypsum veins. Gypsum increases in abundance with depth. Gypsum occurs on joint surfaces and as vein-like ribbons up to 1/4 in. across
350	Bottom of hole

DH-8A.--Instrumentation Hole

Depth, ft	Description
0	Landslide debris, silty clay, similar to materials in DH-8. No core
195	Hole squeezing
210	Ankareh Formation, claystone, dark red, contact approximate
300	Bottom of hole. Piezometers installed at 55, 119, 170, 234, and 290 ft

DH-9.

Depth, ft	Description
0	Landslide debris, gravelly clay, reddish brown, firm. Gravel fragments are mostly claystone and limestone derived from the North Horn Formation
10	Drilling fluid surfacing near drill
20	Hole producing small amount of water
32	Initial hole abandoned, surfacing drill fluid creating soft ground and drill tilted. Began new DH-9 at nearby location, squeezing ground at 16 to 20 ft
59	Very soft zone
60	Ankareh Formation, claystone, dark red to purple, blocky structure, weathered, jointed, not greatly disturbed
73	Sandstone in Ankareh Formation, fine grained, light and dark red and gray, friable, dips 30^{o}
87	Mudstone in Ankareh Formation, purple
93	Sandstone, light red, to 128 ft is alternately highly sheared rubble with a few sections of intact rock
95	Claystone, dark red to purple
128	Sandstone, gray with errigular maroon-colored inclusions, fine grained
178	Bottom of hole Piezometers installed at 30, 60, and 121 ft

RB&G Boring P-1.

Depth, ft	Description
0	Landslide debris, gravelly clay, brown, soft to firm
63	Color change to red and gray
80	Debris is stiffer except for a soft zone above a boulder at 90 ft
107	Nugget Sandstone, white to tan, fine grained, well cementd
123.5	Bottom of hole Open-tube piezometer installed at 100 to 102 ft

RB&G Boring P-2.

0	Landslide debris, gravelly clay, brown, soft to firm
10	Color change to brown and gray
40	20-ft zone of very stiff gravelly clay
60	Debris becomes firm
79	Color change to red gravelly clay with numerous cobbles and boulders
90	Red and gray gravelly clay, very stiff
210	Began coring, material is very stiff gravelly clay
245	Alluvium, gravel, cobbles and boulders
284	Bottom of hole. Open-tube piezometer installed to bottom of hole. Failure surface not identified

RB&G Boring P-3.

Depth, ft	Description
0	Landslide debris, gravelly clay, brown, firm to soft
9	Color change to gray green
25	Color change to brown
45	Color change to light brown
55	Becomes very stiff
75	Color change to light purple
99	Color change to brown
139	Debris becomes more sandy, distinctly softer between 145 and 160 ft
165	Soft zone at 165 ft
217	Red clay
225	Bottom of hole. Open-tube piezometer installed. Soft zones are possible failure zones; principal failure surface slightly below bottom of hole

RB&G Boring P-4.

0	Landslide debris, clay, brownish green, firm to soft
9	Gravelly clay, brown, soft, very soft zone at 30 ft
76	Silty clay, black
79	Sandy, gravelly clay, brown, soft at top, stiffer with depth
105	Gravelly, sandy clay, reddish-brown, stiff except for a soft zone at 120 ft
189	Nugget Sandstone, white to tan, fine grained, well cemented
192	Bottom of hole. Open-tube piezometer sealed at bottom of hole. Principal failure surface assumed to be at bedrock contact

SH-1.

Depth, ft	Description
0	Landslide debris, gravelly clay, grayish brown to brown, firm
77.5	Casing binds in hole
130	Zone of very sticky clay above a concentration of large rocks
150	Water-saturated gravel containing some railroad ballast, difficult drilling
169	Alluvium, clean water-saturated gravel
172.5	Nugget Sandstone, buff to white, closely spaced fractures, longest piece of core was 18 in.
193	Bottom of hole. Piezometer sealed between 161 and 171 ft. Failure surface appears to be at about 169 ft

SH-2.

0	Landslide debris, gravelly clay, red, firm
95	Distinctly softer zone in red gravelly clay
106	Sandstone boulder
145	Talus, angular rock fragments of red and gray to white sandstone. Intermixed red clay with rock fragments. A 4.5-ft interval of very plastic, red gravelly clay was directly on bedrock
208	Nugget Sandstone, white, very hard, fractured
225	Bottom of hole. Piezometers installed in depth intervals of 57 to 67 ft and 183 to 193 ft

SH-3.

Depth, ft	Description
0	Landslide debris, clay, red
5	Clay, black, organic odor
20	Gravelly clay, brown, sticky, difficult drilling
40	Free water in boring. Hole was redrilled at least twice and finally drilled to 50 ft with hollow-stem augers. Hole could not be advanced deeper because of squeezing ground
50	Bottom of hole. Piezometers installed in depth intervals of 20 to 30 ft and 39 to 45 ft. Boring did not reach principal failure surface at base of landslide

APPENDIX E

GEOLOGIC DESCRIPTION OF BORINGS DH-1 THROUGH DH-9

Core samples from boreholes DH-1 through DH-9 were inspected and logged by the Thistle Slide Committee. In addition, the Committee was provided driller's logs, summary logs by Northern Engineering and Testing, Inc., and geologic logs prepared by Dr. Irving J. Witkind of the U.S. Geological Survey. Although core recovery was poor, particularly in critical sections of the corings, every boring penetrated through the surficial deposits and into bedrock. Summary logs of all the borings are presented in Appendix D.

The Committee has used the collective information on boreholes DH-1 through DH-9 to help answer four fundamental questions about the Thistle landslide. These are:

1. What is the source of the debris in the Thistle landslide?

2. Is bedrock involved in the landslide?

3. What is the cross-sectional shape of the landslide?

4. What is the shape of the failure surface in the floor of Spanish Fork Canyon?

Our interpretations of the geology of the area are reflected in the maps and cross sections given in Appendix C.

Source of the Debris--The principal source of the debris in the Thistle landslide is the North Horn Formation. Witkind has extensive experience mapping the materials exposed in the vicinity of the Thistle landslide including the North Horn Formation. In his examination of core samples (Witkind, written commun, 1985), he identified debris from the North Horn Formation as the primary landslide constituent in all the borings except parts of DH-4, DH-6, and perhaps part of DH-8. An interval of Ankareh-like debris was found in DH-4 between 148 and 163 ft. In DH-6, debris from the Ankareh Formation is the primary constituent with minor amounts of debris from the North Horn Formation. Specifically, the debris above 90 ft in DH-6 was a mixture of North Horn and Ankareh Formations. Below 90 ft, the debris appeared to be entirely derived from Ankareh Formation. In DH-8, an 18-ft-thick layer of yellowish-brown, clayey sand is of uncertain origin, but probably is not from the North Horn Formation. All the other debris appeared to be derived from the North Horn Formation.

The main part of the landslide is underlain by Ankareh Formation and, in the floor of Spanish Fork Canyon, by Nugget Sandstone (see plate 2, geologic map, and plate 3, cross section). North Horn Formation is exposed in the topographic basin at and above the extreme western end of the landslide. Thus, it can be concluded that debris from the North Horn Formation has been transported, primarily by sliding and earth flow, into a pre-existing valley cut in Ankareh Formation. Minor amounts of Ankareh Formation and Nugget Sandstone were incorporated into the North Horn debris by rockfalls, debris slides, and debris flows along the flanks of the Thistle landslide.

Role of Bedrock in the Landslide--There are at least six observations that suggest bedrock was not transported by the landsliding. There are, however, two observations that suggest failure of intact bedrock might have been involved and perhaps should be investigated further. Evidence supporting failure within the surficial deposits and on top of bedrock included the following:

1. Driller's notes and engineer's field logs repeatedly reported difficult drilling conditions. The reports generally pertained to drilling in the surficial deposits. When the borings reached bedrock, drilling generally went more smoothly.

2. Core samples of the bedrock revealed that it was generally intact. There was some evidence of minor faulting in the bedrock. However, the bedrock did not appear to have undergone deformation consistent with 500 ft of displacement.

3. Where the bedrock contact between the Ankareh Formation and the Nugget Sandstone was encountered in the borings, the contact was in the location that it should be. The contact is exposed outside both flanks of the landslide and dips toward the floor of the canyon at about 40°. Drill holes DH-1 through DH-5 encountered the expected formations at the expected locations. In particular, the presence of the Nugget Sandstone overlying Ankareh Formation in DH-1, DH-2, and DH-5 strongly suggests that the bedrock in this area of the landslide has not been significantly displaced.

4. The slickensided surfaces on core samples of bedrock dipped more steeply than a projected failure surface would dip in the bedrock. The range of dips of slickensides was about 20° to 60°. The dip of the base of the landslide should be 12° or less. Therefore, the steeper dips are more indicative of minor tectonic structures than landsliding in the bedrock.

5. In the floor of Spanish Fork Canyon, there is little room for a toe of movement that involves significant amounts of bedrock. The record of movement during mid-April, 1983, suggests that debris was pushed across the floor of the canyon rather than emerging on a steeply curved failure surface.

6. Near coordinates N605750 and E1997400 (plate 2) in the upper part of the landslide, the Ankareh Formation was exposed in the floor of a gully. There, a layer of slickensided gouge was observed to rest directly on bedrock. The bedrock was soft and weathered but not visibly remolded.

One observation that bedrock might be involved in landslide movement is contained in table 4. The evidence is related to measurements of tilt in the inclinometer borings. In several cases it was not possible to lower the inclinometer the full depth of the inclinometer casing. Drill holes DH-2, DH-4, DH-6, and DH-9 were all blocked below the expected position of the base of the landslide, but above the reported bottom of the inclinometer casing. The causes of the blockages, which were in the bedrock portions of the borings, are unknown. Currently, the blockages are not thought to be at the principal failure surface of the landslide. However, this conclusion should be reviewed as further evidence develops.

The other observation that bedrock may be involved in the landslide is in a photograph in Sumsion (1983, p. 37) and described in Surficial Features, p. 13. In the narrow part of the landslide, downslope from the bend, previously intact Ankareh Formation has been fractured by landslide movement.

The Cross-Sectional Shape of the Landslide--The main part of the landslide, extending from coordinate N604800 and E1996100 to N607700 and E1999400 (see plate 2), follows the strike of the Ankareh Formation. Along this reach, the Ankareh Formation dips toward the southwest at about 40^o. Because the bedrock appears to influence the shape of the landslide, the landslide should be thicker in the downdip (southwest) direction. This interpretation is supported by the geologic units shown on cross section C-C' (plate 5) and a comparison of longitudinal sections A-A' and B-B' (plates 3 and 4).

There is uncertainty in the location of the failure surface in the vicinity of DH-6 on cross section C-C' (plate 5). Difficult drilling conditions occurred within colluvium between depths of 60 and 90 ft. Bedrock was encountered at 132 ft. The cross section C-C' was drawn assuming that the failure surface was at the top of the bedrock. It is certainly possible that the failure surface is more shallow and somewhere above 90 ft. If so, the shape of the failure surface would be a crude assymetrical triangle.

Shape of the Failure Surface in the Floor of Spanish Fork Canyon--The lower part of the landslide, downslope from coordinates N607700 and E1999400 (plate 2), turns at the bend from following the strike direction to following the dip direction of the underlying Ankareh Formation. There, the failure surface is relatively U-shaped and dips about 2^o easterly toward the canyon floor. The modest relief on the failure surface (plate 3) could indicate the location of the thalweg of a buried valley in the Ankareh Formation. All of the borings in the Thistle landslide except RB&G-2 indicate a simple landslide geometry. RB&G-2 penetrated alluvium below the estimated position of the failure surface. The implications of the presence of this alluvium are discussed in Appendix C.

APPENDIX F

DIRECT SHEAR TEST PROCEDURES AND TEST RESULTS

The following procedures for direct shear testing were outlined in a letter from Committee member Patton to Mr. Robert L. Morgan dated May 10, 1985.

Type of Tests--The tests should be drained, direct shear strength tests conducted on remolded soil. The object is to determine the angle of residual frictional resistance uninfluenced by excess fluid pressures that may tend to develop during the test.

The methods described in this section are not standard ASTM testing methods. However, these methods have been employed in studies of major slides in North America and elsewhere over the past 10 to 15 years.

Sample Preparation--The samples should be passed through a #40 seive to remove all particles retained by the sieve. If the samples are allowed to dry, water should be added to bring the soil to a consistency near the plastic limit, and the sample should be allowed to equilibrate for 2 to 4 days before proceeding.

Testing Conditions--A relatively thin layer of the sample should be placed in the direct shear box with a porous stone above and below the sample. The test should be conducted so that the sample will remain saturated throughout the test. The sample should be subjected to a vertical load that would be on the order of 100% or more of the estimated vertical stress level on the sample before it was recovered by coring. The consolidation of the sample under the maximum vertical stress should be measured vs time and the data used to determine the rate of shear displacement.

A series of four tests should be run on each sample. Each of these tests should be made under approximately the following vertical stress levels:

Test	(a)	300 psi
	(b)	150 psi
	(c)	75 psi
	(d)	25 psi

Following loading, a horizontal shear plane may be precut in the sample with a wire knife. Precutting should reduce the amount of shearing displacement required to reach the residual value of shearing resistance.

The rate of shearing is generally calculated using standard methods from the consolidation data. Alternatively, one may simply use the next to slowest rate available on the machine. During shearing, it is desirable to have a continuous record of the vertical displacements of the sample (preferably in 4 locations, that is, 4 corners of the sample) as well as of the horizontal displacements. The vertical displacements can serve to help correct the results for the effect of non-horizontal movements of the upper shear platform and to help recognize non-representative results should large particles interfere with platen movements. When a minimum equilibrium (residual) shear strength has been obtained under a given rate of displacement, the rate of displacement should be increased 10 to 100 times and the shearing resistance is recorded for several minutes. Following this, the rate is decreased from the original for several minutes or longer if required. These increases and decreases in shearing rates serve to provide positive evidence that the rate selected for the primary testing was correct and was uneffected by excess pore water pressures.

If the displacements required to achieve the residual value exceed the capacity of the machine, then the test must be stopped and the direction of shear displacement reversed.

When the tests are complete for each vertical load increment, the load is reduced and the test is continued for the next lowest vertical stress. Tests at four levels of vertical stress constitute the series of tests required for each sample.

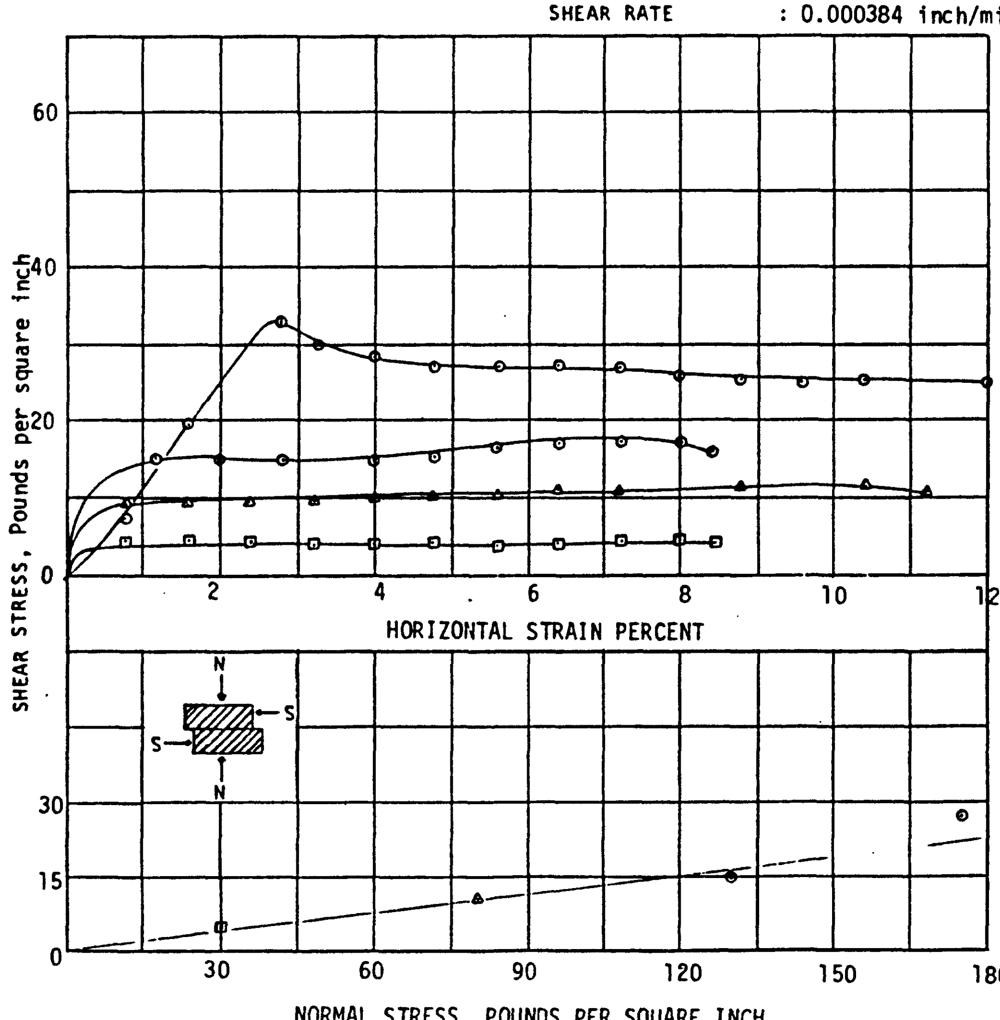
Sample Description and Clay Mineral Analyses--When the series of tests are completed on each sample, the failure plane should be described, if this is possible. At this time a small soil sample should be selected from the center of the failure plane and the water content of this sample should be determined. It would also be desirable to have a clay mineral analyses completed on at least three of the samples. The material for these analyses should be taken from the failure plane of the sample used in the direct shear strength test.

Plots--Plots of shearing resistance recorded vs normal stress should be provided for each sample. These results should be accompanied by the complete set of lab data sheets including the plots of shear strength vs vertical and horizontal displacement obtained during the laboratory testing.

DIRECT SHEAR TEST

DRILL HOLE: 3
DEPTH: 38.5 - 39.5
SAMPLE NO.: 3000

MOIST UNIT WEIGHT: 120.8 pcf
DRY UNIT WEIGHT : 90.1 pcf
MOISTURE CONTENT : 34.0%
CLASSIFICATION :
FRICTION ANGLE :
COHESION INTERCEPT:
SHEAR RATE : 0.000384 inch/minute



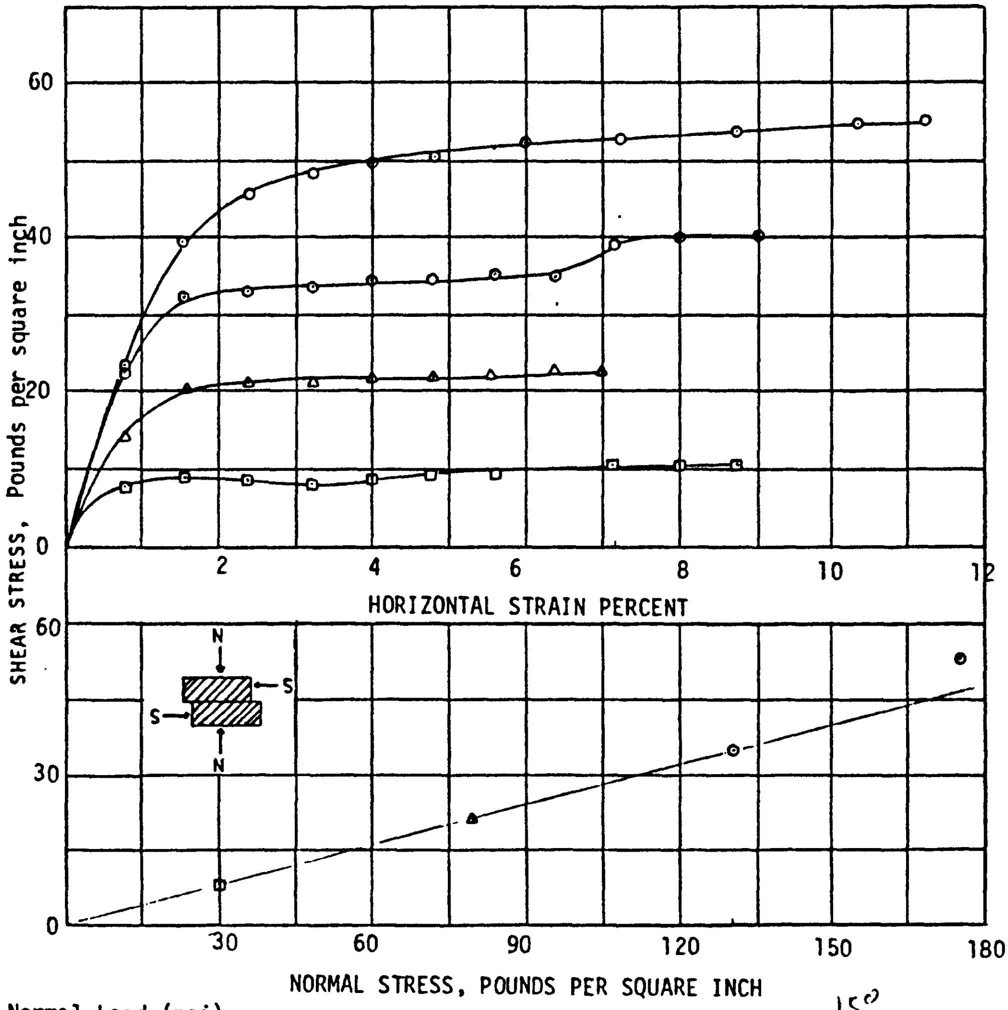
Normal Load (psi)
- ⊙ 175
- o 130
- Δ 80
- □ 30

Thistle Slide Direct Shear Tests Thistle, Utah	Northern Engineering and Testing, Inc. Figure 9
State of Utah - Division of Water Rights Salt Lake City, Utah	JOB NO. 85-2368 PLATE NO. 1

DIRECT SHEAR TEST

DRILL HOLE: 4
DEPTH: 233.5 - 235.5
SAMPLE NO.: 3018

MOIST UNIT WEIGHT: 129.7 pcf
DRY UNIT WEIGHT : 102.1 pcf
MOISTURE CONTENT : 27%
CLASSIFICATION :
FRICTION ANGLE :
COHESION INTERCEPT:
SHEAR RATE : 0.00048 inch/minute



Normal Load (psi)

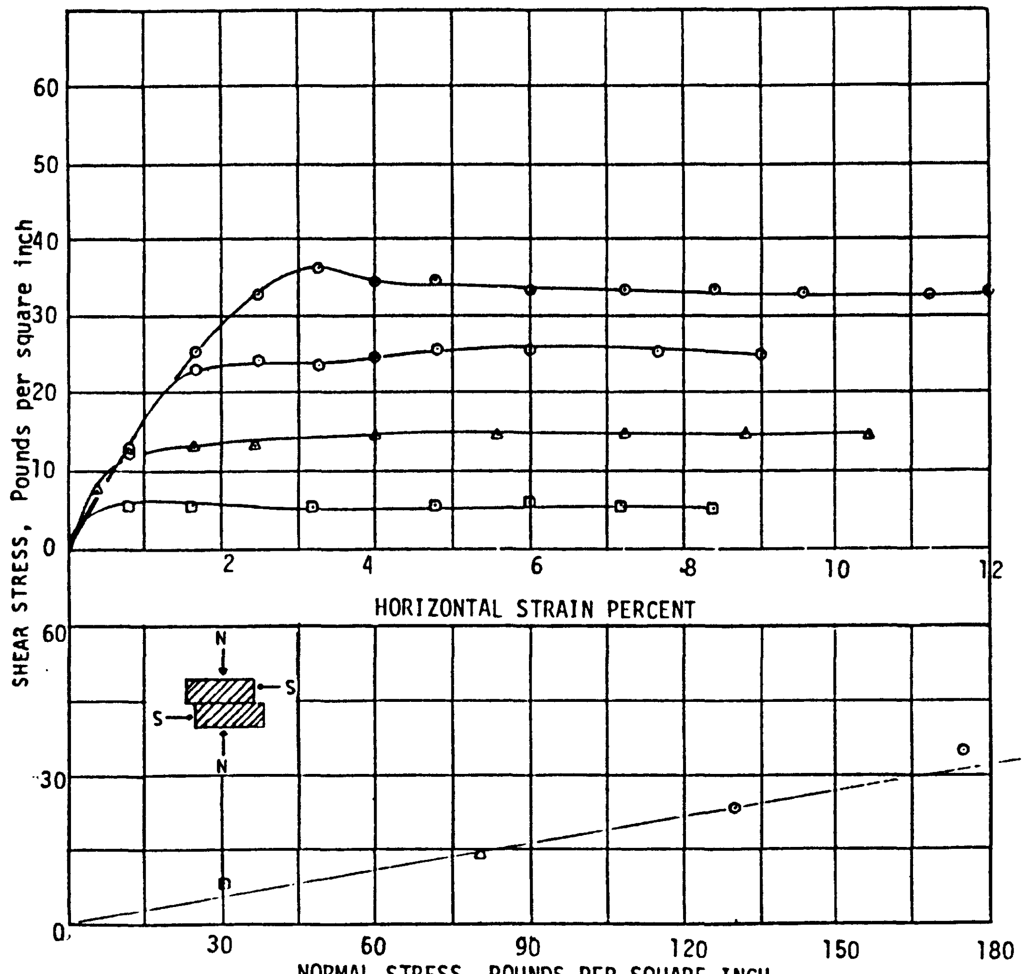
- o 175
- o 130
- △ 80
- □ 30

Thistle Slide Direct Shear Tests Thistle, Utah	Northern Engineering and Testing, Inc — Figure 10
State of Utah - Division of Water Rights Salt Lake City, Utah	JOB NO. 85-2368 PLATE NO. 3

DIRECT SHEAR TEST

DRILL HOLE: 8
DEPTH: 11.5 - 12.5
SAMPLE NO.: 3020

MOIST UNIT WEIGHT: 128.3 pcf
DRY UNIT WEIGHT : 99.1 pcf
MOISTURE CONTENT : 29.4%
CLASSIFICATION :
FRICTION ANGLE :
COHESION INTERCEPT:
SHEAR RATE : 0.000384 inch/minute



Normal Load (psi)

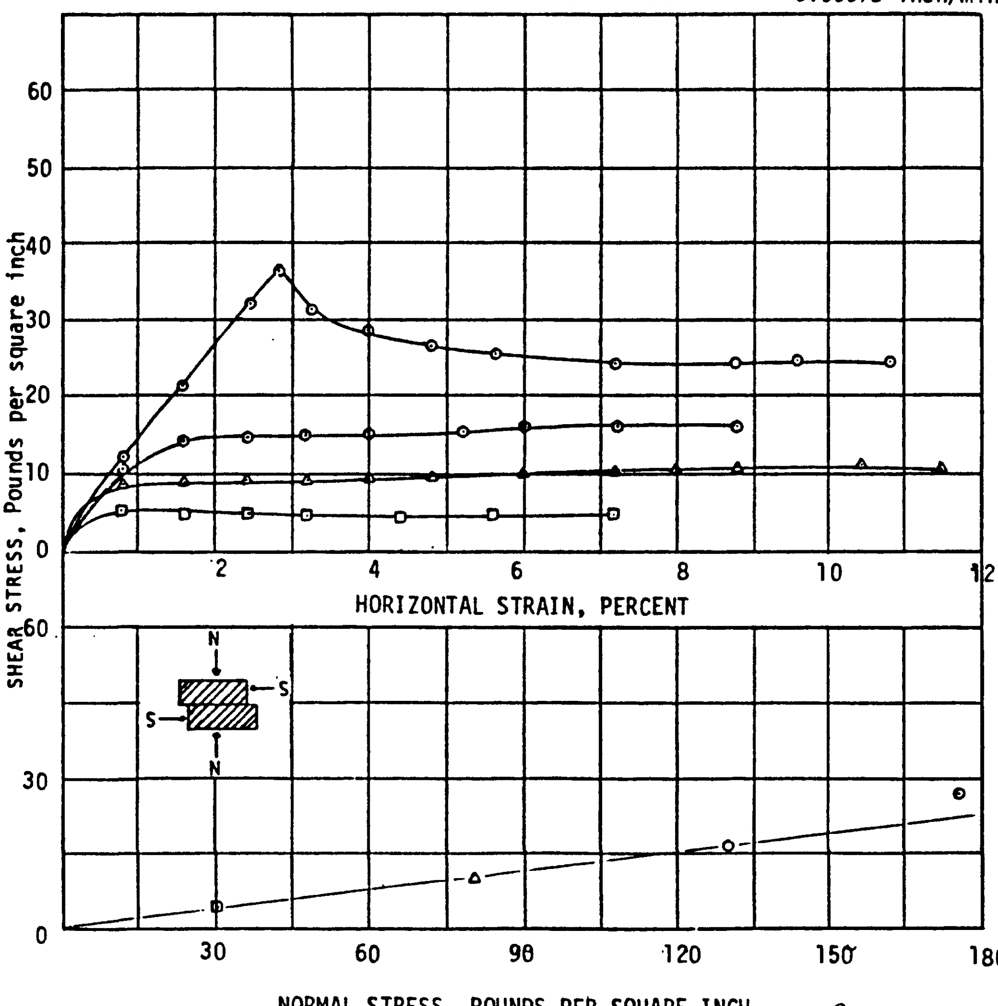
- o 175
- O 130
- Δ 80
- □ 30

Thistle Slide Direct Shear Test Thistle, Utah	Northern Engineering and Testing, Inc. Figure 11
State of Utah - Division of Water Rights Salt Lake City, Utah	JOB NO. 85-2368 PLATE NO. 5

DIRECT SHEAR TEST

DRILL HOLE: 8
DEPTH: 114.5 - 115.5
SAMPLE NO.: 3027

MOIST UNIT WEIGHT: 121.7 pcf
DRY UNIT WEIGHT : 91.8
MOISTURE CONTENT : 32.6%
CLASSIFICATION :
FRICTION ANGLE :
COHESION INTERCEPT:
SHEAR RATE : 0.00078 inch/minute



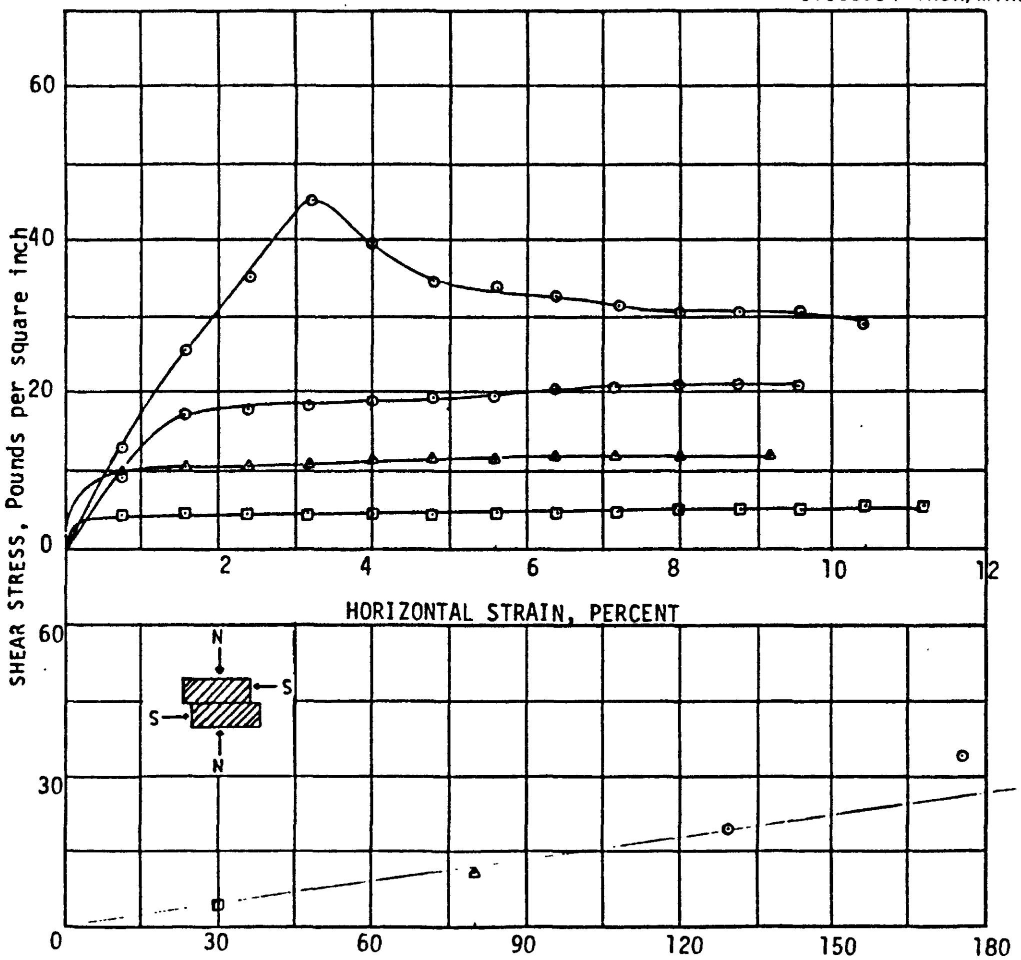
Normal Load (psi)
○ 175
○ 130
△ 80
□ 30

Thistle Slide Direct Shear Test Thistle, Utah	Northern Engineering and Testing, Inc. Figure 12
State of Utah - Division of Water Rights Salt Lake City, Utah	JOB NO. 84-2368 PLATE NO. 7

DIRECT SHEAR TEST

DRILL HOLE: 7
DEPTH: 103.0 - 104.0
SAMPLE NO.: 3037

MOIST UNIT WEIGHT: 117.5 pcf
DRY UNIT WEIGHT : 87.0 pcf
MOISTURE CONTENT : 35.0%
CLASSIFICATION :
FRICTION ANGLE :
COHESION INTERCEPT:
SHEAR RATE : 0.000384 inch/minute



X.4

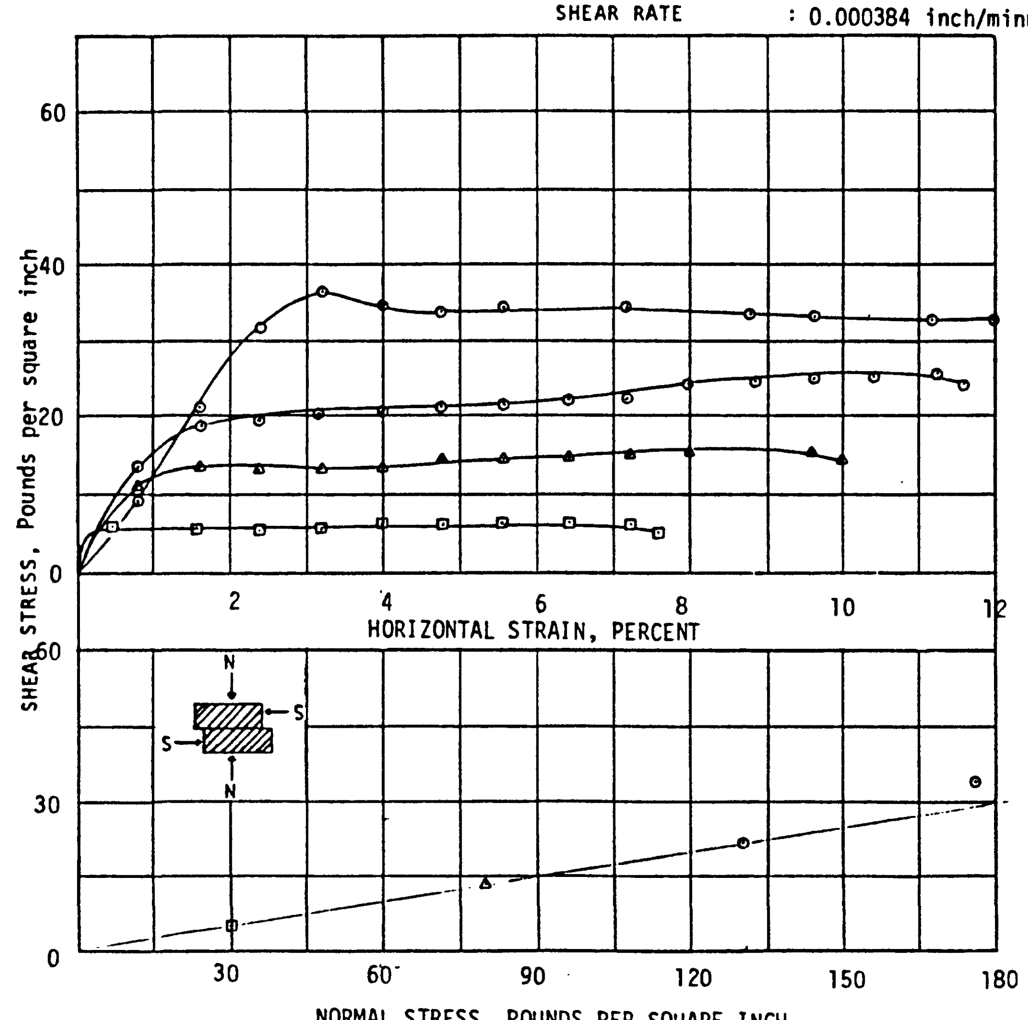
Normal Load (psi)
- ○ 175
- ○ 130
- △ 80
- □ 30

Thistle Slide Direct Shear Test Thistle, Utah	Northern Engineering and Testing, Inc. Figure 13
State of Utah - Division of Water Rights Salt Lake City, Utah	JOB NO. 85-2368 PLATE NO. 9

DIRECT SHEAR TEST

DRILL HOLE: 8A
DEPTH: 20.0 - 22.0
SAMPLE NO.: 3057

MOIST UNIT WEIGHT: 124.9 pcf
DRY UNIT WEIGHT : 97.1 pcf
MOISTURE CONTENT : 28.6%
CLASSIFICATION : --
FRICTION ANGLE : --
COHESION INTERCEPT: --
SHEAR RATE : 0.000384 inch/minute



9.5°

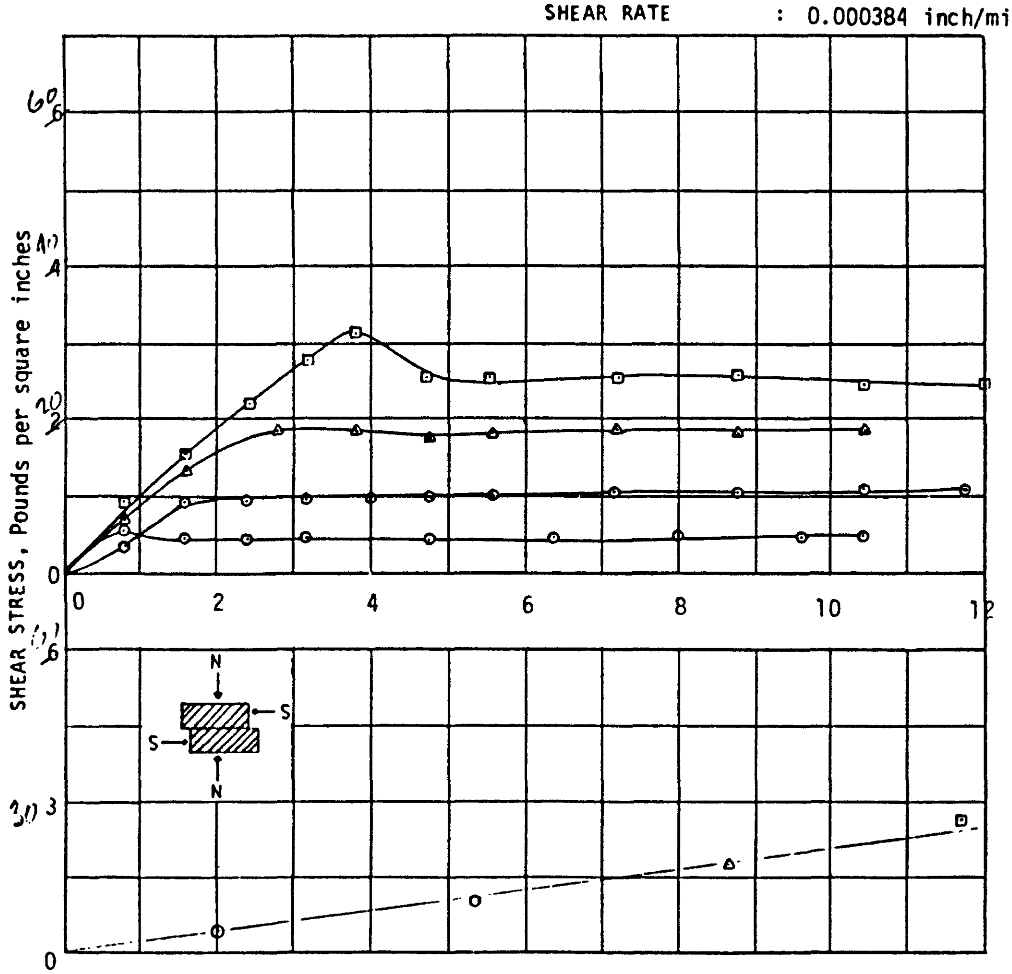
Normal Load (psi)
- ⊙ 175
- ○ 130
- △ 80
- □ 30

Thistle Slide Direct Shear Tests Thistle, Utah	Northern Engineering and Testing, Inc. Figure 14
State of Utah - Division of Water Rights Salt Lake City, Utah	JOB NO. 85-2368 PLATE NO. 11

DIRECT SHEAR TEST

DRILL HOLE: 8
DEPTH: 176.3 - 176.8
SAMPLE NO.:

MOIST UNIT WEIGHT: 125.1 pcf
DRY UNIT WEIGHT : 97.0 pcf
MOISTURE CONTENT : 29%
CLASSIFICATION :
FRICTION ANGLE :
COHESION INTERCEPT:
SHEAR RATE : 0.000384 inch/minute



Normal Load (psi)
o 30
o 80
△ 130
□ 175

7.8°

Thistle Slide Direct Shear Tests
Thistle, Utah

State of Utah - Division of Water Rights
Salt Lake City, Utah

Northern Engineering and Testing, Inc.

Figure 15

JOB NO. 84-2368 PLATE NO. 13

APPENDIX G

PRESSURE HEAD, GROUNDWATER, AND LAKE WATER DATA

Table 5

Piezometer Data — Thistle Slide

PSI

	DH-1						DH-2				DH-4			
WELL CAP ELEV						5239				5248				5251
DATE	46	85	125	162	200	246	23	68	153	295	92	115	230	272
INITIAL	14.7	32.1	55.4	63.8	75.5	13.5	4.3	28.6	69.9	31.3	66.0	67.0	152.2	62.5
16,17,18 DEC 84	9.2	28.9	54.7	83.1	*	13.5	1.3	31.7	71.2	30.8	49.0	63.0	153.5	67.4
15 JAN 85	7.9	29.3	58.4	98.7	0*	13.5	0.6	32.4	73.4	30.7	55.3	75.5	153.6	62.9
21 22 FEB 85	6.7	*	57.7	99.3	*	13.7	0.3	33.2	75.0	31.3	55.2	73.6	153.1	66.2
26 28 MAR 85	5.8	29.1	57.8	73.2	*	13.7	0.0	33.3	70.6	30.5	55.3	73.3	152.3	66.3
9 10 APR 85	5.7	29.3	60.0	73.2	*	13.5	0.2	33.3	70.5	30.9	55.1	72.8	152.7	66.4
24 25 APR 85	5.5	29.4	57.7	72.8	91.5	13.7	0.1	33.4	70.6	30.7	55.0	72.5	152.0	66.3
8 9 MAY 85	5.5	29.5	60.1	73.2	93.2	13.6	0.3	33.4	70.7	30.8	54.9	72.5	151.8	66.1
11,12,13 JUNE 85	4.7	29.5	60.2	73.2	91.4	13.4	0.2	33.4	70.3	30.5	55.2	72.6	151.6	65.9
8, 12 Aug 85	4.8	29.9	60.3	73.2	99.7	13.0	0.3	33.9	70.7	30.5	59.7	71.3		65.8

	DH-5				DH-6				DH-7				DH-8					DH-9		
WELL CAP ELEV				5249				5449				5449					5370			5494
DATE	40	90	182	275	25	55	85	120	18	32	85	125	55	119	170	234	290	30	60	121
INITIAL	4.5	45.5	82.5	17.5	8.5	33.3	45.8	54.7	10.4	18.9	36.3	31.8	12.0	51.5	55.6	66.5	45.6	11.1	25.0	52.9
16,17,18 DEC 84	4.4	43.2	81.1	17.2	10.8	31.5	44.5	53.2	10.3	18.1	43.3	31.8	12.0	51.5	55.6	66.5	45.6	1.8	23.4	52.6
15 JAN 85	4.3	43.6*	81.7	17.4	11.1	31.2	44.6	54.0	10.0	18.1	41.8	32.5	7.2	47.5	49.3	65.5	128.2	1.7	23.6	56.9
21 22 FEB 85	*	43.9*	81.3	17.3	11.4	31.3	45.1	53.9	9.9	17.7	42.6	32.9	5.6	54.7	47.8	66.3	124.2	1.7	23.9	57.1
26 28 MAR 85	4.2	43.8*	80.8	17.1	11.7	31.8	45.6	53.7	9.8	17.6	42.9	33.2	4.7	55.2	47.1	66.4	123.9	1.9	23.9	57.0
9 10 APR 85	4.2	43.9*	80.7	17.0	11.5	31.9	45.6	53.8	9.6	17.3	42.9	33.2	4.2	55.3	47.0	66.1	121.4	1.6	23.9	57.1
24 25 APR 85	4.4	43.9*	80.4	16.8	11.5	32.0	45.7	53.9	9.5	17.1	42.9	33.4	3.9	55.3	46.7	66.2	120.7	1.7	23.8	57.2
8 9 MAY 85	4.3	43.7*	80.4	16.9	11.5	32.1	45.9	53.9	9.7	17.1	43.0	33.4	3.9	55.2	46.5	66.2	120.4	1.7	22.0	57.2
11,12,13 JUNE 85	4.1	43.5	78.8	16.6	11.2	32.1	45.9	54.0	9.7	16.6	43.0	33.6	3.3	55.0	46.1	66.1	119.2	1.5	24.0	57.6
8, 12 Aug 85	4.1	43.6	79.3	16.4	11.2	31.6	45.4	54.3	9.9	16.7	43.3	34.0	3.0	59.8	45.7	66.4	117.3	1.6	23.8	57.5

* MISSING OR SUSPECT READING

Table 6

Piezometer Data - Thistle Slide

FEET OF WATER	DH-1						DH-2				DH-4			
WELL CAP ELEV	5239						5248				5251			
DATE	46	85	125	162	200	246	23	68	153	295	92	115	230	272
INITIAL	34	74	116	159	174	31	10	66	115	72	101	155	346	158
16,17,18 Dec 84	21	67	126	192	*	31	3	73	164	71	113	165	354	155
15 JAN 85	18	68	135	228	0*	31	1	75	169	71	128	174	354	154
21,22 FEB 85	15	*	138	229	*	32	1	77	173	72	128	170	354	154
26,28 MAR 85	13	68	138	169	*	32	0	77	163	71	128	169	352	153
9,10 APR 85	13	68	139	169	*	31	0.5	77	163	71	127	168	352	153
20,25 APR 85	13	68	138	168	211	32	0	77	163	71	127	167	351	153
8,9 MAY 85	13	68	139	169	215	31	1	77	163	71	127	167	351	153
11,12,13 JUNE 85	11	68	139	169	211	31	.5	77	162	70	128	168	350	152
9,12 Aug 85	11	62	139	169	219	30	.7	77	163	70	126	165	348	152

FEET OF WATER	DH-5				DH-6				DH-7				DH-8					DH-9		
WELL CAP ELEV	5249				5449				5449				5370					5494		
DATE	40	90	182	275	25	55	85	120	18	32	85	125	55	119	170	234	290	30	60	121
INITIAL	10	105	190	40	20	77	106	126	24	44	84	73	28	119	123	153	336	26	58	127
16,17,18 Dec 84	10	100	187	40	25	73	103	123	24	42	100	73	28	119	122	153	336	4	54	131
15 JAN 85	10	101*	188	40	26	72	105	125	23	42	96	75	17	110	114	151	296	4	54	131
21,22 FEB 85	*	101*	188	40	26	72	104	124	23	41	98	76	13	126	110	153	287	4	55	132
26,28 MAR 85	10	101*	187	40	27	73	105	124	23	40	99	77	11	128	109	153	282	4	55	132
9,10 APR 85	10	101*	186	29	27	74	105	124	22	40	99	77	10	128	109	153	280	4	55	132
20,25 APR 85	10	101*	186	39	27	74	106	125	22	40	99	77	9	128	108	153	279	4	55	132
8,9 MAY 85	10	101*	186	39	27	74	106	125	22	40	99	77	9	128	107	153	[illegible]	4	55	132
11,12,13 JUNE 85	9	100*	184	38	26	74	106	125	22	38	99	78	8	127	106	153	275	3	55	133
9,12 Aug 85	9	101	183	38	26	73	105	125	23	39	100	79	7	127	106	153	272	4	55	133

FEET OF WATER = 2.31(P.S.I.)

* MISSING OR SUSPECT READING

TABLE 7.--Groundwater temperatures measured near Thistle slide

[Source: State of Utah Division of Water Rights]

Date	Test Site	Water Temp.	Weather	Comments
9/29/83	Castilla Hot Springs	101° F	Cloudy/windy	Test taken where spring comes from hill
9/29/83	"D" Cafe	66° F	Cloudy/windy	Tap water
9/29/83	Lowdermilk batch Plant well	79° F	Cloudy/windy	Taken from tap on trailer
9/29/83	Thistle Lake water	60° F	Overcast/windy	Taken from entrance to overflow
9/29/83	Sandstone Warm Springs	86° F	Overcast/windy	Taken from end of drain tunnel in small pool
9/29/83	Seepage into drain tunnel 1,600 ft	68° F	Overcast/windy	Taken from weep hole 1,600 ft
9/29/83	Seepage into drain tunnel 2,200 ft	64° F	Overcast/windy	Taken from weep hole 50 ft behind bulkhead
9/29/83	Upper slide drain water	63° F	Overcast	Taken from surface ditch
9/29/83	State test hole #3 Red Cap	58° F	Overcast	Hard to get good sample
9/29/83	State test hole #3 standpipe	56° F	Overcast	Hard to get good sample

TABLE 8.--Thistle water temperatures and analyses for samples taken Sept. 29, 1983

[Source: Utah County Engineering]

Parameter	Thistle Lake water	Upper slide surface water	State test hole #3 south	State test hole #3 redcap	Seepage drain tunnel bulk head	Seepage from end of drain tunnel	Sandstone warm spring end of tunnel	Lowdermilk batch plant	D. Cafe tap water	Castilla Hot Springs S. F. Canyon
Temperature (^{o} F)	60^{o}	63^{o}	56^{o}	58^{o}	64^{o}	68^{o}	86^{o}	79^{o}	66^{o}	101^{o}
Alk. (tot) as $CaCO_3$*	243	277	386	890	181	105	180	315	231	331
Bicarbonate as HCO_3*	296	338	470	479	221	128	220	384	282	403
Calcium as Ca*	65	52	173	48	64	81	113	110	90	231
Carbonate as CO_3*	<0.1	<0.1	<0.1	22	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Chloride as Cl*	32	131	385	16	76	103	1881	1891	201	886
Conductivity (25^{o} C)**	625	1133	2198	1133	721	727	6937	6866	1326	4979
Hardness as $CaCO_3$*	332	384	836	521	255	304	408	386	326	785
Hydroxide as OH*	<.02	<.03	---	<.03	<.01	<.01	<.01	<.01	<.01	<.01
Magnesium as Mg*	41	62	98	97	23	25	31	27	24	51
pH	8.25	8.30	7.75	8.39	8.01	7.55	7.52	7.32	7.49	7.15
Potassium as K*	3.2	7.5	31	1.1	7.2	7.5	6.9	35	7.4	72
Sodium as Na*	38	147	183	86	85	53	1380	1368	176	940
Sulfate as SO_4*	100	205	265	120	145	445	400	95	1150	
Total Diss. Solids*	390	700	1431	712	436	472	4332	4438	740	3467

* (mg/l) milligrams per liter
** (µS/cm)

Legend

Geology from boring logs provided by Northern Engineering and Testing, Inc.

A Clay, Silty; very stiff, moist to wet, med. plast., red brown, soft zones

B Clay, Gravelly; stiff, moist, med. plasticity, gray to red brown,

C Clay, Sandy; firm to hard, moist, low plasticity, brown, colluvium?

D Gravel; gravel, cobbles and boulders

E Claystone; soft to mod hard, red brown, very soft seams with slickensides

F Sandstone; well cemented, fine grained, thick bedded to massive, tan to gray

G Shale; Claystone; soft to mod. hard rock, gray to purple, highly jointed

GRAPHIC SYMBOLS

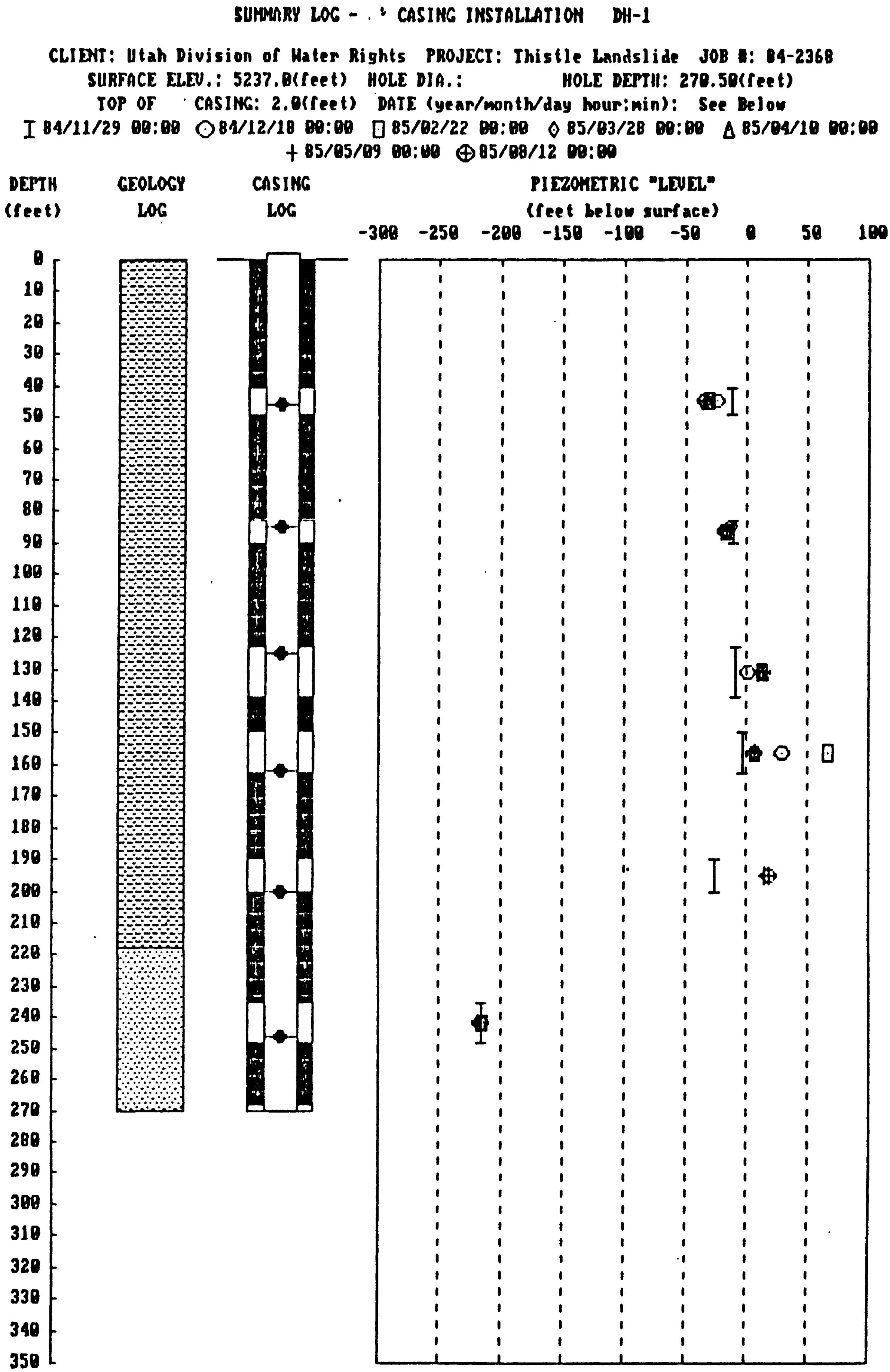
PIEZOMETER

measurement interval

DRILL HOLE SEAL

Client: Utah Division of Water Rights
Project: Thistle Landslide

Figure 16



SUMMARY LOG - CASING INSTALLATION DH-1
CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
SURFACE ELEV.: 5237.0(feet) HOLE DIA.: HOLE DEPTH: 270.50(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): See Below
84/11/29 00:00 84/12/18 00:00 85/02/22 00:00 85/03/28 00:00 85/04/10 00:00
85/05/09 00:00 85/08/12 00:00
DEPTH (feet)
GEOLOGY LOG
CASING LOG
PIEZOMETRIC "LEVEL" (feet below surface)
-300 -250 -200 -150 -100 -50 0 50 100
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350

Figure 17

SUMMARY LOG - CASING INSTALLATION DH-2

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
SURFACE ELEV.: 5246.0(feet) HOLE DIA.: HOLE DEPTH: 349.0(feet)
TOP OF MP CASING: 2.0(feet) DATE (year/month/day hour:min): See Below
I 84/10/09 00:00 ⊙84/12/10 00:00 ⊡ 85/02/22 00:00 ◊ 85/03/28 00:00 Δ 85/04/10 00:00
+ 85/05/09 00:00 ⊕85/08/12 00:00

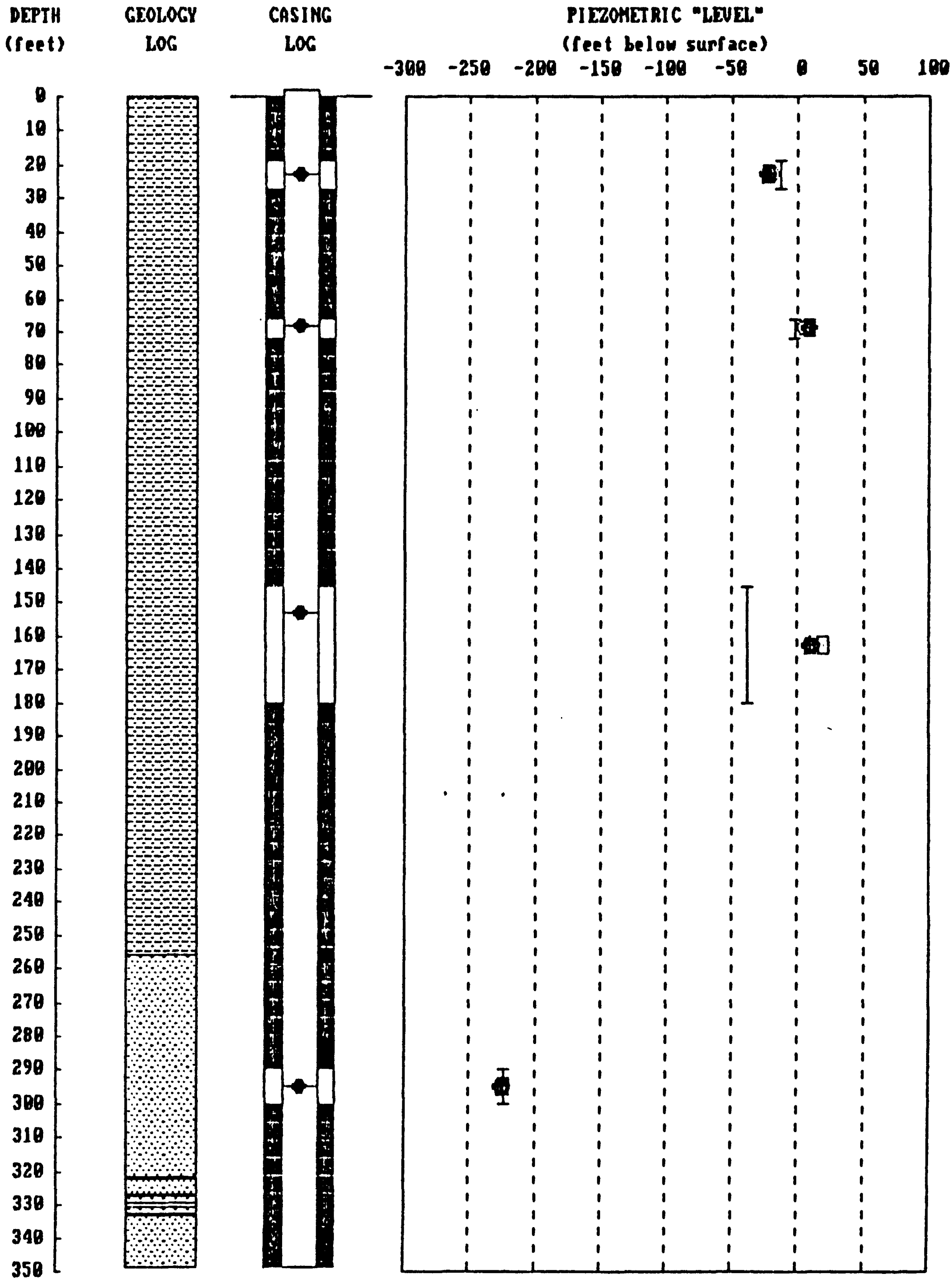


Figure 18

SUMMARY LOG - CASING INSTALLATION DH-3

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
SURFACE ELEV.: 5237.0(feet) HOLE DIA.: HOLE DEPTH: 253.0(feet)
TOP OF MP CASING: 2.0(feet) DATE (year/month/day hour:min): 84/11/29 00:00

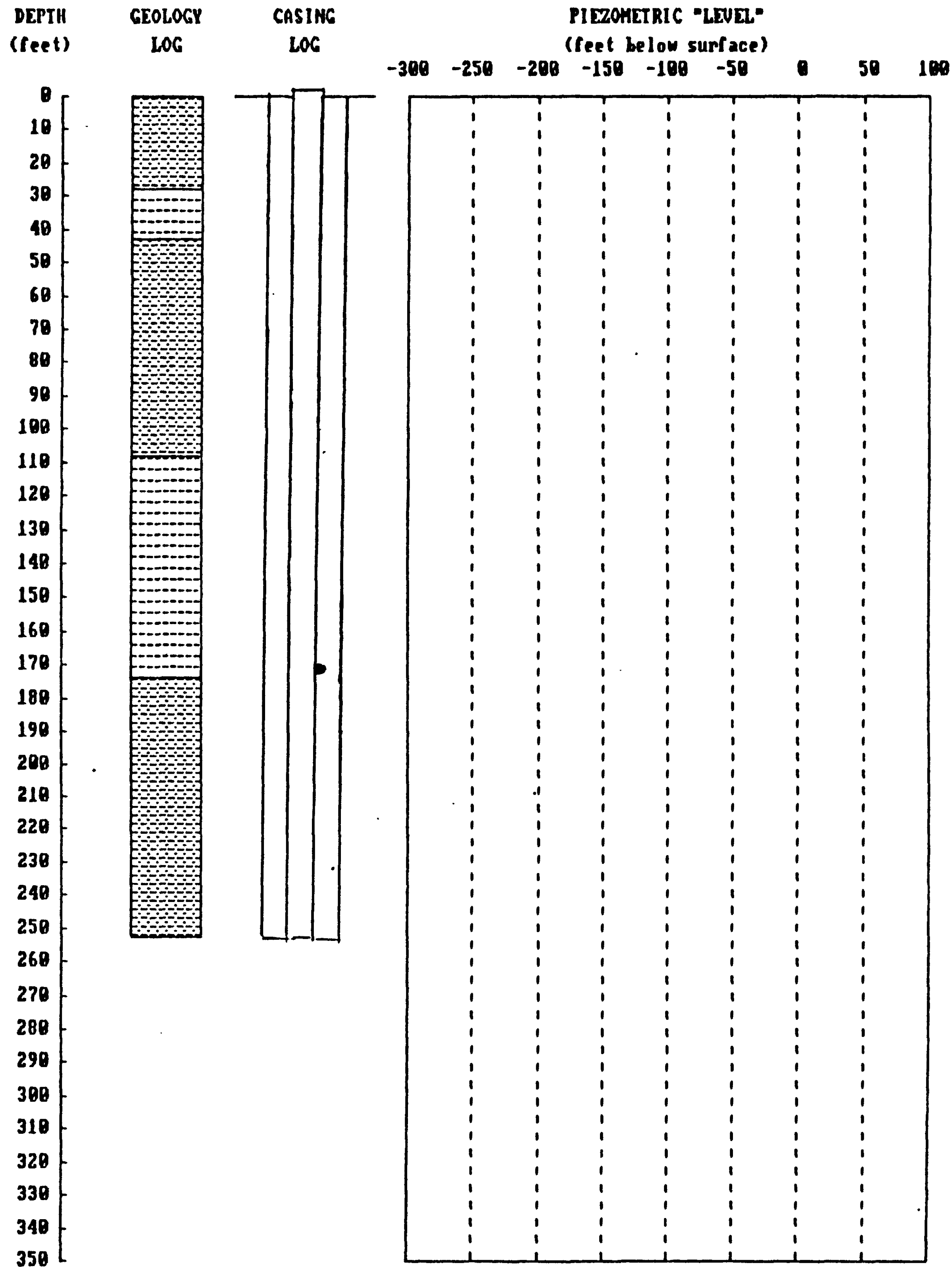


Figure 19

SUMMARY LOG - CASING INSTALLATION DH-4

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
SURFACE ELEV.: 5249.0(feet) HOLE DIA.: HOLE DEPTH: 305.0(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): See Below
I 84/12/03 00:00 ○ 84/12/18 00:00 □ 85/02/22 00:00 ◇ 85/03/28 00:00 △ 85/04/10 00:00
+ 85/05/09 00:00 ⊕ 85/08/12 00:00

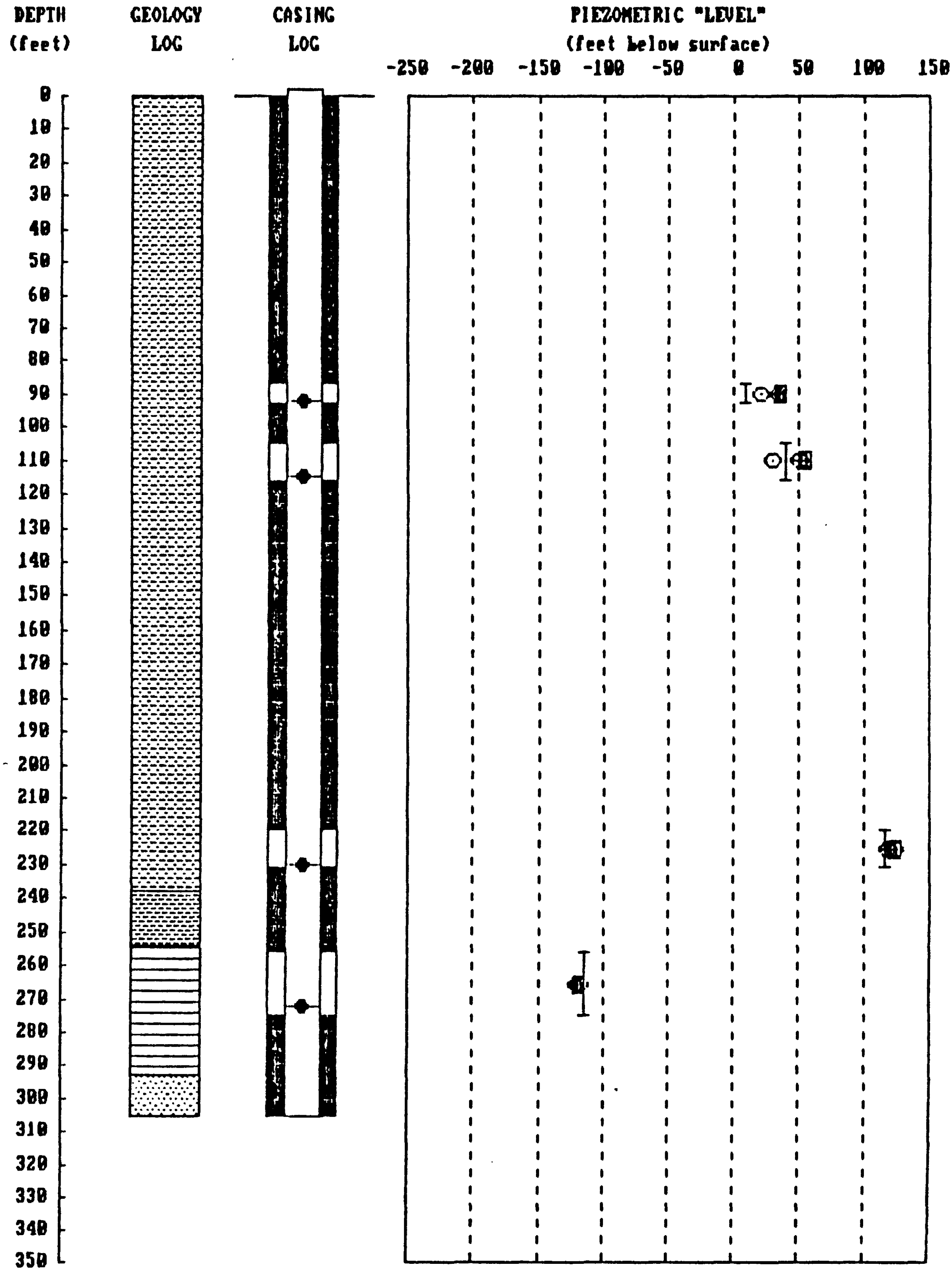


Figure 20

SUMMARY LOG - CASING INSTALLATION DH-5

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
SURFACE ELEV.: 5247.0(feet) HOLE DIA.: HOLE DEPTH: 335.50(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): See Below
I 84/11/12 00:00 ○ 84/12/18 00:00 □ 85/02/22 00:00 ◊ 05/03/28 00:00 Δ 85/04/10 00:00
+ 85/05/09 00:00 ⊕ 85/08/12 00:00

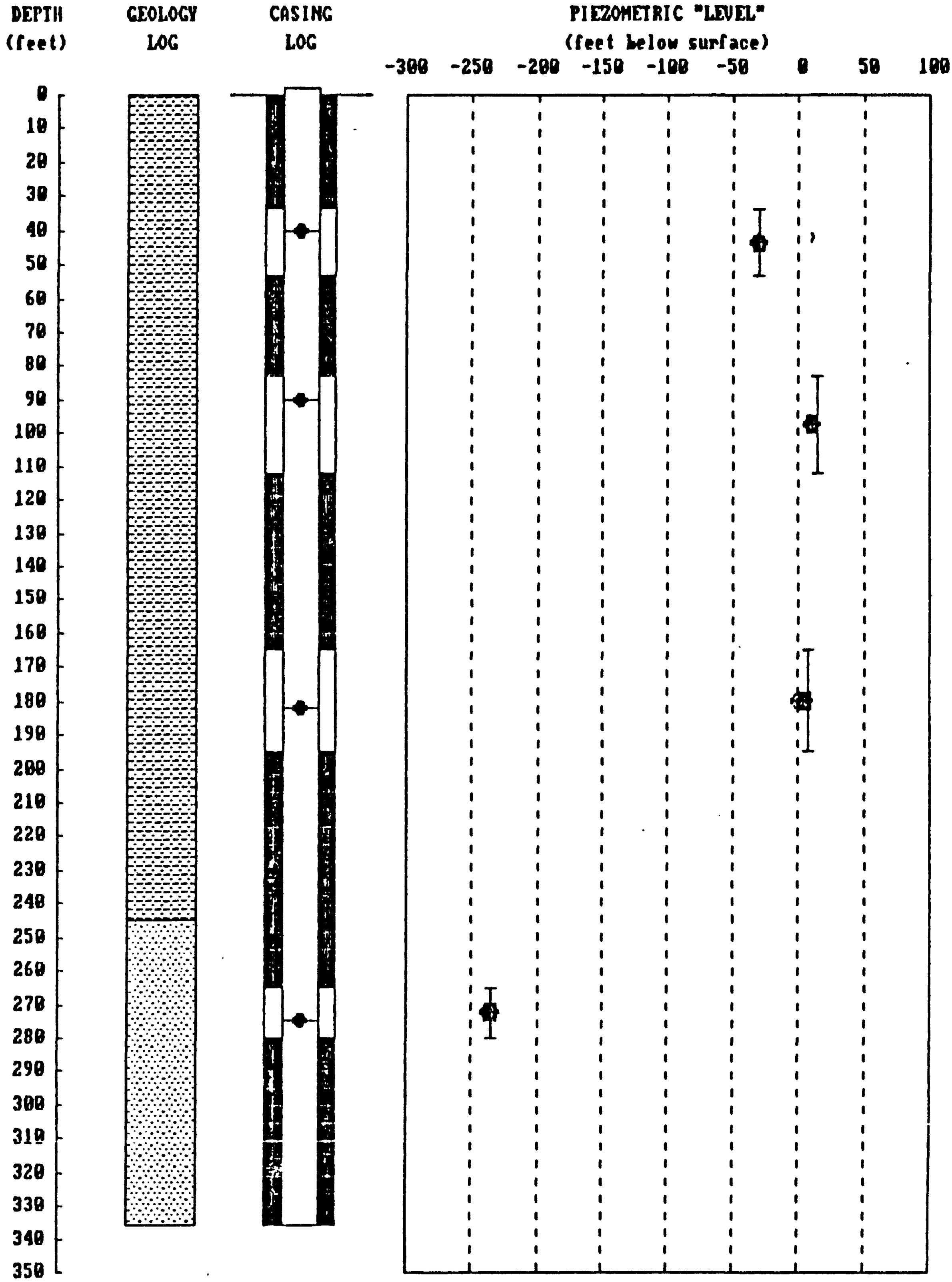


Figure 21

SUMMARY LOG - CASING INSTALLATION DH-6

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
SURFACE ELEV.: 5447.0(feet) HOLE DIA.: HOLE DEPTH: 178.50(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): See Below
I 84/10/06 00:00 ⊙ 84/12/18 00:00 ⊡ 85/02/22 00:00 ◊ 85/03/28 00:00 Δ 85/04/10 00:00
+ 85/05/09 00:00 ⊕ 85/08/12 00:00

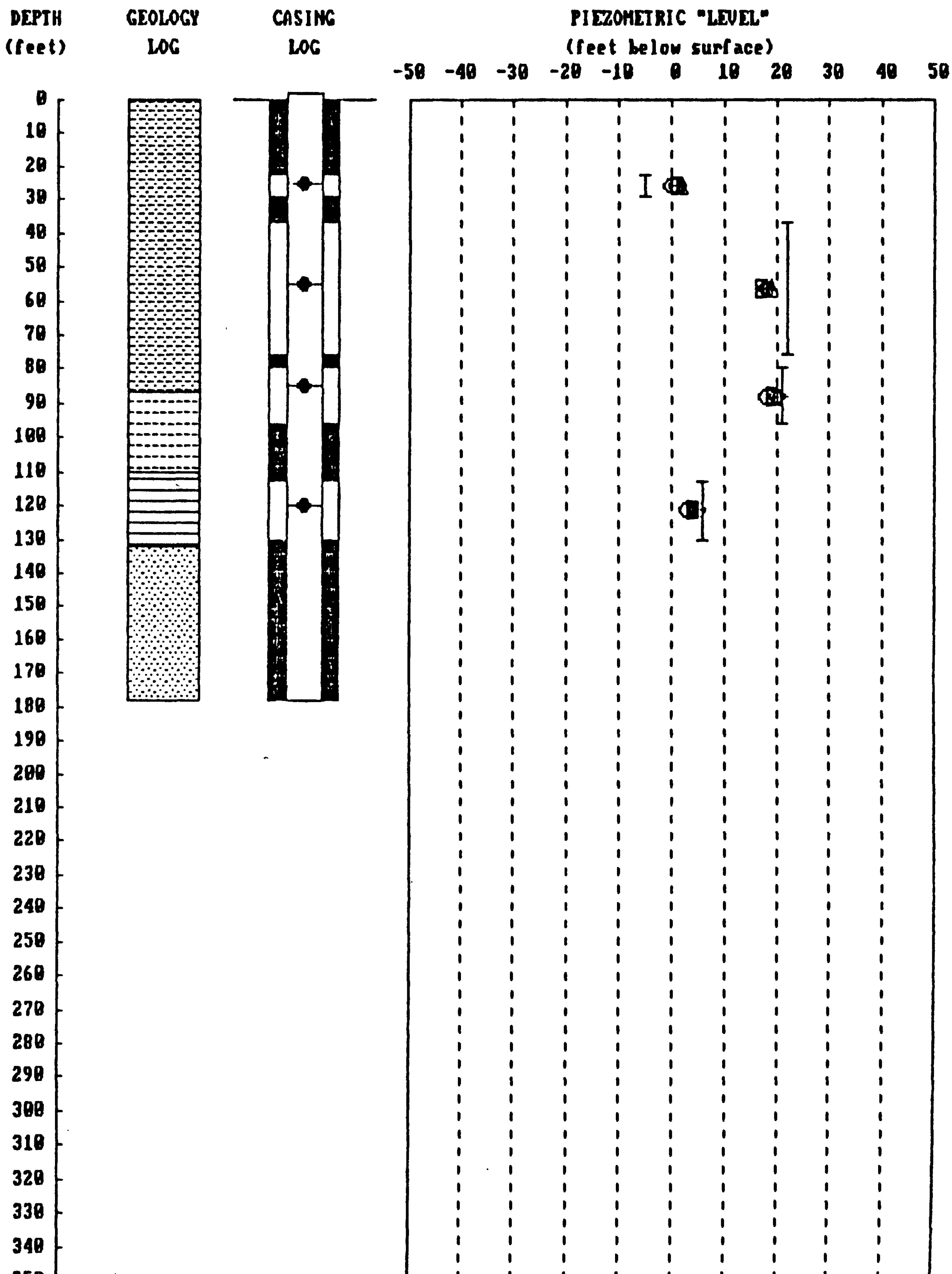


Figure 22

SUMMARY LOG - CASING INSTALLATION DH-7

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
SURFACE ELEV.: 5447.0(feet) HOLE DIA.: HOLE DEPTH: 209.0(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): See Below

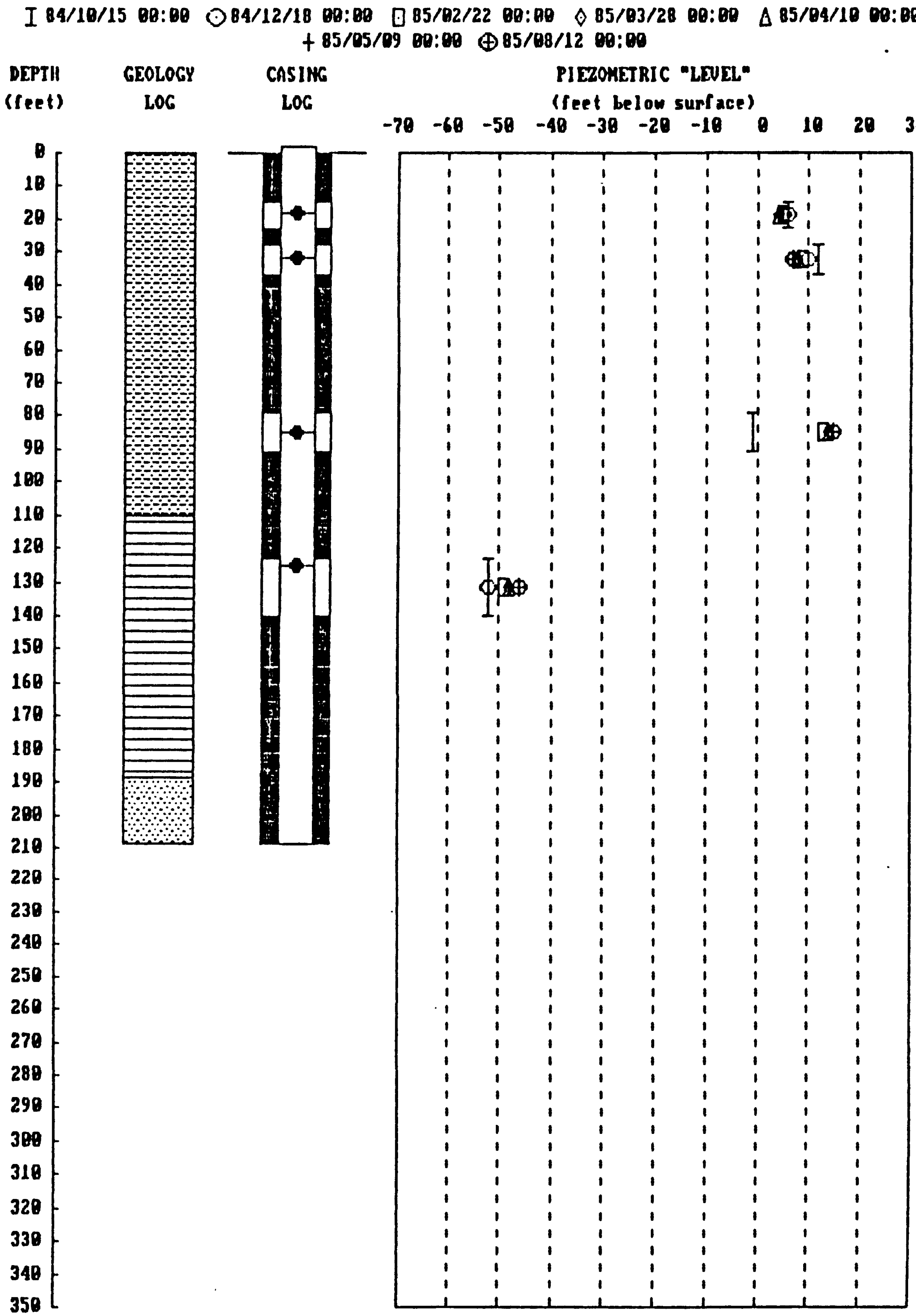


Figure 23

SUMMARY LOG - CASING INSTALLATION DH-8

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
SURFACE ELEV.: 5360.0(feet) HOLE DIA.: HOLE DEPTH: 349.60(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): See Below
I 84/12/14 00:00 ○ 84/12/18 00:00 ⊡ 85/02/22 00:00 ◊ 85/03/28 00:00 Δ 85/04/10 00:00
+ 85/05/09 00:00 ⊕ 85/08/12 00:00

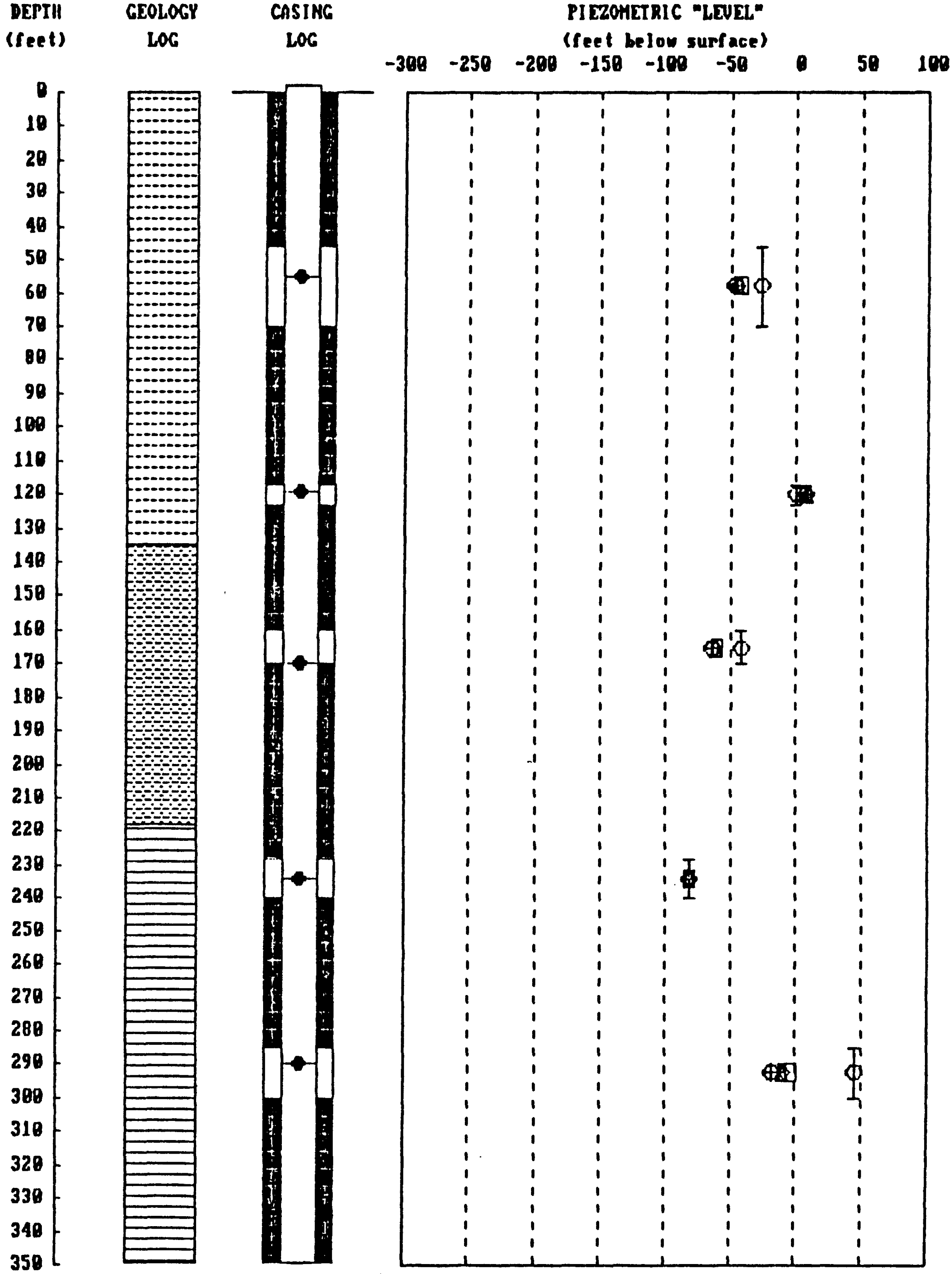


Figure 24

SUMMARY LOG - CASING INSTALLATION DH-9

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 84-2368
[illegible]
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): See Below
I 84/10/29 00:00 ○ 84/12/18 00:00 □ 85/02/22 00:00 ◇ 85/03/28 00:00 △ 85/04/10 00:00
+ 85/05/09 00:00 ⊕ 85/08/12 00:00

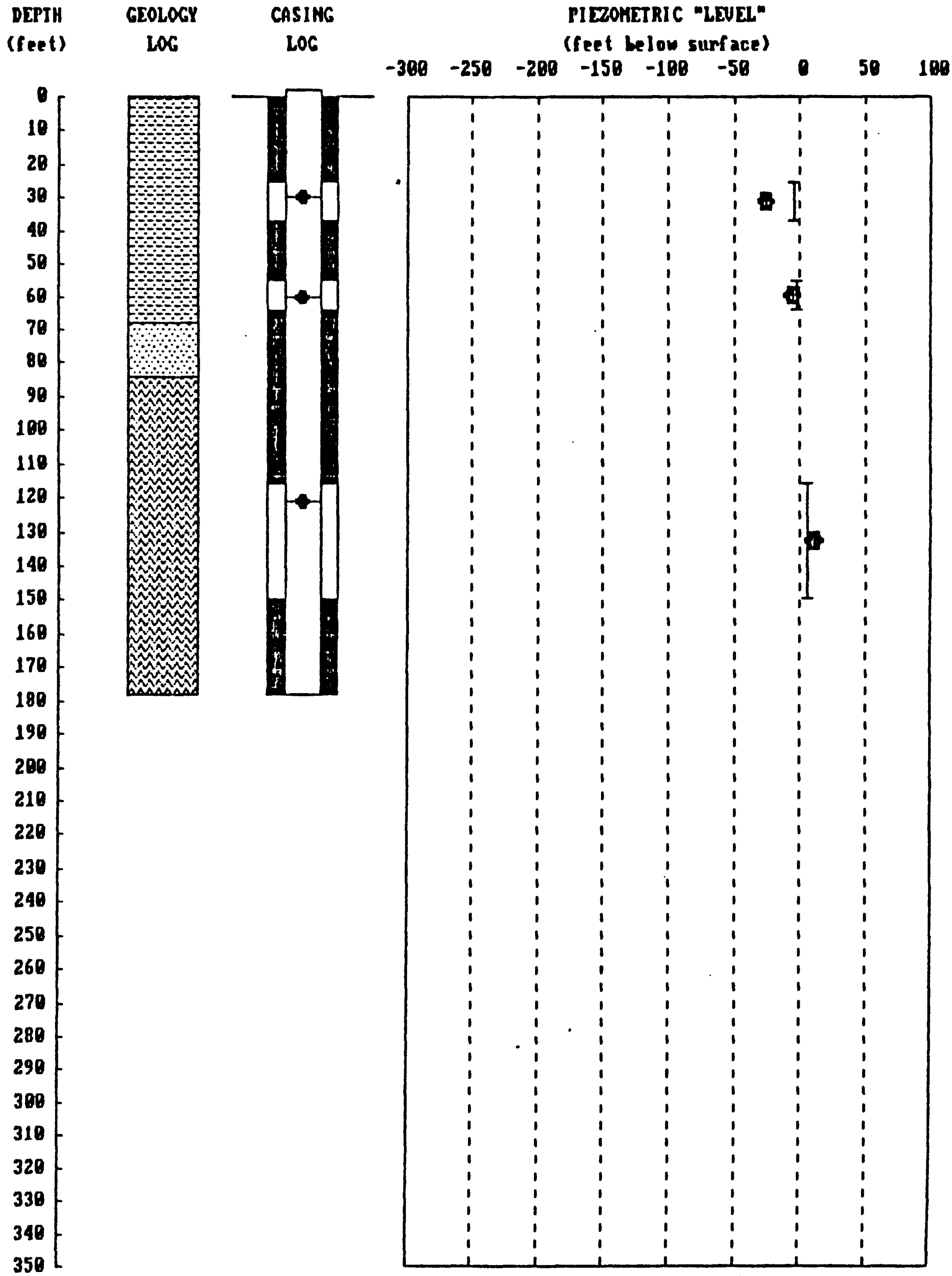


Figure 25

SUMMARY LOG - CASING INSTALLATION SH-1 (W/C Drillhole from S

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 15843B
SURFACE ELEV.: 5171.0(feet) HOLE DIA.: HOLE DEPTH: 193.0(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): 83/10/04 00:00

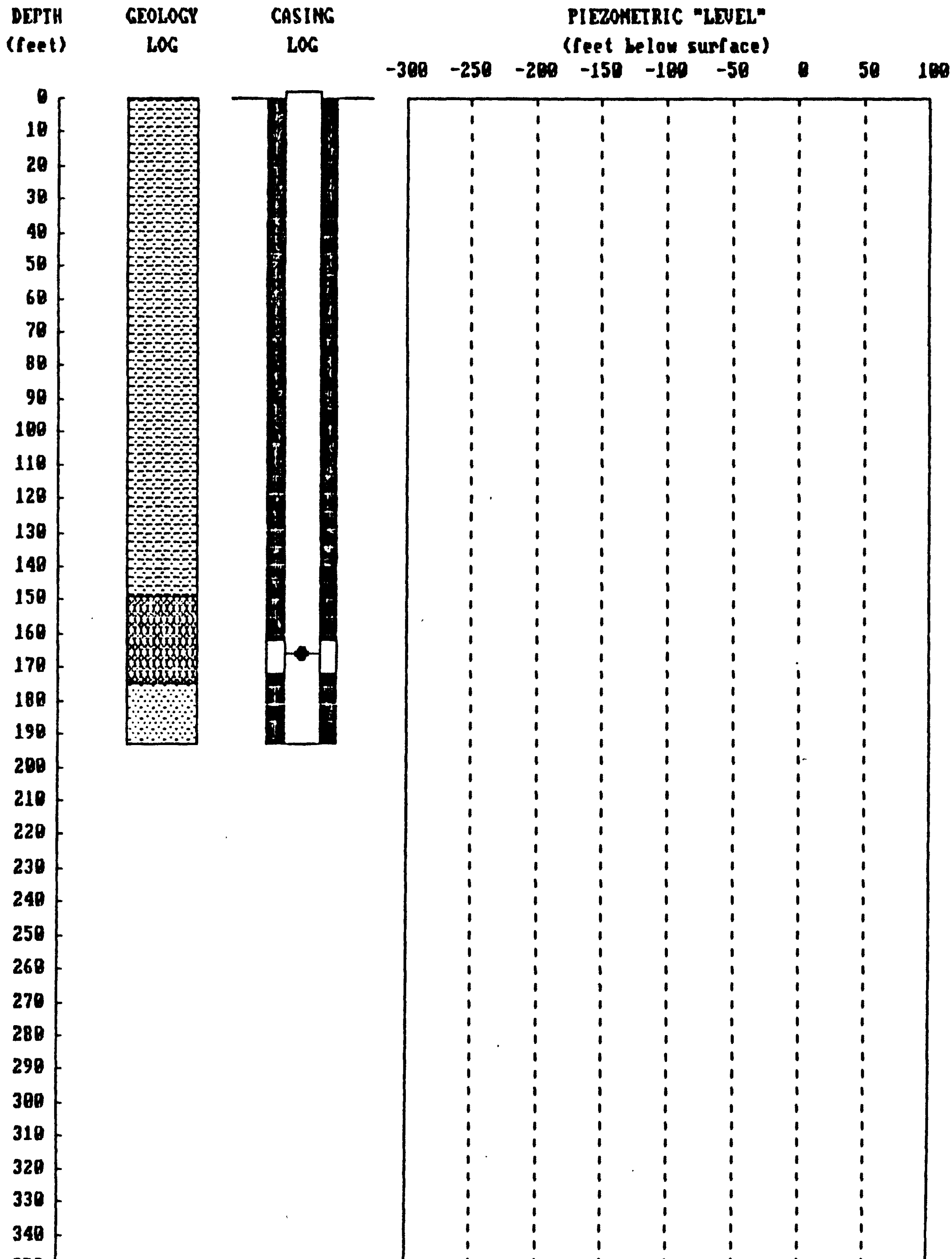


Figure 26

SUMMARY LOG - . CASING INSTALLATION SH-2 (W/C Drillhole from Sta

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 15043B
SURFACE ELEV.: 5222.0(feet) HOLE DIA.: HOLE DEPTH: 225.0(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): 83/10/04 00:00

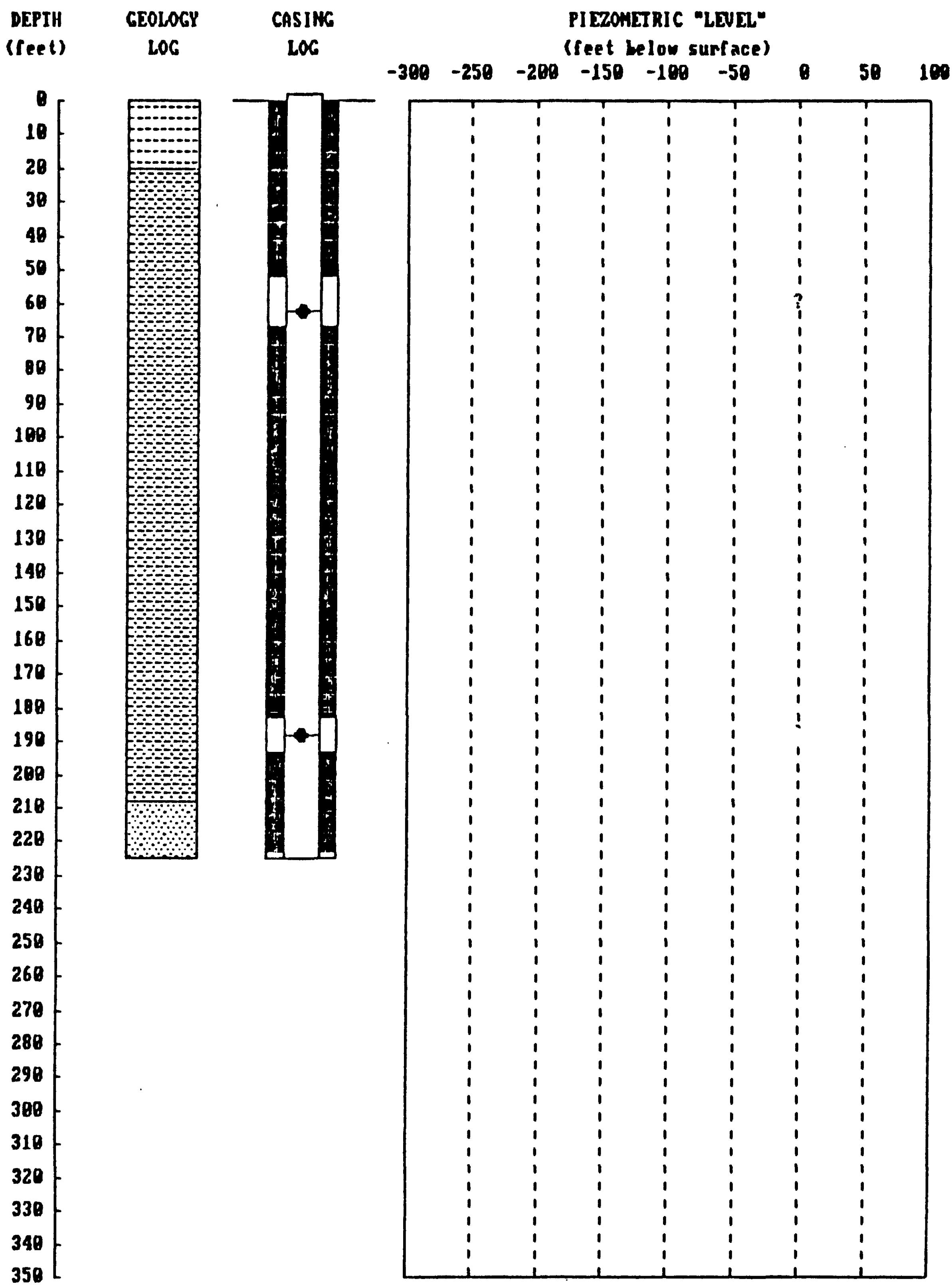


Figure 27

SUMMARY LOG - CASING INSTALLATION SH-3 (W/C Drillhole from Sta

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #: 15843B
SURFACE ELEV.: 5265.0(feet) HOLE DIA.: HOLE DEPTH: 50.0(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): 83/10/04 00:00

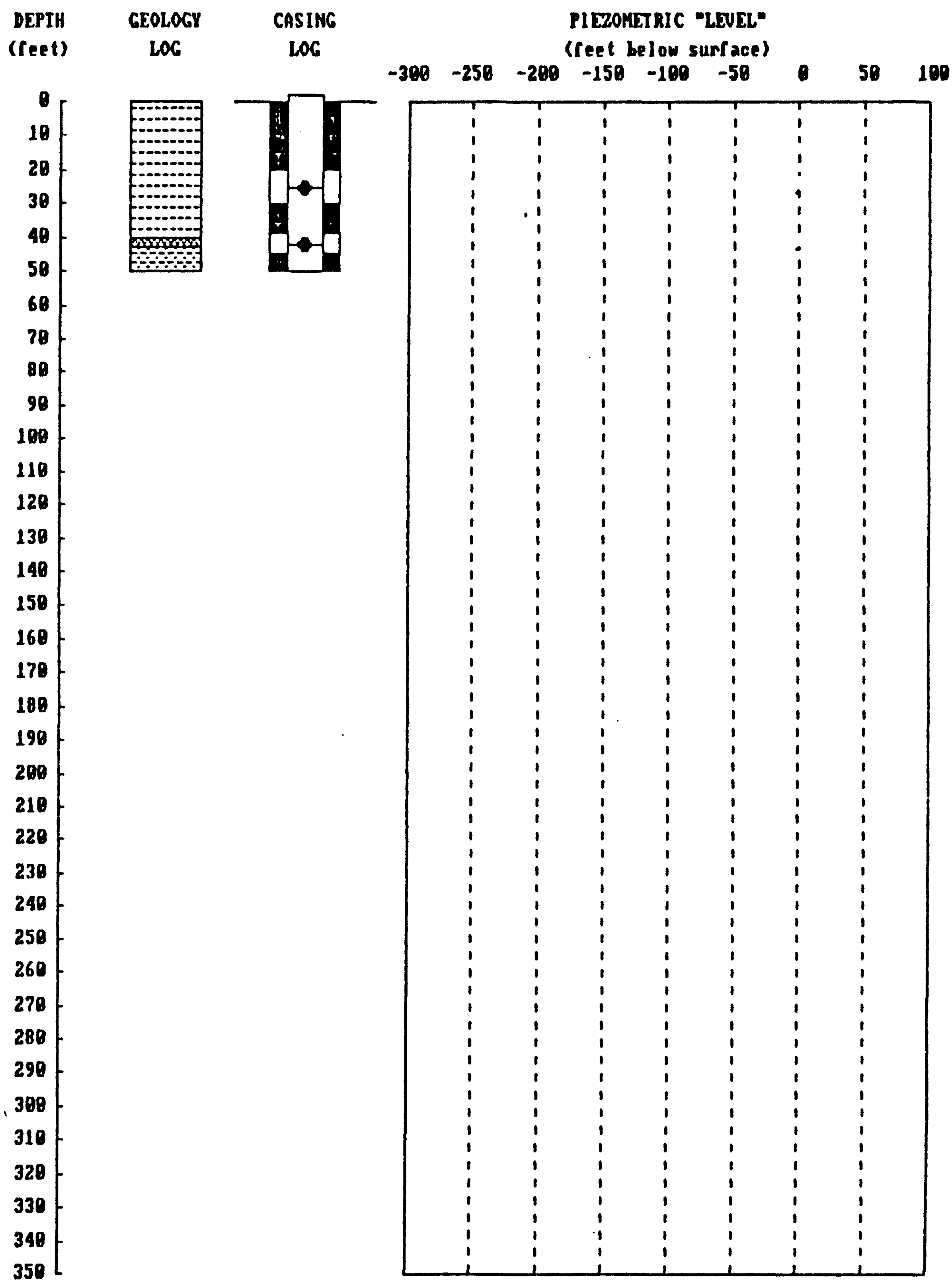


Figure 28

SUMMARY LOG - CASING INSTALLATION P-1 (RB & G Drillhole)

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #:
SURFACE ELEV.: 5249.0(feet) HOLE DIA.: HOLE DEPTH: 123.60(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): 00/00/00 00:00

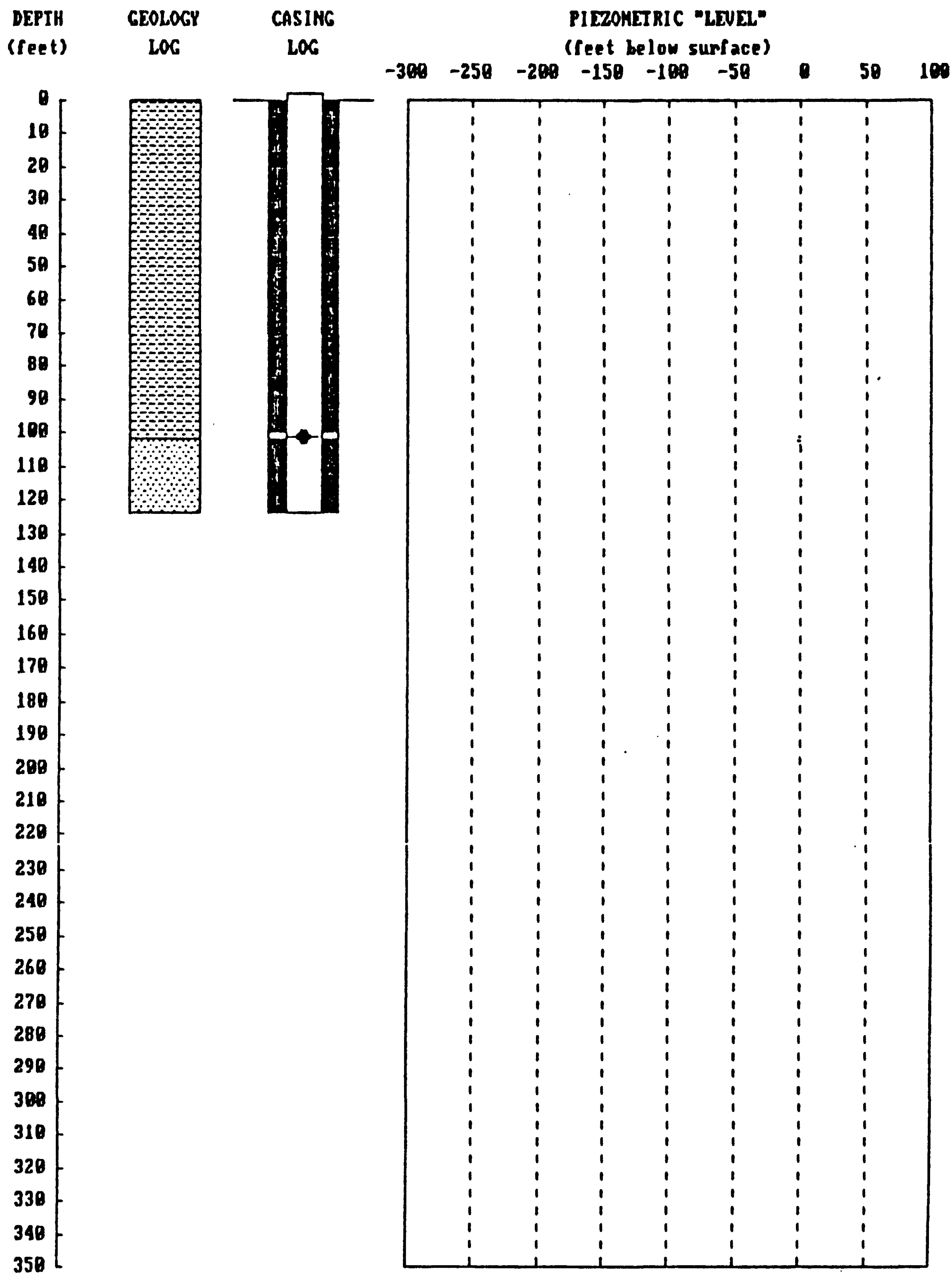


Figure 29

SUMMARY LOG - CASING INSTALLATION P-2 (RB & G Drillhole)

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #:
SURFACE ELEV.: 5249.0(feet) HOLE DIA.: HOLE DEPTH: 284.0(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): 83/10/04 00:00

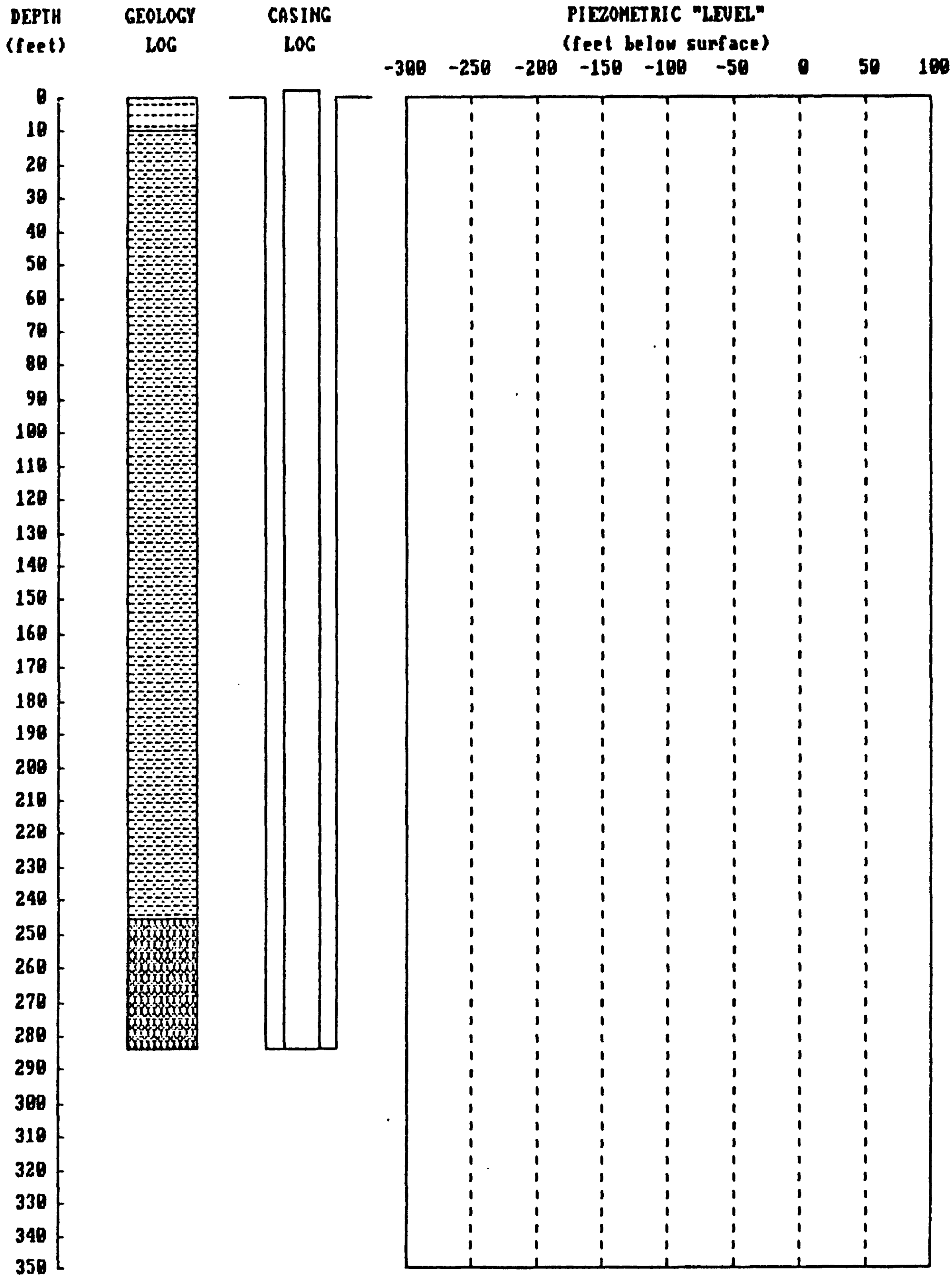


Figure 30

SUMMARY LOG - ' CASING INSTALLATION P-3 (RB & G Drillhole)

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #:
SURFACE ELEV.: [illegible](feet) HOLE DIA.: HOLE DEPTH: [illegible](feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): 83/10/04 00:00

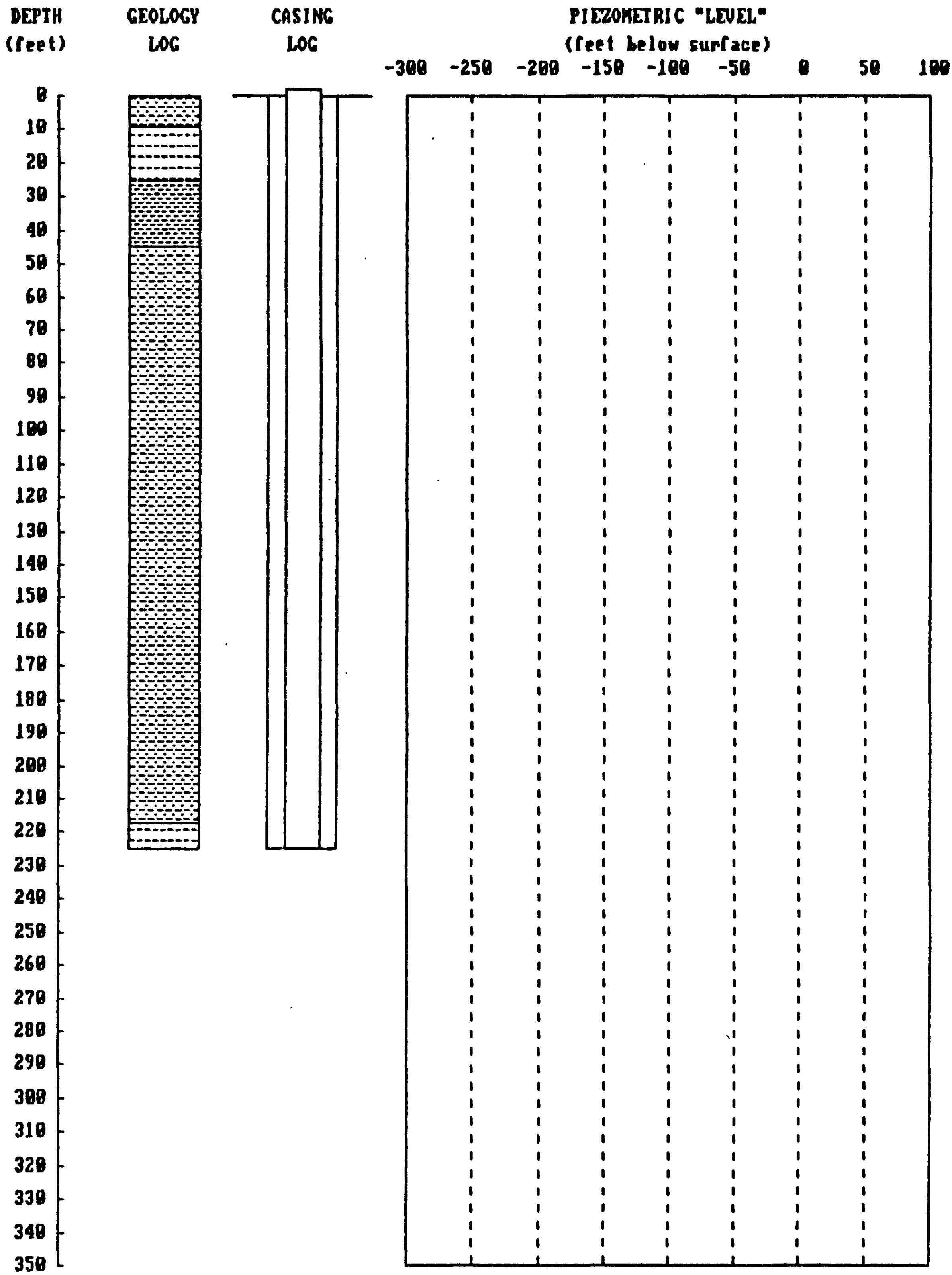
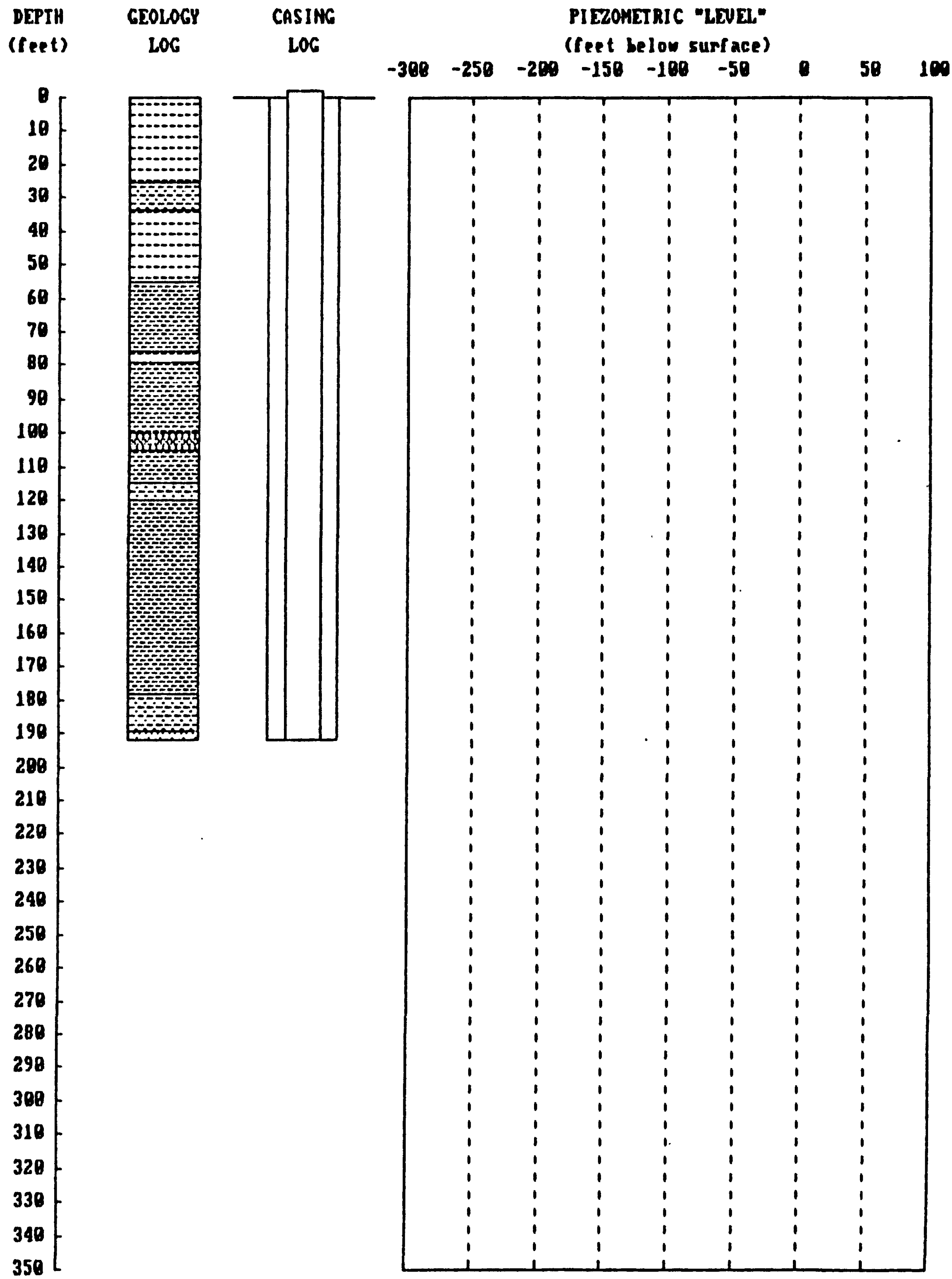
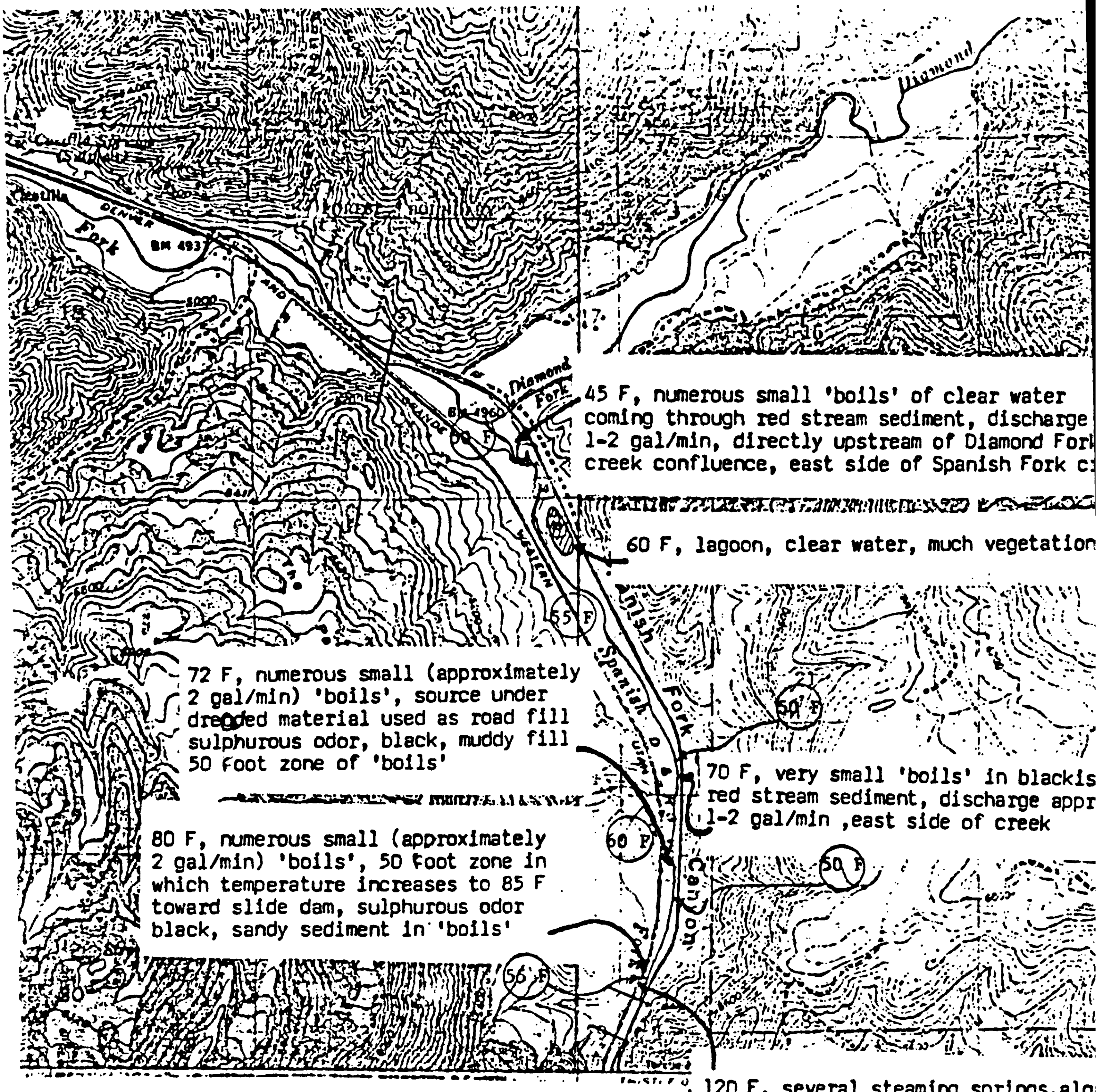


Figure 31

SUMMARY LOG - CASING INSTALLATION P-4 (RB & G Drillhole)

CLIENT: Utah Division of Water Rights PROJECT: Thistle Landslide JOB #:
SURFACE ELEV.: 5249.0(feet) HOLE DIA.: HOLE DEPTH: 192.0(feet)
TOP OF CASING: 2.0(feet) DATE (year/month/day hour:min): 83/10/04 00:00





120 F, several steaming springs,alg in water, sulphurous odor, gray, sa sediment in spring, discharge appro 20 gal/min, located at downstream e of stilling basin for overflow tunn (as of 14 May 1983, 1400 hours

ackground temperatures of Spanish Fork creek range from 50 F near the slide to 50 F at Diamond Fork tributary air temperature approximately 40 - 45 F, average depth of Spanish Fork creek approximately 1 foot, the water was extremely turbid -visibility less than one inch- due to sediment being supplied from runoff of the north flank of he slide

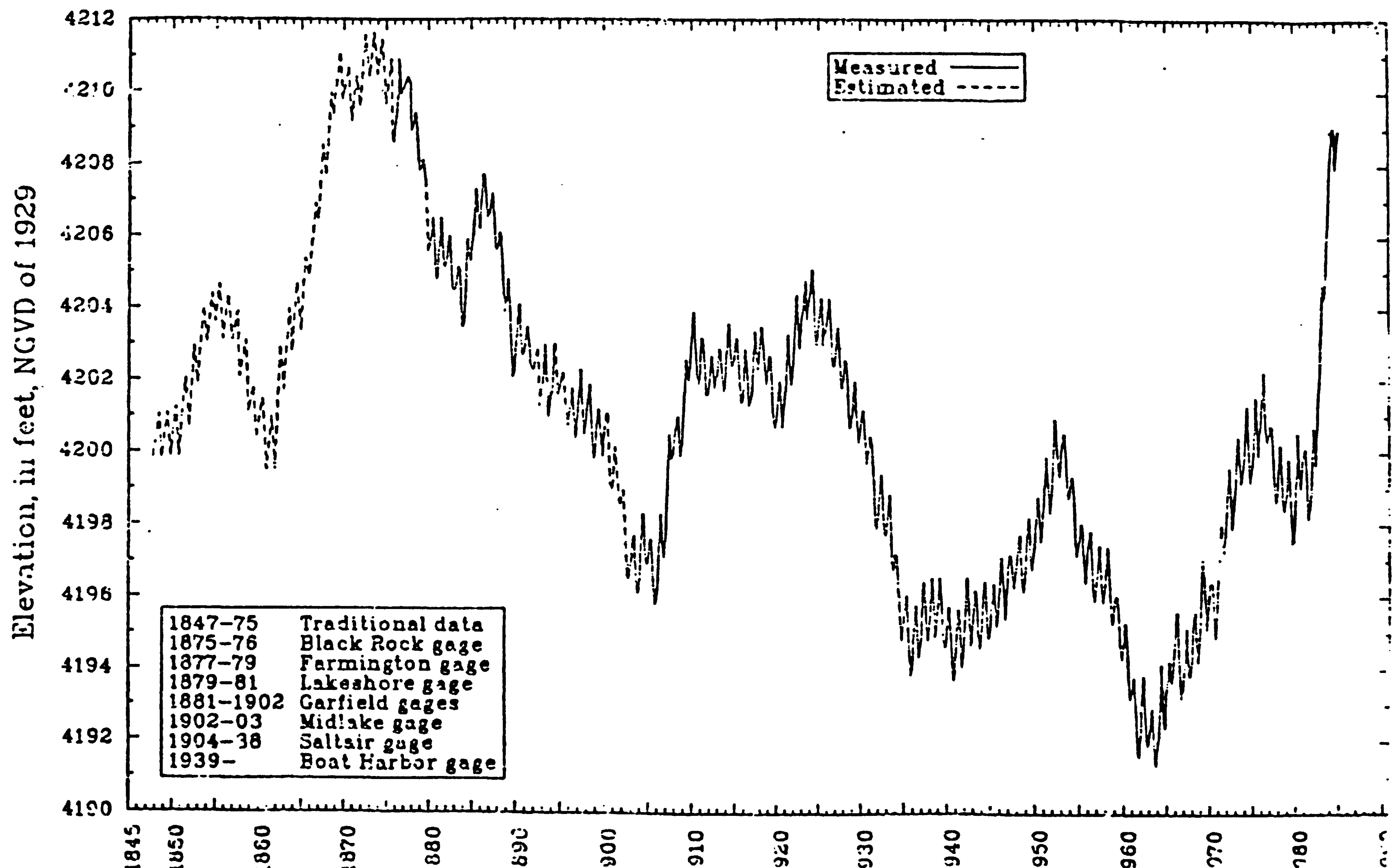
id based on Utah coordinate system, central zone
niversal Transverse Mercator grid ticks.
n in blue
d lines indicate selected fence lines

TAH GEOLOGICAL & MINERAL SURVEY, HAZARDS SECTION
William F Case
16 May 1983

Figure 32 Groundwater Temperatures Along Spanish Fork River Near Thistle Slide.

Figure 33 Fluctuations of Great Salt Lake

Source: U. S. Geological Survey
in cooperation with Utah
State Division of Water Rights



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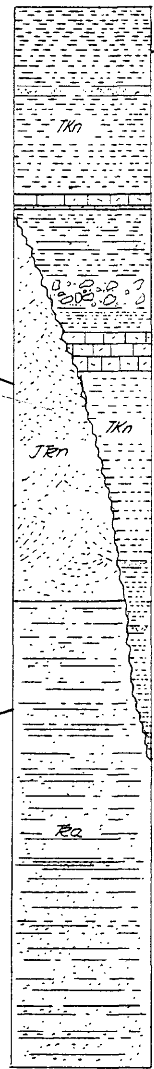

NORTH HORN FORMATION (TKn)-- Reddish-brown, orange-brown, light-brown, gray and greenish-gray mudstone that contains interlayered beds of light-brown to light-gray sandstone, conglomeratic sandstone, conglomerate, and a few light-gray limestone beds similar to those that form the Flagstaff Limestone. Medium bedded to massive. Mudstone is very unstable when wet, and tends to slump; consequently outcrops of the North Horn Formation are almost completely concealed beneath large and small slump masses Unconformably overlies all older units in Thistle Slide area. Ranges in thickness from about 600 to 700 ft (183 to 213 m) in Thistle Slide area.

UGGET SANDSTONE (also known as NAVAJO SANDSTONE) (JTRn)--Light-tan and reddish-brown quartzose sandstone; thick bedded to massive; crossbedded in large sweeping tangential festoons; fine to coarse grained. Moderately well cemented by calcium carbonate and iron oxide. Friable. Forms cliffs and steep slopes. In places, light-tan aspect is broken by large, irregular, reddish-brown mottles These reddish parts consist of fine sand grains that are not as well cemented as light tan parts, and thus are less likely to stand as vertical walls Very stable. Conformably overlies Ankareh Formation Thickness ranges from 1,400 to 1,500 ft (425 to 460 m)

VKAREH FORMATION (TRa)--Reddish brown to deep reddish shaly siltstone and sandstone; thin to thick bedded; even bedded. Some sandstone units are crossbedded. Sandstones are fine to medium grained. Ripple marked. Forms gentle to moderate slopes and long strike valleys. About 1,400 ft (425 m) thick.

PLATE 7- *Columnar section*