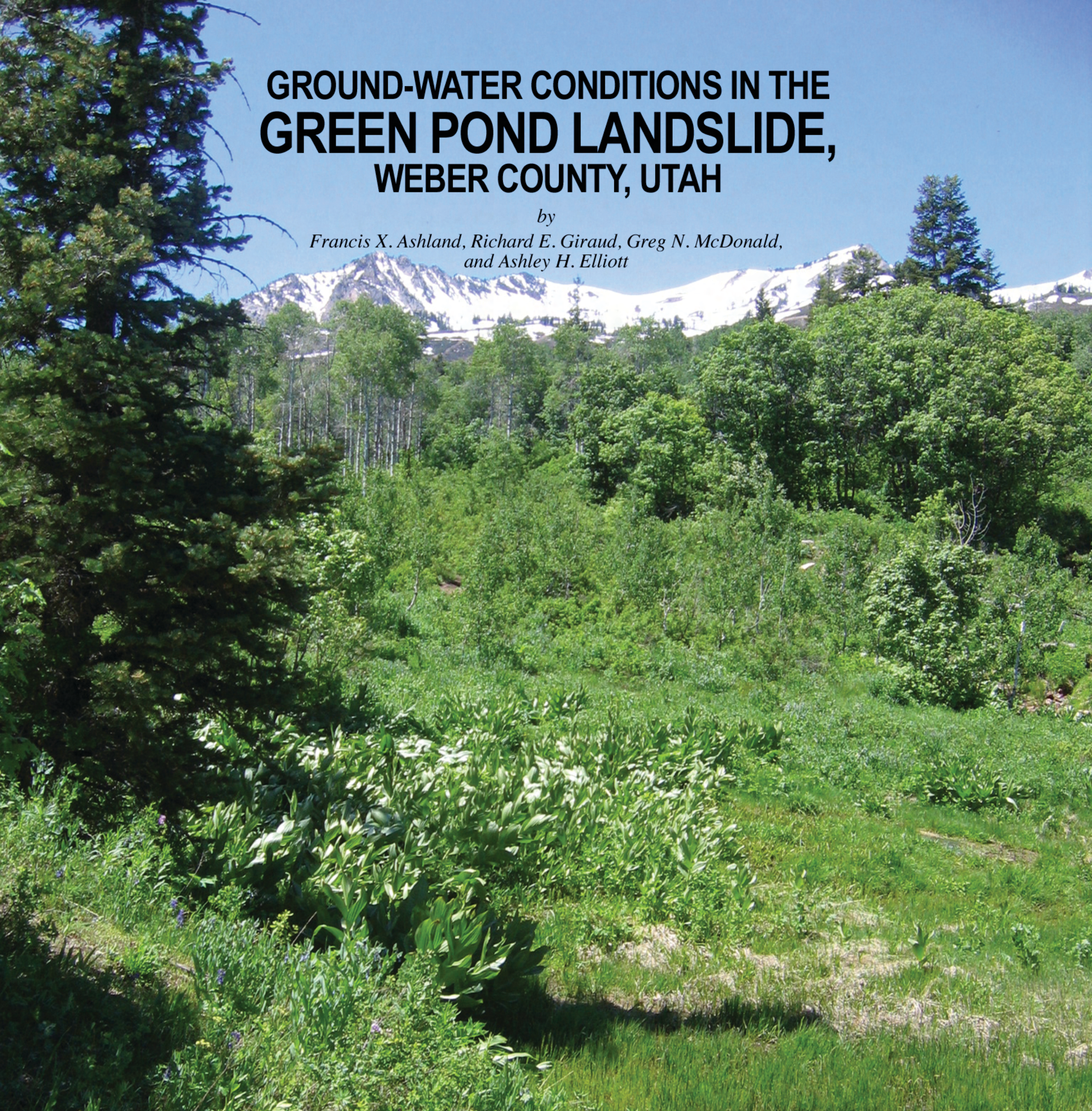
GROUND-WATER CONDITIONS IN THE
GREEN POND LANDSLIDE,
WEBER COUNTY, UTAH

by

Francis X. Ashland, Richard E. Giraud, Greg N. McDonald,
and Ashley H. Elliott



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Cover photos: View of southeast edge of landslide. Wasatch Range near Snowbasin ski resort. Inset photo is view of upper part of Green Pond.

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ABSTRACT

We analyzed ground-water-level data from five observation wells and two vibrating wire piezometers to characterize ground-water conditions in the Green Pond landslide. The wells and piezometers are in a narrow part of the approximately 1.5-mile (2.4-km) long landslide, where State Route 226 crosses it. Ground-water-level data, collected between 2000 and 2005, from two vibrating wire piezo-meters in the active middle part of the landslide, revealed differences in seasonal peak and low ground-water levels. In the downslope piezometer, seasonal peak ground-water levels fluctuated with annual precipitation; however, in the upslope piezometer, peak levels generally increased. In contrast, the seasonal low ground-water level in the downslope piezometer generally declined; however, the level increased in the upslope piezometer. In the inactive northwestern part of the slide, shallow ground-water levels fluctuated synchronously between July 2006 and December 2007. Variations in ground-water conditions, elevations, fluctuation patterns, in addition to local, hypothetical ground-water gradients suggest compartmentalization of ground water in the landslide that is likely the result of low permeability clay gouge along strike-slip shear zones and internal thrusts.

INTRODUCTION

Ground-water-level data for Utah landslides are limited, and most are from landslides in Wasatch Front communities (Ashland, 2003; Ashland and others, 2005, 2006). Even less ground-water-level data exist for large landslides in Utah (Duncan and others, 1986) or for landslides in the Tertiary Norwood Tuff (Ashland, 2001).

As part of geotechnical investigations for State Route 226 (SR-226), seven monitoring wells were installed in and near the Green Pond landslide, a large, historically active landslide in the Norwood Tuff. Data from two of these wells, collected by the Utah Department of Transportation (UDOT), provide information on ground-water level fluctuations over an approximately six-year period between 2000 and 2005. In addition, we monitored ground-water levels monthly at three wells, and made periodic ground-water level observations at two others between June 2006 and December 2007. This report summarizes the results of our ground-water-level monitoring and analysis of the UDOT data.

GREEN POND LANDSLIDE

The Green Pond landslide (figure 1) is a large historically active landslide crossed by SR-226 in Weber County, Utah. The landslide is elongate, somewhat irregularly shaped, about 7800 feet (2380 m) long, and has a length to width ratio that varies between about 78:1 and 7:1. Monitoring and observations indicate that the landslide is recurrently or possibly even continuously active, but can be subdivided into currently active and inactive parts. Active parts of the slide have been moving approximately at a very slow rate since October 2005.

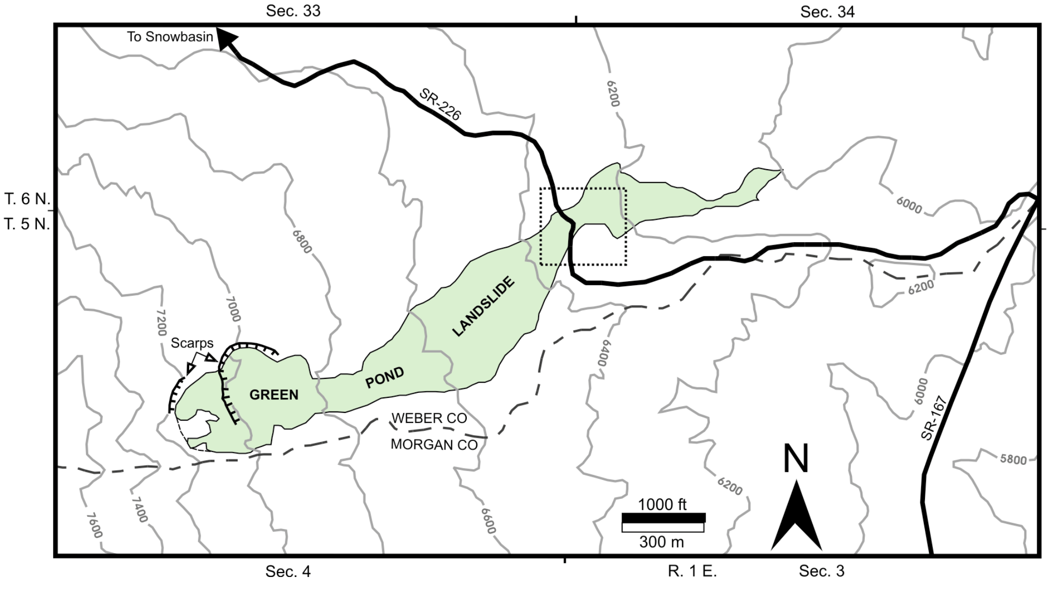

Figure 1. *Location of Green Pond landslide and SR-226. Box shows approximate area of figure 2. Topography from U.S. Geological Survey Snow Basin 7-1/2′ quadrangle map. Contour interval is 200 feet.*

The Green Pond landslide consists of relatively high-strength glacial debris overlying weathered Norwood Tuff. Borehole logs from two of the wells (BH121 and BH123) indicate that landslide deposits derived from glacial debris extend to a depth of about 23 and 30 feet (7 and 9 m), respectively. The underlying landslide debris is derived from weathered Norwood Tuff that locally consists of weak lean and fat clays. Slickensided clay zones form along deformation features in and bounding the landslide.

GROUND-WATER CONDITIONS

Figure 2 shows existing ground-water-monitoring wells in the Green Pond landslide separated by both active and inactive internal deformation features, including thrust systems and strike-slip shear zones. Clay gouge likely exists along the thrusts and shear zones and inhibits ground-water flow across these features and compartmentalizes ground water.

Seasonal Ground-Water-Level Fluctuations in the Active Landslide

A geotechnical investigation for the Utah Department of Transportation (Landslide Technology, 2002) documented ground-water-level fluctuations between 2000 and 2005 in the middle active part of the Green Pond landslide, near where it is crossed by SR-226. Continuously recording, vibrating wire piezometers were installed in two boreholes

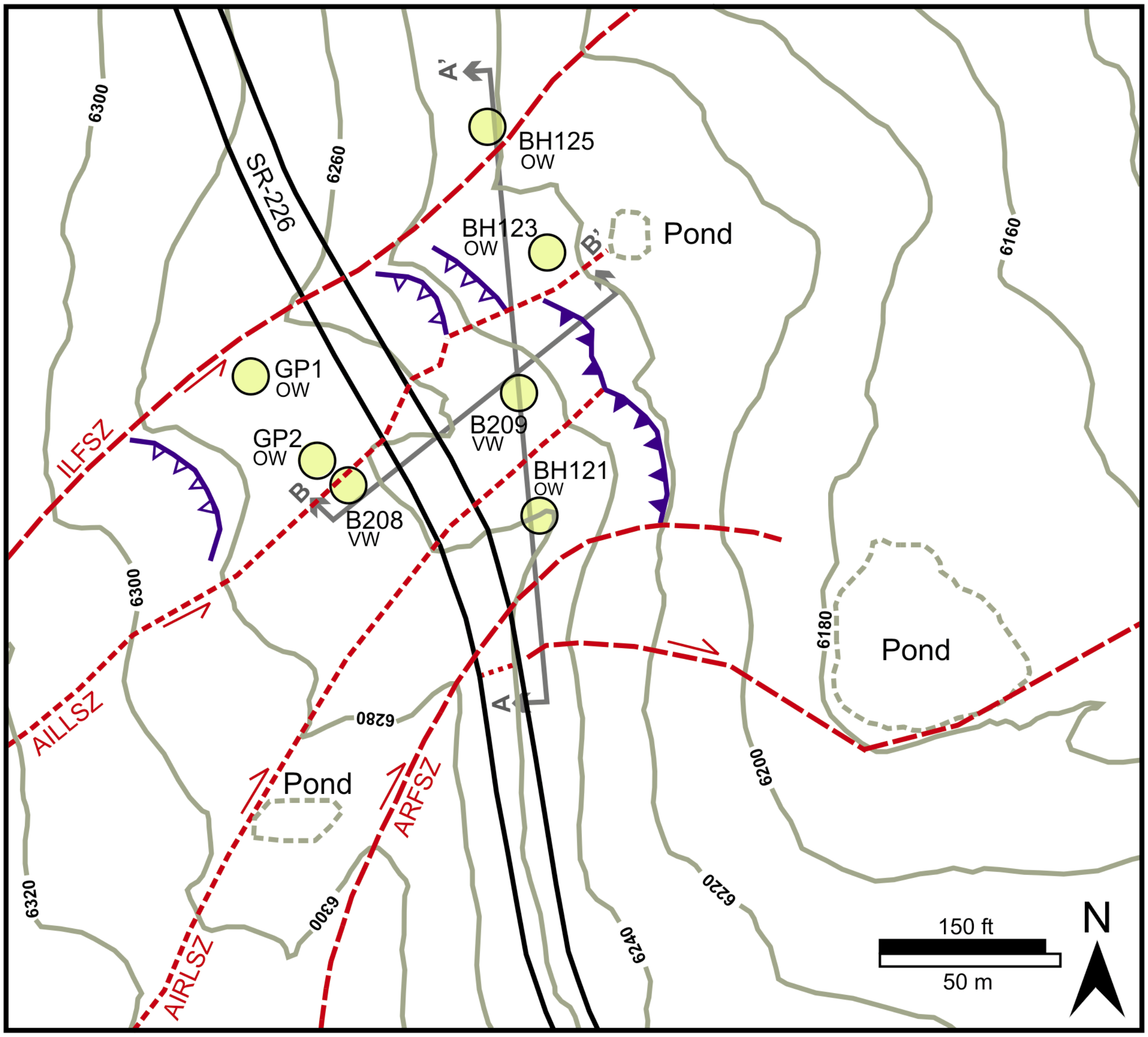

Figure 2. Detailed map of Green Pond landslide at SR-226 showing monitoring well locations (yellow circles). See text for additional information. Triangles (open: inactive in 2005–06; closed: active) on upthrown side of internal thrusts. Red dashed lines are longitudinal strike-slip shear zones. Arrows indicate direction of movement. Red dots show road cracks along active right-flank shear zone (alternate trace shown to east of highway). Section lines for cross sections A-A′ (figure 5) and B-B′ (figure 6) shown. Topography from Landslide Technology (2002). See figure 1 for approximate location. Contour interval is 20 feet. Abbreviations: ARFSZ – active right-flank shear zone, AIRLSZ – active internal right-lateral shear zone, AILLSZ – active internal left-lateral shear zone, ILFSZ – inactive left-flank shear zone, OW – observation well, VW – vibrating wire piezometer.

adjacent to SR-226, one upslope (B208) and one downslope (B209) of the highway (figure 2). Data from these piezometers are summarized in table 1 and figure 3.

During the nearly six-year period, flowing artesian ground-water conditions existed through 2005 in piezometer B208, indicating confined ground water upslope of the highway, and the maximum measured fluctuation in ground-water level was about 6.3 feet (1.9 m). The variation in the seasonal peak ground-water level was slightly higher than that in the seasonal low ground-water level, 3.6 and 2.4 feet (1.1 and 0.7 m), respectively, but the difference may be influenced by the lack of the seasonal low ground-water level in 2005. For the five years from 2000 to 2004, the variation in the seasonal peak and low ground-water levels was very similar, 2.5 and 2.4 feet (0.8 and 0.7 m), respectively. Figure 3A shows that the peak ground-water level in piezometer B208 rose consistently between 2000 and 2005. In five of six years, the peak ground-water level occurred during the summer (either in June or July), but in 2005 it occurred in February. The seasonal low ground-water level fluctuated slightly, but generally rose between 2000 and 2004 (figure 3C). The low ground-water level occurred between September and early November.

In downslope piezometer B209, the ground-water level remained more than 30 feet (10 m) below the ground surface through 2005, and the maximum measured fluctuation reached 12.3 feet (3.8 m). The seasonal peak ground-water level fluctuated closely with annual precipitation at the nearby (about 5.5 miles [8.8 km] northeast) Huntsville National Weather Service station (figure 3B) and occurred in either March or April. Similar to piezometer B208, the variation in the seasonal peak ground-water level in piezometer B209 was higher than that in the seasonal low ground-water level, 7.4 and 2.8 feet (2.3 and 0.9 m), respectively, including for the period from 2000 to 2004 for which both the seasonal peak and low ground-water levels are available. The low ground-water level behaved differently than the peak ground-water level, continuously declining between 2000 and 2003 (figure 3D), with a slight rebound in 2004. The low ground-water level occurred between late August and October.

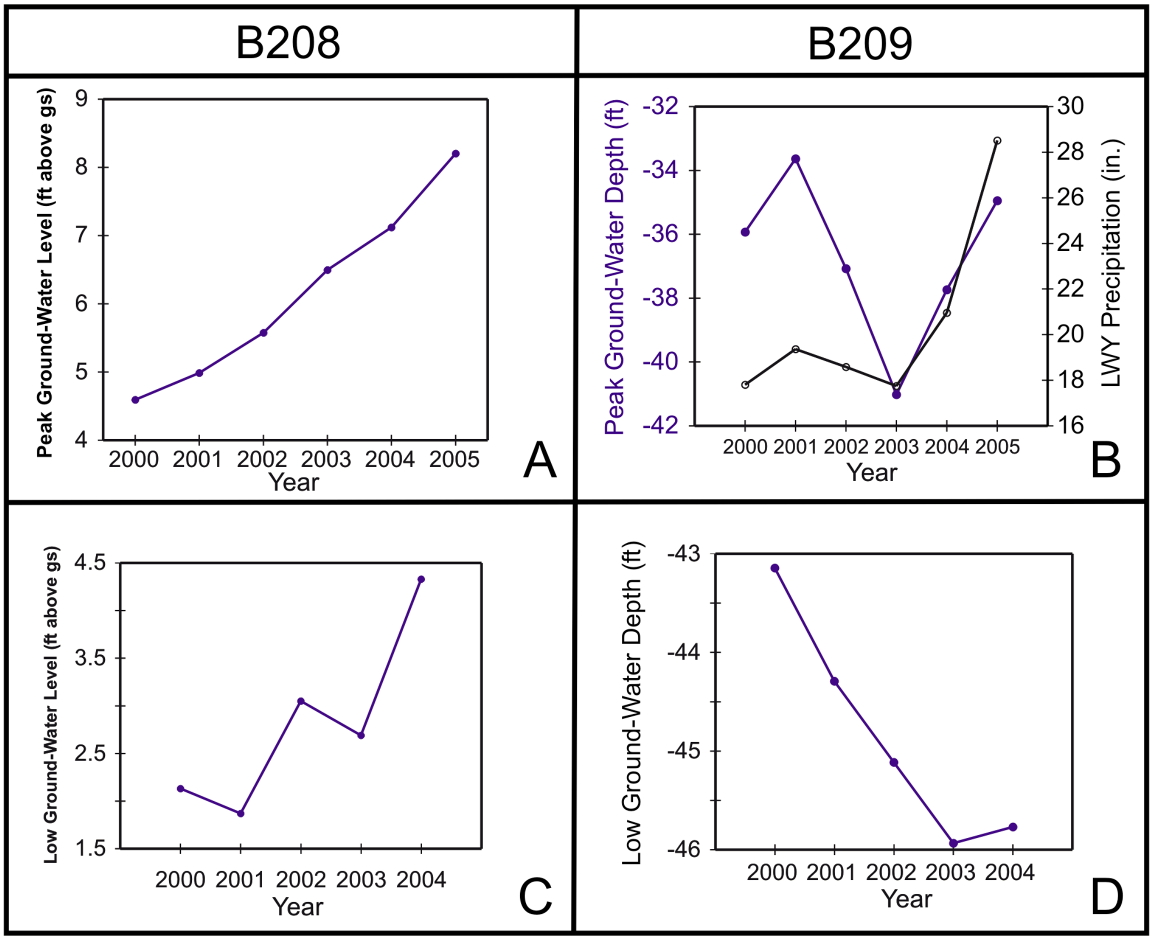

Figure 3. Plots showing fluctuations in ground-water levels in the active middle part of the Green Pond landslide between 2000 and 2005. (A) Rise in seasonal peak ground-water level between 2000 and 2005 in piezometer B208 upslope of SR-226. (B) Fluctuation in seasonal peak ground-water level in piezometer B209 downslope of SR-226. Peak ground-water level fluctuated closely with precipitation (black open circles). (C) Fluctuation in seasonal low ground-water level between 2000 and 2004 in piezometer B208. (D) General decline in seasonal low ground-water level in piezometer B209. Data provided by Leslie Heppler, Utah Department of Transportation. See figure 2 for piezometer locations. Abbreviations: gs – ground surface; LWY – landslide water year (September-August).

Table 1. *Summary of vibrating wire piezometer information and measured ground-water-level fluctuations between 2000 and 2005. Ground-water levels determined from graphical data provided by the Utah Department of Transportation. See figure 3 for plots.*

Piezometer B208	**Ground Elev.**[1] (ft)	**Depth**[1] (ft)	**MGWLF** (ft)
	6263	38	6.3
Year	**SPGWL**[2] (ft)	**SLGWL**[2] (ft)	**SGWLF**[2] (ft)
2000	4.6	2.1	2.5
2001	5.0	1.9	3.1
2002	5.6	3.1	2.5
2003	6.5	2.7	3.8
2004	7.1	4.3	2.8
2005	8.2	NA	NA
Piezometer B209	**Ground Elev.**[1] (ft)	**Depth**[1] (ft)	**MGWLF** (ft)
	6248	47	12.3
Year	**SPGWL**[2] (ft)	**SLGWL**[2] (ft)	**SGWLF**[2] (ft)
2000	-35.9	-43.1	7.2
2001	-33.6	-44.3	10.7
2002	-37.1	-45.1	8.0
2003	-41.0	-45.9	4.9
2004	-37.7	-45.8	8.0
2005	-34.9	NA	NA

[1] Approximate ground elevation and piezometer depth from Landslide Technology (2002).

[2] Positive values indicate level of potentiometric surface above the ground surface, negative values indicate ground-water levels below ground surface.

Abbreviations: MGWLF – maximum ground-water-level fluctuation (for measurement period [2000-2005]); SPGWL – seasonal peak ground-water level; SLGWL – seasonal low ground-water level; SGWLF – seasonal ground-water-level fluctuation; NA – not available.

Seasonal Ground-Water-Level Fluctuations in the Inactive Landslide

Our monthly monitoring of ground-water levels in the inactive part of the Green Pond landslide between June 2006 and December 2007 revealed relatively shallow ground-water levels that fluctuated synchronously (figure 4). Seasonal peak ground-water levels in 2007 occurred in April in each well, coinciding with the melting of most of the snowpack near the wells. In the two upslope wells, GP1 and GP2, the seasonal ground-water-level fluctuation in 2007 was 11.4 and 11.6 feet (3.5 and 3.5 m), respectively. However, because ground-water levels dropped below the bottom of well GP1, the measured seasonal fluctuation is a minimum value. The measured seasonal fluctuation in well BH123 was less, about 7.1 feet (2.2 m), but may have been larger due to measurement gaps during the period that the seasonal low ground-water level likely occurred.

Interpretation

Despite the two vibrating wire piezometers (B208 and B209) being separated by only a distance of about 180 feet (55 m) (figure 5), significant variation exists in the fluctuation of seasonal peak and low ground-water levels (figure 3). The continuous rise in peak ground-water level in the upslope piezometer B208 (figure 3A) between 2000 and 2005 contrasts with the fluctuations in peak ground-water level in downslope piezometer B209 (figure 3B). The synchronous fluctuation of seasonal peak ground-water level in piezometer B209 with annual (measured September through August) precipitation (figure 3B) suggests that snowpack (specifically, the snow water equivalent of the local snowpack) is the primary control on peak ground-water level. Thus, ground-water levels appear to fluctuate primarily in response to local recharge during snowmelt. In upslope piezometer B208, the variation in precipitation during the measurement period appears to not affect peak ground-water levels, and the cause for the continuous increase is unknown. The lack of response of peak ground-water level to annual precipitation in B208 is somewhat problematic given its possible location in a shallower thrust sheet than piezometer B209 (figure 5). One possibility is that the landslide debris surrounding piezometer B209 is more transmissive than that surrounding piezometer B208, allowing for efficient infiltration of directly overlying snowmelt water. Alternatively, the nearest underlying thrust (or thrusts) to piezometer B209 (figure 5) may allow for more effective flow of ground water perched above clay gouge due to the presence of laterally continuous transmissive debris possibly resulting from dilation of the debris during shear.

Seasonal low ground-water levels in the two wells have an inverse relationship, generally rising in upslope piezometer B208 (figure 3C), while declining in downslope piezometer B209 (figure 3D). The continuous decline in the seasonal low ground-water level in downslope piezometer B209 suggests relatively effective discharge during the dry sum-

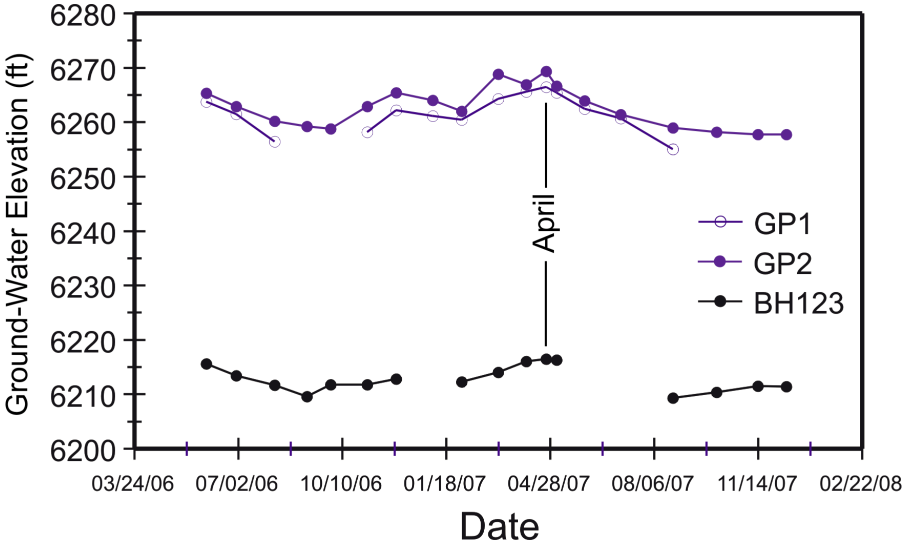

Figure 4. *Plot showing fluctuations in ground-water levels in the inactive northwestern part of the Green Pond landslide between June 2006 and December 2007. Seasonal peak ground-water levels in 2007 occurred in April in each well. Gaps in curves indicate periods where no measurements were made (BH123) or ground-water depth fell below the bottom of the well (GP1).*

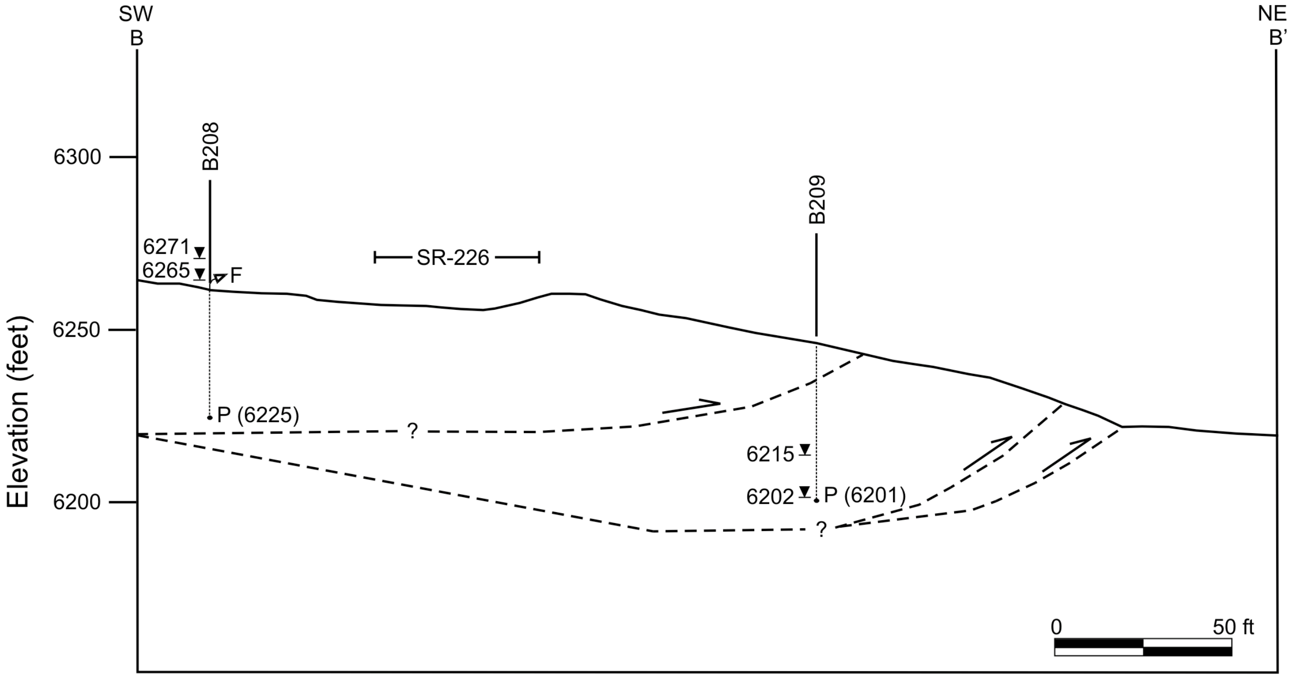

Figure 5. *Longitudinal cross section showing ground-water conditions across SR-226. Perennial flowing conditions exist in piezometer B208 upslope of SR-226. The inferred upper internal thrust is based on inclinometer data from Landslide Technology (2002). Other thrusts downslope of piezometer B209 are inferred based on geologic mapping. Thrust geometries (queried dashed lines) are conceptual, and many other possible thrusts (not shown) may exist. Approximate highest and lowest ground-water elevations shown for measurement periods described in text. Ground-water gradient is between 3 and 4 times steeper than average slope of ground between piezometers, suggesting ground water is compartmentalized by low permeability clay gouge along the thrusts. Abbreviations: P – vibrating wire piezometer, F – flowing well. See figure 2 for section line location.*

mer months. The well is located in a local moderate slope above a wetland area, and directly upslope of an internal thrust system (figures 2 and 5) in the active part of the slide. Ground water likely perches above clay gouge along the thrusts and discharges where the thrusts intercept the ground surface downslope of the piezometer. The abrupt flattening of the curve between 2003 and 2004 (figure 3D) may be due to the ground-water level declining to the approximate elevation of the piezometer.

Shallow ground-water-level fluctuations in the inactive part of the landslide are synchronous (figure 4). The very similar ground-water-level fluctuations in the wells, particularly given that the measured value in downslope well BH123 is a minimum, suggest that local snowpack is likely the controlling factor on seasonal fluctuations of ground-water levels in the inactive part of the landslide.

EVIDENCE SUGGESTING COMPARTMENTALIZATION OF GROUND WATER

Ground-water conditions directly adjacent to the landslide appear to differ from those within the inactive northwestern part of the slide. In monitoring well BH125, located outside the northwestern boundary of the landslide (inactive left-flank shear zone [ILFSZ] on figures 6 and 7), ground-water measurements indicate confined ground water and seasonal flowing artesian conditions. The borehole log for well BH125 suggests that either weathered Norwood Tuff, or landslide material derived from it, is as shallow as 12.5 feet (3.8 m). In contrast, the three monitoring wells in the inactive northwestern part of the landslide, between the ILFSZ and the currently active internal left-lateral shear zone (AILLSZ), all exhibit relatively similar ground-water-level conditions. As indicated previously, ground water is shallow in these wells and seasonal peak levels occurred concurrently in April 2007 in each well. However, the exact ground-water conditions (confined or unconfined) remain unknown. Nevertheless, the shallow depth of peak ground-water levels (with a few feet [1 m] of the ground surface) may allow for determination of ground-water conditions in the future.

In addition, the AILLSZ that separates the inactive northwestern part of the slide from the active middle part of the slide appears to be a barrier to ground-water flow. Despite the proximity of piezometer B208 to two of the shallow wells (GP1 and GP2) in the inactive part of the slide, perennial flowing artesian conditions exist in the piezometer. The different ground-water conditions in the wells separated by the AILLSZ suggest piezometer B208 is in a separate ground-water compartment than wells GP1 and GP2.

Differences in ground-water levels downslope of SR-226 also suggest that the AILLSZ forms a ground-water barrier. Although the measurement dates for ground-water levels for piezometer B209 and well BH123 shown on figure 6 do not overlap, the levels suggest higher ground water in the downslope well BH123 than in piezometer B209. This is confirmed by measured ground-water levels on May 25, 2002 (Landslide Technology, 2002) that indicate the ground-water level in downslope well BH123, located in the inactive part of the slide, was higher than in piezometer B209, despite the ground surface at the upslope well being about 20 feet (6 m) higher in elevation (figures 6 and 7).

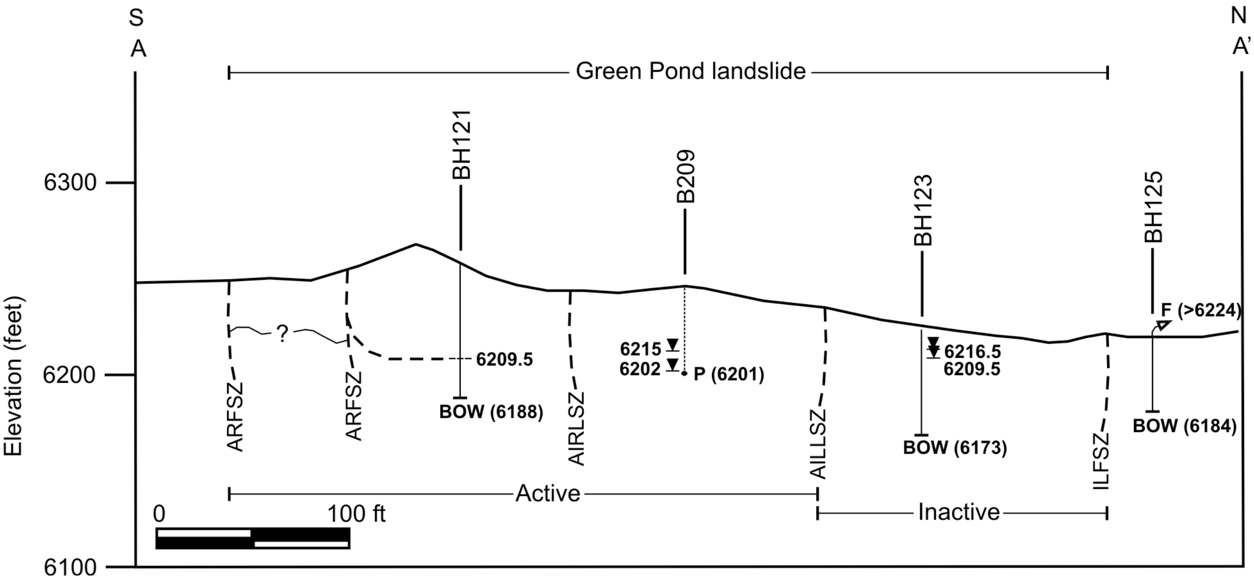

Figure 6. *Cross section showing ground-water conditions downslope of SR-226. Ground-water levels (elevations [in feet]) are higher in two downslope wells (BH123 and BH125) in the inactive northwestern part of the Green Pond landslide and north of the slide, respectively, than in vibrating wire piezometer B209 in the active part of the slide. Well BH121 in the active southern part of the slide is dry to a depth below the range in ground-water levels measured in B209, but is partly sheared off by an internal thrust in the slide (at approximate elevation 6209.5 feet). Other thrusts not shown. Uncertainty in the exact location of the active right-flank shear zone (ARFSZ) shown. Approximate elevations of vibrating wire piezometers or bottom of standpipe wells shown in parenthesis. Approximate highest and lowest ground-water elevations shown for measurement periods described in text. Abbreviations: P – vibrating wire piezometer, BOW – bottom of observation well, F – flowing well. See figure 2 for shear zone abbreviations and section line location.*

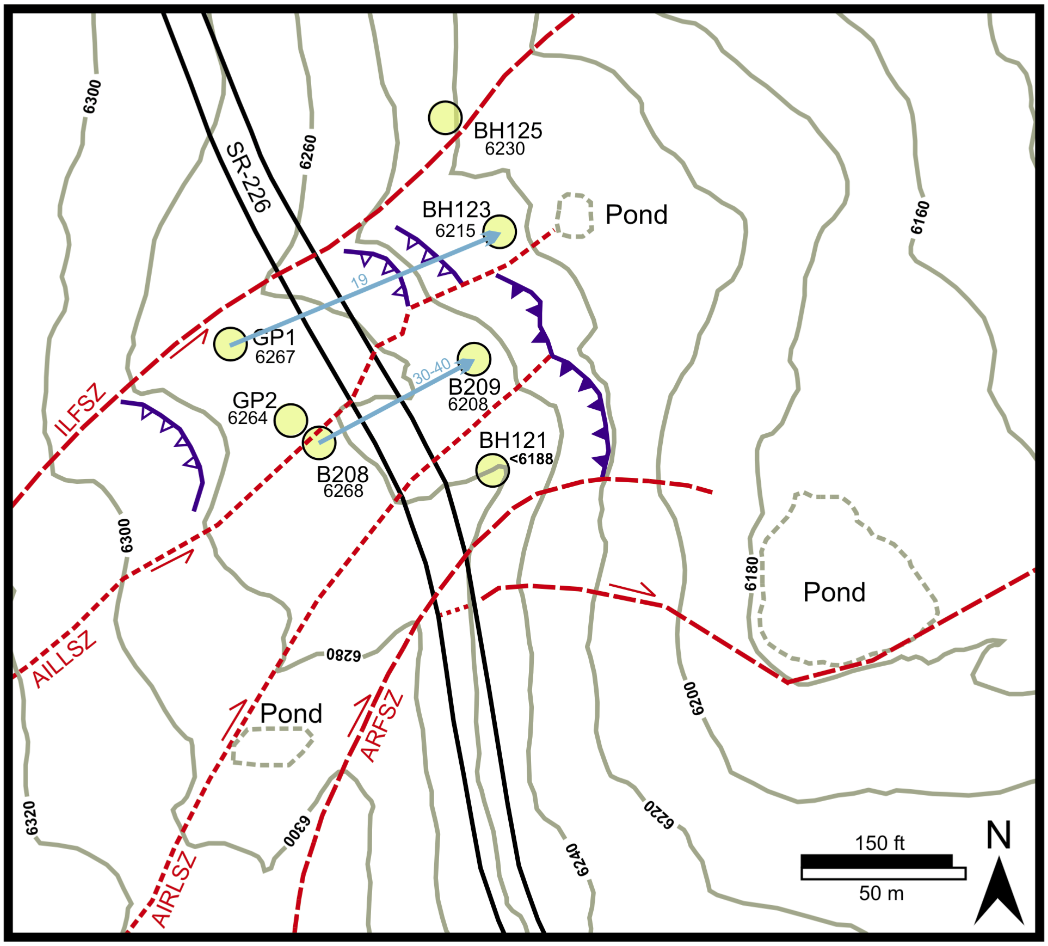

***Figure 7.** Detailed map of Green Pond landslide at SR-226 showing ground-water elevations on May 25, 2002, (Landslide Technology, 2002) and ground-water gradients (blue arrows; gradient in percent). Topography from Landslide Technology (2002). Contour interval is 20 feet. See figure 2 for additional information.*

Figure 7 also shows differences between two "hypothetical" ground-water gradients (the inferred gradients assume no barriers to ground-water flow) defined by wells GP1 and BH123 and piezometers B208 and B209, in the inactive and active middle parts of the landslide, respectively. The "hypothetical" ground-water gradient in the inactive northwestern part of the slide is about half as steep as that in the active middle part of the slide; however, the lowermost well/piezometer in each pair is in a different location in the thrust system downslope of SR-226 (figure 7). One possibility is that ground water in each longitudinal section of the slide is also controlled by ground-water barriers formed by clay gouge along thrusts in the internal thrust systems.

Compartmentalization of ground water by the internal thrust systems in the landslide is suggested by differences in ground-water conditions in the active middle part of the slide. Unlike piezometer B208, piezometer B209 does not indicate flowing artesian conditions, and ground-water-level fluctuations differ from those in piezometer B208. Figure 5 shows that the "hypothetical" ground-water gradient between the two piezometers is between 3 and 4 times greater than the ground slope between the two wells. One possible cause for the oversteepened "hypothetical" gradient is that both piezometers are located in separate ground-water compartments. These compartments may be bounded by low permeability clay gouge that forms along internal thrusts (figure 5).

The only well (BH121) in the southeastern longitudinal section of the landslide defined by the active right-flank (ARFSZ) and active internal right-lateral shear zones (AIRLSZ) is dry to a depth of about 51 feet (bottom of well). Thus, ground-water levels are below at least the upper part of the range in ground-water levels in piezometer B209 (figures 6 and 7). The dry well suggests the AIRLSZ that separates well BH121 from piezometer B209 may also be a barrier to ground-water flow.

The structural complexity of the Green Pond landslide, particularly the part crossed by SR-226, likely results in a similarly complex ground-water-flow system where longitudinal strike-slip shear zones facilitate ground-water flow downslope, but limit flow across the zones. Clay gouge along numerous internal thrusts (figure 5 only shows a few of many likely thrusts) inhibits flow downslope and generally allows local recharge to only the uppermost thrust sheet in a vertical section of stacked thrusts. Folds and thrust ramps likely further complicate ground-water flow, creating higher pore pressures on upslope-tilted surfaces and lower pore pressures on downslope-tilted surfaces (Baum and Johnson, 1993).

SUMMARY

Ground-water-level measurements from five observation wells and ground-water-level data from two vibrating wire piezometers allowed us to analyze ground-water conditions in the narrow part of the Green Pond landslide crossed by SR-226. Shallow ground-water levels fluctuated synchronously between June 2006 and late 2007 in the inactive northwestern part of the landslide. However, variations were ob-served over approximately six years in seasonal peak and low ground-water levels in two vibrating wire piezometers in the active middle part of the slide. In the lowermost of the two piezometers, fluctations appeared to be related to variation in annual precipitation. We interpret these results as indicating that ground water is locally recharged in parts of the slide, including in the inactive northwestern part. Differences in ground-water elevation and "hypothetical" ground-water gradients, and local flowing artesian conditions suggest compartmentalization of ground water in the slide, possibly by low permeability clay gouge along deformation features.

LIMITATIONS

A significant limitation of this report is the lack of subsurface information for all the monitoring wells. Leslie Heppler (Utah Department of Transportation) provided borehole logs for three of the wells (BH121, BH123, and BH125), but we did not have access to borehole logs for the remaining wells and piezometers. The three boreholes were logged by a consultant, and reliance on subsurface interpretation by others is also a limitation. Well construction information is restricted to well or piezometer depth, and no information on wellscreen interval or well construction is provided. More critical is the lack of data on ground-water conditions where flowing artesian conditions were not present, such as the depth and thickness of saturated soils. Two of the wells (GP1 and GP2) were installed in test pits (UDOT TH-1 and TH-2, respectively), but appear to provide accurate shallow ground-water levels. In one of these wells (GP1), the ground-water level dropped below the bottom of well in the latter part of the year. Our interpretation related to possible ground-water compartmentalization would have been aided by temporal overlap of our ground-water-level monitoring and the UDOT ground-water-level data for piezometers B208 and B209.

ACKNOWLEDGMENTS

Leslie Heppler (Utah Department of Transportation) provided the ground-water-level data for piezometers B208 and B209 and some borehole logs. We appreciate helpful review comments from Steve Bowman and Mike Hylland (UGS).

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