ACTIVE LANDSLIDES

IN THE CREEKSIDE DRIVE AREA, MOUNTAIN GREEN, MORGAN COUNTY, UTAH, BETWEEN JUNE 2005 AND DECEMBER 2006

by

Francis X. Ashland

REPORT OF INVESTIGATION 260
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Cover photos: Damage and ground deformation caused by the Creekside Drive area landslides: (A) main scarp across access road on lot 18, (B) cracks in northwest wall of house at 5983 N. River View Circle, (C) main scarp at 6023 N. Creekside Drive, (D) cracking and distortion to attached garage at 6023 N. Creekside Drive, (E) driveway partially suspended above ground surface due to movement of the Cascade Drive landslide, (F) road crack in Creekside Drive, (G) folded and displaced shallow soil and sod in backyard at 6023 N. Creekside Drive, (H) kinked drainpipe in Southern Sewer-Line landslide.

ISBN 1-55791-777-9

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CONTENTS

FIGURES

TABLES

ACTIVE LANDSLIDES IN THE CREEKSIDE DRIVE AREA, MOUNTAIN GREEN, MORGAN COUNTY, UTAH, BETWEEN JUNE 2005 AND DECEMBER 2006

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ABSTRACT

Landsliding in the Creekside Drive area of Mountain Green, Utah, in 2005 and 2006 damaged three houses, a road, and buried utilities, and threatened a buried sewer line, another house, and several other residential lots. The landslides resulted from the total and partial reactivation of pre-existing slides in slopes underlain by Tertiary Norwood Tuff. Monitoring by the Utah Geological Survey showed that two of the three largest slides remained active between June and December 2005. Renewed or accelerated movement of the landslides in 2006 was accompanied by the formation of new slides, one of which affected two residential lots and threatened a house.

Damaging landslides occurred despite both subdivision-wide and lot-specific, predevelopment, geologic and geotechnical studies by consultants hired by the developer. The earliest study recommended avoidance of the landslide hazard at many of the proposed lots, and adherence to this recommendation would have reduced the losses in 2005 and 2006. None of the studies indicated the potential for reactivation of the large, pre-existing, deep-seated landslides in the area, which resulted in the largest and most damaging of the slides, the Creekside Drive landslide, in 2005. Damaging landsliding occurred less than four years after construction of a house on the head of the Creekside Drive landslide and the completion of lot-specific geotechnical studies.

The potential for continued landslide movement is high in the absence of expensive landslide stabilization. Thus, additional losses are likely as landslide movement and ground deformation continue. This landslide case history illustrates the marginal stability of pre-existing landslides in the area (western Morgan County) and the need for stabilization of the slides prior to development.

INTRODUCTION

Background

Sometime in early 2005, landsliding initiated in the Creekside Drive area of the Highlands West subdivision in Mountain Green (figures 1 and 2), an area of pre-existing landslides with local historical movement (Kaliser, 1972) underlain by Tertiary Norwood Tuff. By June 2005, movement of the largest landslide and accompanying ground deformation had caused severe damage to a house and residential lot at 6023 N. Creekside Drive, damaged Creekside Drive, and had caused minor cracking in two other houses. Two landslides also threatened a buried sewer line (Ashland, 2006). Movement at two of three monitored slides continued at a very slow rate throughout 2005 and into 2006. By early 2006, the rate of movement at the two slides increased, and movement of the largest, the Creekside Drive landslide, caused additional damage to the three houses on it as well as to Creekside Drive, disrupting buried utilities in the spring. By 2006, two additional moderate-size, active landslides and several small slides were identified in and abutting the Highlands West subdivision. In 2006, a rock wall behind a house at 6067 N. Creekside Drive also failed.

At the request of Morgan County officials, the Utah Geological Survey (UGS) began investigations on June 8, 2005, that remain ongoing to characterize landsliding in the Creekside Drive area and assess the short-term public-safety issues and long-term implications for development. Preliminary results of the investigations, particularly landslide movement data, were provided routinely to various county officials and other interested parties including affected residents. This report summarizes the results of the UGS investigations, incorporating some data from a county-funded subsurface investigation by Cotton Shires and Associates, Inc. UGS Technical Report 06-04 (Ashland, 2006) summarizes the results of an investigation of the two landslides threatening a Mountain Green Sewer Improvement District sewer line. This report provides supplemental data on the movement of those two slides following the release of the 2006 UGS report.

Active landsliding was not limited to only the Creekside Drive area in 2005 and 2006, but occurred throughout western Morgan County and the adjoining part of Weber County. Most of the pre-existing landslides in cut slopes along State Routes 167 (SR-167; Trappers Loop Road) and 226 (SR-226; Snowbasin access road) reactivated in 2005 and 2006. Two landslides that had initially formed in a soil-waste dump along the south side of SR-167 in 2004 reactivated and enlarged in size in both 2005 and 2006. In addition, a partial reactivation of the 2001 Frontier Drive landslide (Ashland, 2001), about a mile to the northeast of the Creekside Drive area, occurred in early 2006 despite a buttress having been constructed to stabilize the slide by 2002. Movement monitoring and field observations by the UGS also indicated minor movement of two large landslides, the Green Pond and Bear Wallow slides, along SR-226 in 2006.

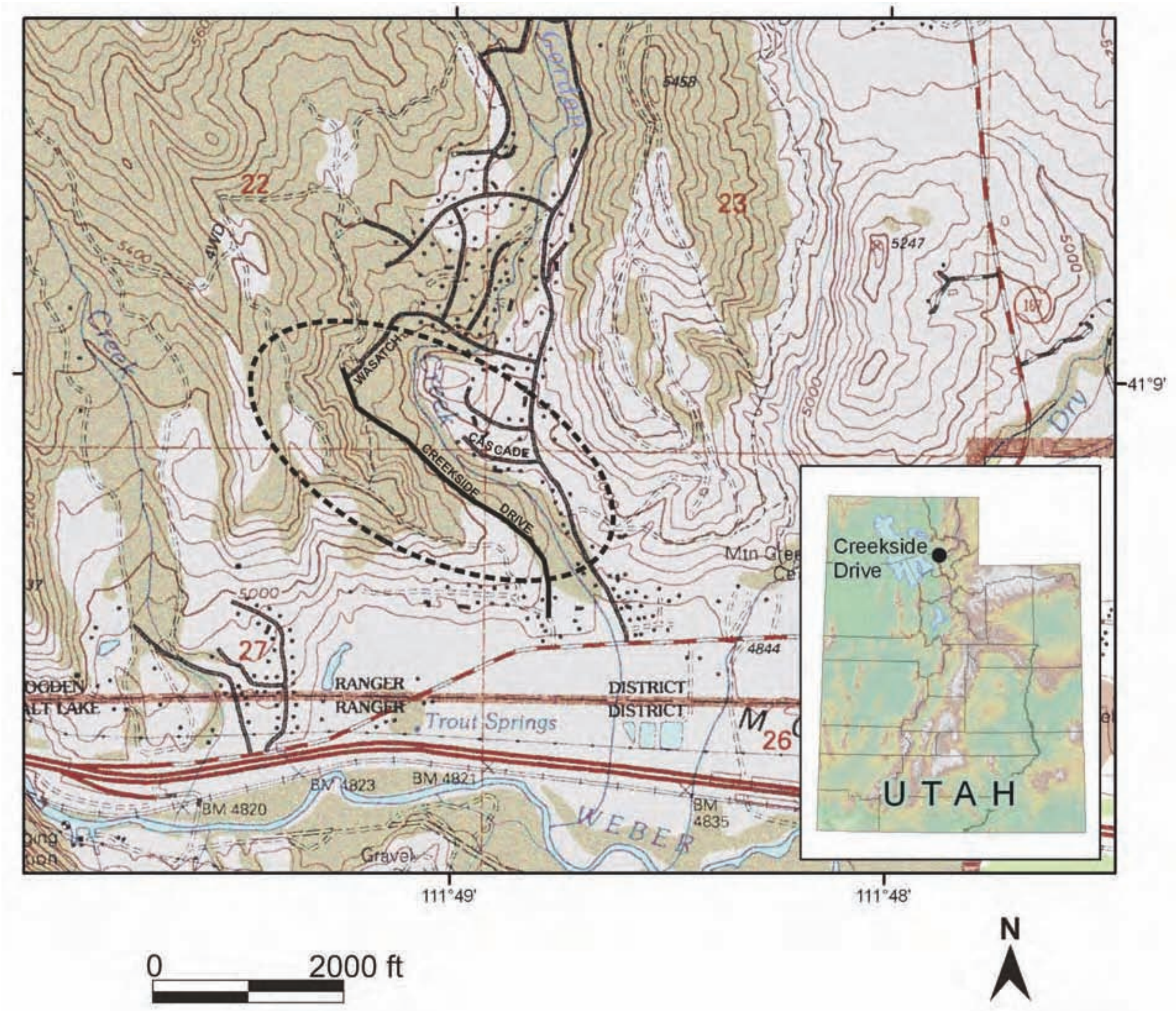

Figure 1. Location of the Creekside Drive area in the Highlands West subdivision, Mountain Green, Utah. Dashed oval shows approximate area of landsliding. Base from U.S. Geological Survey Snow Basin 7.5′ quadrangle.

Field Methods

Landslide boundaries and ground deformation features were mapped using recreation-grade Global Positioning System devices with an approximate horizontal accuracy range of between 10 and 30 feet at the time of the fieldwork. Maps of the 2005 and 2006 landslides (figure 2) and some of the dimensions listed in this report were derived using this method. Short-term variation in location was tested using duplicate measurements from the same device and was typically less than 2 feet. Larger, northeast-directed systematic errors were noted when transferring field data onto orthophoto or other bases. Dimensions of the small slides were measured using a steel tape and clinometer.

CONCLUSIONS

Based on the results of geologic investigations of landslides in the Creekside Drive area and other nearby active slides, the UGS concludes the following:

- The active landslides of 2005 and 2006 included as many as five moderate or larger size slides and several small slides. The largest, the Creekside Drive landslide, was a reactivation of a pre-existing landslide. Most of the others were the result of partial reactivation of pre-existing slides. The smaller slides formed in cut slopes or embankment fills.

- In 2005 and 2006, most of the movement likely occurred in March and April. Since June 2005, movement occurred at a very slow rate at three monitored slides. The timing of the movement suggests the triggering mechanism was a rise in ground-water levels coincident with the snowmelt. Movement at the Creekside Drive and Southern Sewer-Line landslides may have been continuous between June 2005 and December 2006.

- Most of the damage was caused by movement of the Creekside Drive landslide, which affects at least five, and perhaps as many as seven, lots and has damaged three houses, one so severely it was abandoned in 2006. The landslide has also damaged

Creekside Drive and severed buried utilities under the road.

- The coincidence of active landsliding in the Creekside Drive area with active sliding elsewhere in western Morgan and the adjoining part of Weber County suggests a geologic-climatic-hydrologic cause rather than a human one; however, hillside modifications associated with residential development likely were destabilizing, and cut slopes in particular resulted in shallow landslides.
- The losses due to damaging landsliding were avoidable, or could have been greatly reduced, if the landslide hazard had been adequately identified, characterized, and mitigated in predevelopment geologic and geotechnical studies.
- Future movement of some of the landslides is likely, even during periods of near-normal precipitation.
- Future safe development in the area requires avoidance of marginally stable pre-existing landslides, or landslide stabilization prior to development, through mechanical (tiebacks, shear keys, etc.) and/or other means of stabilization such as mass grading.

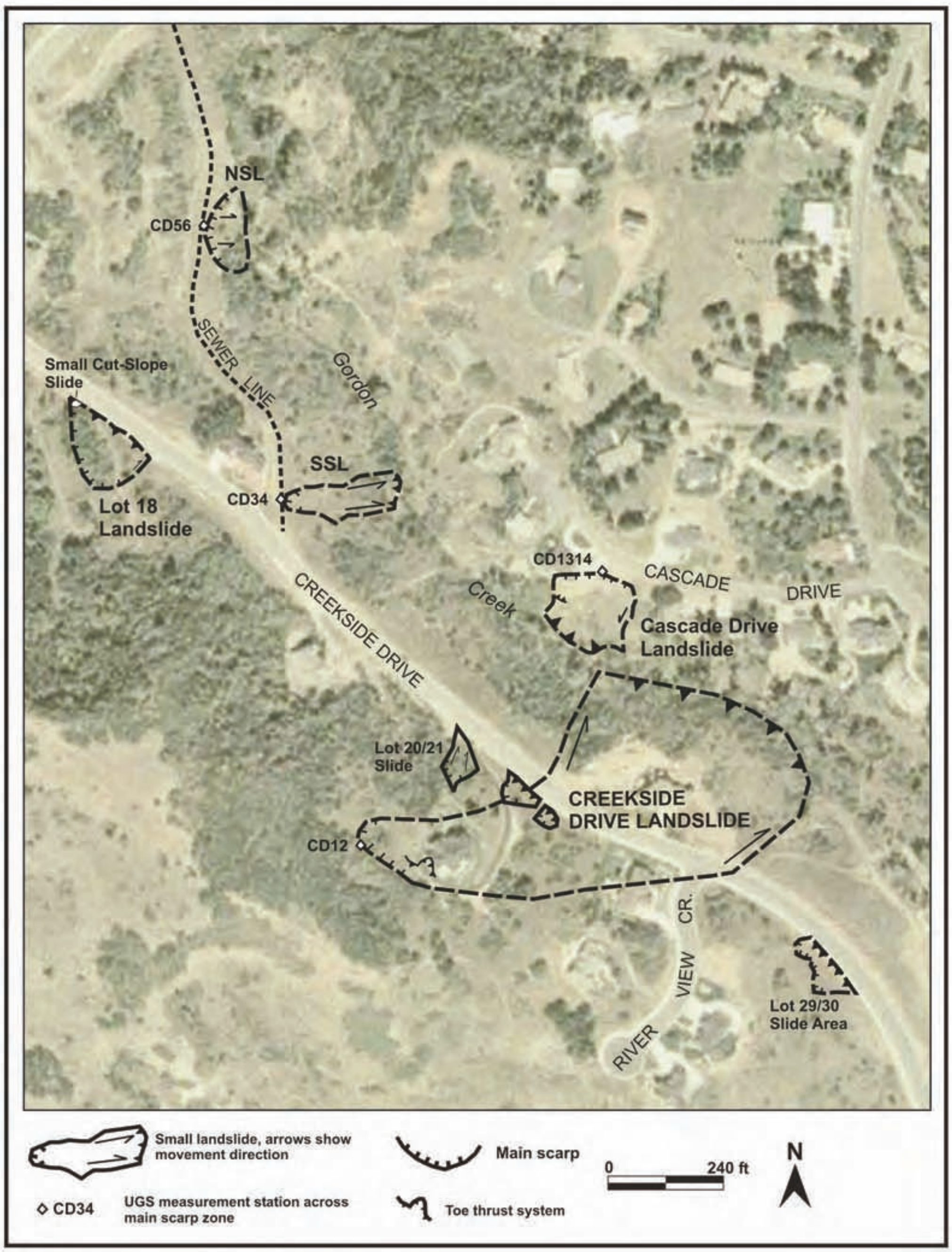

Figure 2. *Aerial photograph showing approximate locations of active landslides in the Creekside Drive area, Mountain Green, in 2005 and 2006. Landslides include the Creekside Drive, Cascade Drive, Lot 18, Northern Sewer-Line (NSL), and Southern Sewer-Line (SSL) landslides, and five small slides along Creekside Drive. Toe of possible upper shallow slide in head of Creekside Drive landslide also shown. All boundaries and dimensions of landslides are approximate. Solid lines used to define boundaries of smaller slides.*

GEOLOGY

The Creekside Drive area of Mountain Green is underlain by a complex of late Holocene and older landslides in the underlying Tertiary Norwood Tuff (Kaliser, 1972; Coogan and King, 2001). The Norwood Tuff consists of tuffaceous sedimentary rocks and crops out along the northwest-trending ridge crest to the southwest of Creekside Drive. The ridge is flanked on three sides (north, east, and south) by landslides in the tuff and Quaternary surficial deposits on the tuff. To the west, the Norwood Tuff overlies the Tertiary Wasatch Formation, which consists mostly of conglomerate and sandstone. The bedding in these formations is poorly exposed, but dips moderately to the east in the Creekside Drive area (Coogan and King, 2001). The moderate dip of the bedding and the aspect of most of the landslides suggest bedding orientation is not a causative factor for the active landsliding in 2005 and 2006. Soils developed in residual, colluvial, and landslide deposits derived from the Norwood Tuff are commonly expansive.

PREHISTORIC AND HISTORICAL LANDSLIDING

Previous landsliding, both prehistoric and historical, has been documented in the Creekside Drive area (Goode, 1972; Kaliser, 1972, 1996, 1999; Earthtec Testing & Engineering [Earthtec], 1996, 1999, 2001a, 2001b, 2001c, 2001d). Kaliser (1972) mapped most of the Creekside Drive area as a pre-existing landslide, including a part of the slope on the northeast side of Gordon Creek. Kaliser (1972) indicated local areas of historical sliding and provided landslide movement data from an extensometer across the head of a 100-foot-long slide in the Creekside Drive area. Goode (1972) conducted a predevelopment geologic study for an early version of the Highlands West subdivision, and identified the area as being underlain by landslides and landslide-prone rock (Norwood Tuff). Goode (1972) characterized much of the area as unstable, including several of the lots affected by landsliding in 2005 and 2006. However, some of the lots Goode characterized as stable and, thus, suitable for proposed residential development were also affected by landsliding by 2005. Goode (1972) also mapped six shallow historical landslides in cut slopes along the future alignment of Creekside Drive and several smaller shallow slides along Gordon Creek. Subdivision-scale, predevelopment geotechnical (Earthtec, 1996, 1999) and geologic (Kaliser, 1996, 1999) studies identified both prehistoric and recent landslides in the proposed Highlands West subdivision. Kaliser's (1999) characterization of subsurface conditions included local shallow ground water and back-tilting due to prehistoric, deep-seated rotational landsliding. Kaliser (1999) also identified landslide scarps, including one as high as 8 feet and one historical scarp, on three separate lots. In 2001, several shallow rotational landslides occurred in cut slopes along the current Creekside Drive (Earthtec, 2001c, 2001d) including one on the northeast corner of the lot at 6023 N. Creekside Drive (lot 21). Earthtec (2001c) also indicated settlement behind a rock wall along Creekside Drive.

2005-06 LANDSLIDE DESCRIPTIONS

In 2005, the UGS identified six separate active landslides or slide areas in the Creekside Drive area (figure 2). The largest, referred to herein as the Creekside Drive landslide, affected three houses and two or more vacant lots. The Creekside Drive landslide included three small, shallow slides that were on or straddled the left flank of the main slide, each in cut slopes either along Creekside Drive or upslope of the house at 6023 N. Creekside Drive. Two moderate-sized landslides occurred directly downslope of the Mountain Green Sewer Improvement District sewer line (Ashland, 2006). In addition, three small landslides or slide areas occurred in cut slopes along Creekside Drive.

By 2006, six other landslides were identified, including two moderate-size landslides (shown on figure 2) that both affected vacant land, one of which also threatened a house on Cascade Drive. Two small landslides also were identified near the intersection of Creekside Drive and Wasatch Drive, one in an embankment and another in a nearby cut slope. A very small rotational slide occurred in a cut slope near the north end of the driveway at 6067 N. Creekside Drive. In addition, an embankment failure also occurred along the lower part of the access road on lot 20.

2005 Landslides

Six separate landslides, or slide areas, were identified in the Creekside Drive area in 2005 including the following:

1. the Creekside Drive landslide,
2. two slides along the sewer line (Southern Sewer-Line and Northern Sewer-Line slides),
3. a small landslide near the boundary between lots 20 and 21,
4. a small slide area in a cut slope east of River View Circle, and
5. a very small slide in a cut slope near a utility box.

Ashland (2006) previously described the two landslides abutting the sewer line and thus no further description is provided in this report.

Creekside Drive Landslide

The landslide that severely damaged the house at 6023 N. Creekside Drive (lot 21) and affected two others was the largest and deepest of the Creekside Drive area slides in 2005. The exact dimensions of the landslide remain unknown due to the lack of continuous ground deformation features along its perimeter. However, the landslide is approximately 850 feet long in a northeast direction, and 500 feet wide along its toe near Gordon Creek. Table 1 summarizes the approximate dimensions, relief, and average slope of the landslide. Figure 3 shows the probable boundaries of the pre-existing landslide, prior to 2005, mapped using a detailed topographic map of the area. The landslide narrows considerably upslope and is shorter and steeper along its left flank than along its right flank. An inclinometer installed by Cot-

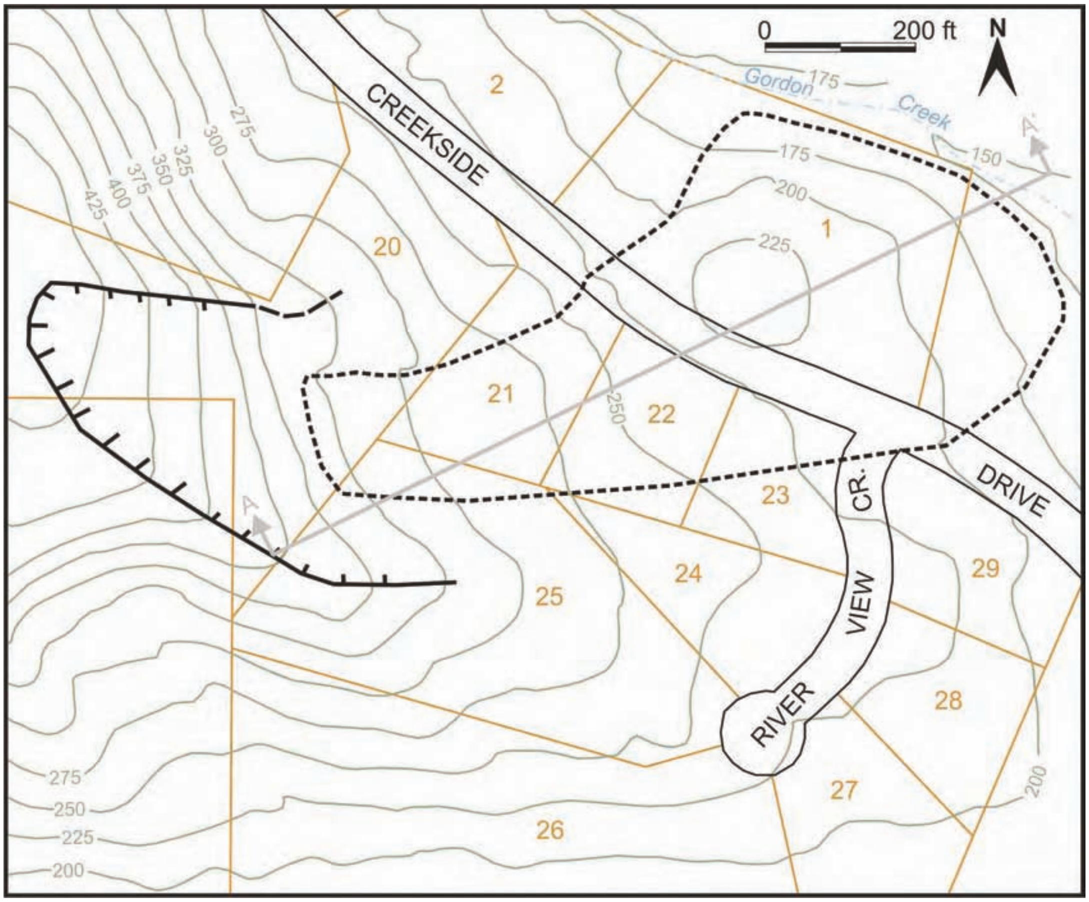

Figure 3. Map of probable pre-existing Creekside Drive landslide prior to 2005. Solid hachured line is main scarp. Dashed line is likely deposit boundary. Line of geologic cross section (figure 4) shown by A-A′. Highlands West lot numbers shown. Landslide mapping based on topographic map provided by David Simon (Simon-Bymaster Inc.).

Table 1. Approximate dimensions, relief, and average slope of the Creekside Drive landslide.

Description	Length (ft)	Width (ft)	Relief (ft)	Slope (%)
General	850	150[a] to 500[b]	—	—
Left flank	620	—	140	22
Right flank	970	—	145	15

[a]Head
[b]Toe

ton, Shires and Associates, Inc. in 2006 revealed the landslide was about 58 feet deep beneath Creekside Drive near its left flank (figure 4).

Three small, shallow slides (figures 5 and 6) on or straddling the Creekside Drive landslide included two in a cut slope directly above Creekside Drive, and a third in a cut slope upslope of the house on the head of the main slide. In June 2005, ground-deformation features associated with these three slides were the most discernable features within the limits of the main landslide. The two landslides along Creekside Drive damaged the driveway, displaced rock walls, severed a buried drainpipe, and threatened other buried utilities (figure 5). The upper slide folded and displaced sod in the backyard, displaced (nearly intact) a small retaining wall, and possibly caused some of the damage to the house (figure 6A, 6B). By early June 2005, the toe of the upper slide was in contact with a garage attached to the house (figures 6B and 7). Table 2 summarizes the approximate dimensions, relief, and average slope of the slides.

The easternmost of the lower slides along Creekside Drive (figure 5A) was mostly in the northeast-facing cut slope, but the head of the slide extended slightly into the natural slope above the crest of the cut slope (figure 5B). The head of the slide was cut by several minor scarps that formed steps in the slope. The toe of the landslide was in the ditch at the base of the cut slope directly southwest of the side-

Table 2. Approximate dimensions, relief, and average slope of the small slides on or straddling the Creekside Drive landslide.

Landslide	Length (ft)	Width (ft)	Relief (ft)	Slope (%)
Lot 21/22	58[a]	42[b]	21[c]	36[c]
Lot 21 – lower	48[a]	60[b]	25[d]	51[d]
Upper	—	19[b]	—	—

[a]Horizontal distance between head and toe
[b]Toe
[c]Head
[d]Crown

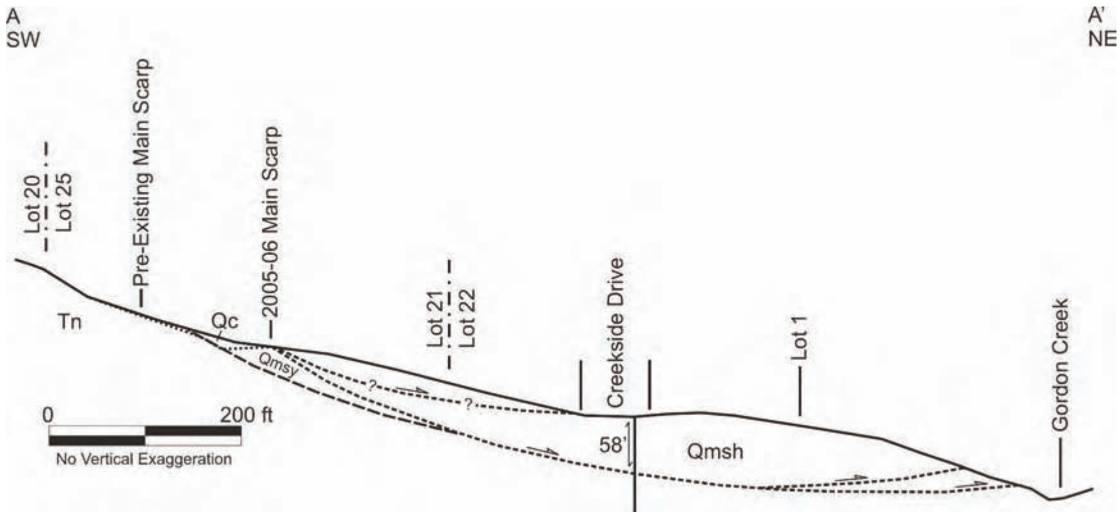

__Figure 4.__ Geologic cross section through the Creekside Drive landslide (Qmsh). Short dashed lines show probable geometry of landslide. Queried dashed line is possible shallow slide that has a surface of rupture which daylights near Creekside Drive. Other small shallow slides not shown (see text). Long dashed line shows probable upslope extension of inactive surface of rupture of pre-existing slide (Qmsy). Dotted line shows possible contact between colluvium (Qc) associated with main scarp of pre-existing slide and landslide deposits. Landslide underlain by weathered Norwood Tuff (Tn). Solid vertical line shows approximate location of inclinometer installed by Cotton Shires & Associates, Inc., in 2006 and depth of active slide. See figure 3 for section line location.

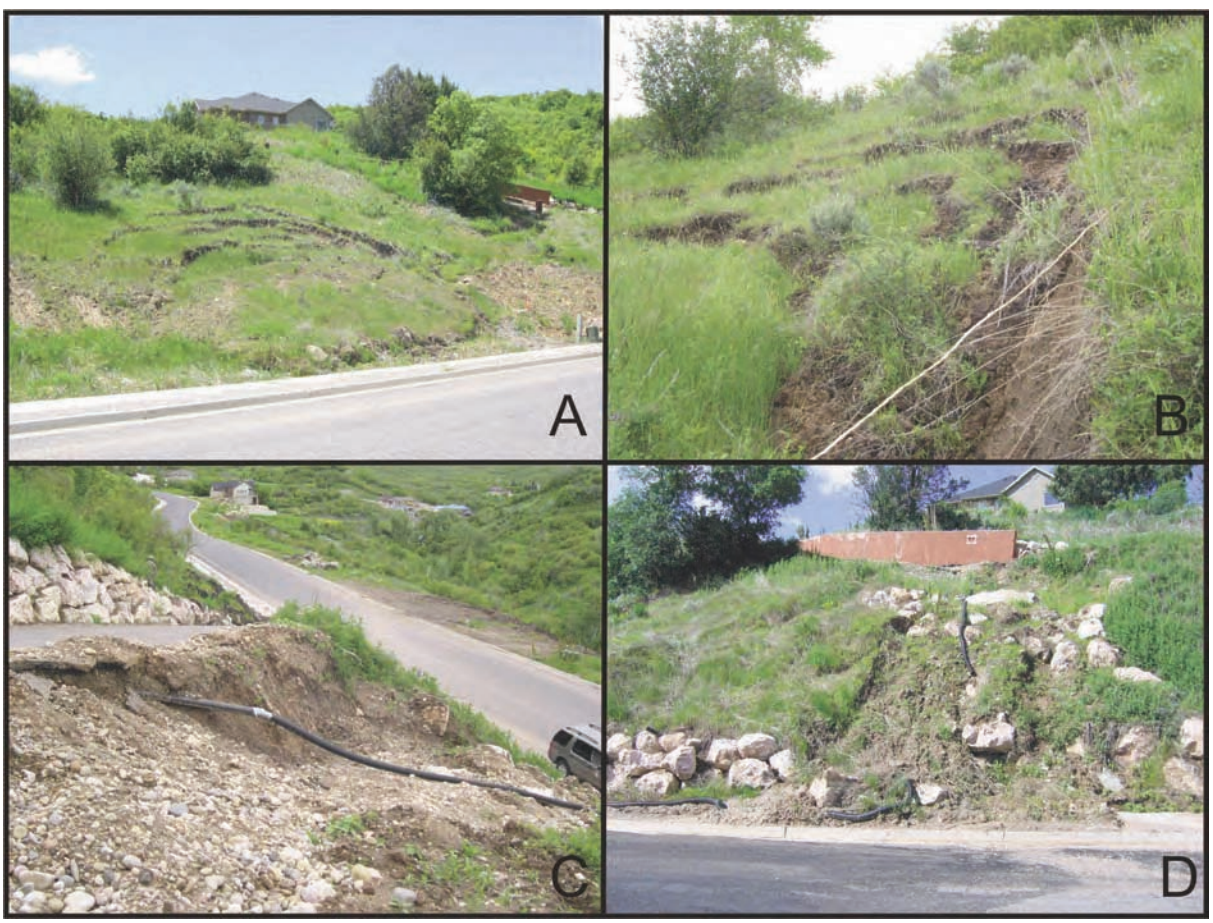

__Figure 5.__ Small shallow slides on or straddling the Creekside Drive landslide. (A) View to the southwest of small shallow landslide in cut slope near boundary between lots 21 and 22. (B) View to the southeast of main scarp zone showing stretched white electric line. (C) View to the west of main scarp and west flank of small landslide between driveway at 6023 N. and Creekside Drive. Main-scarp offset severed drainpipe in 2005 (repaired in photograph). (D) View to the southwest of slide in photograph C in June 2006. Note new damage to drainpipe and displaced material burying sidewalk. Small rock wall on left was continuous across slide in 2005.

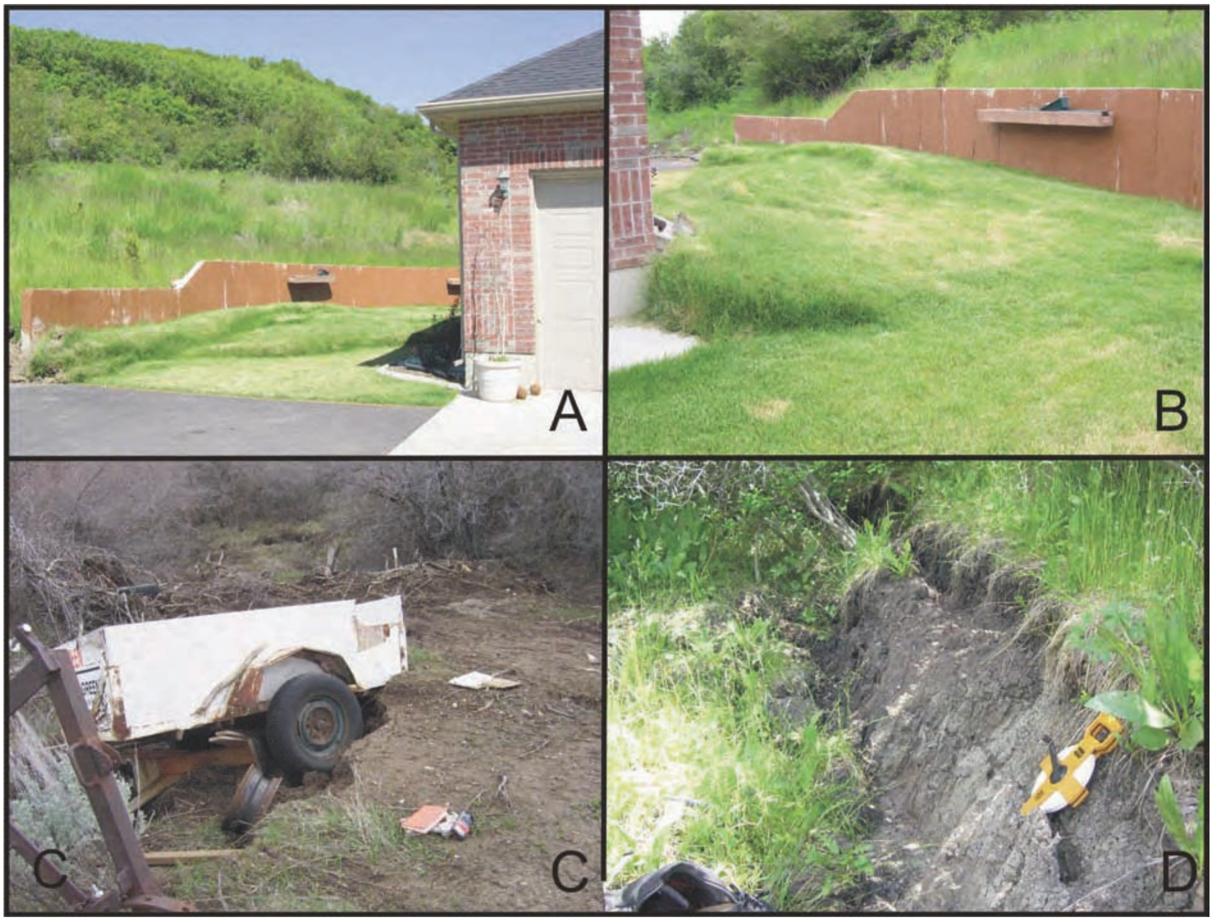

Figure 6. *Landslide deformation features possibly associated with the upper shallow slide in head of Creekside Drive landslide. (A) View to the west of toe thrust system in backyard at 6023 N. Creekside Drive. Shallow soil and sod are folded and displaced between retaining wall and garage. (B) View to the southeast of northern corner of toe thrust system. (C) View to the south of scarp on lot 20. Abandoned trailer is dropped down about a foot due to offset on scarp. (D) View to the east of scarp on lot 21. Scarp height on June 10, 2005, was about 3.4 feet.*

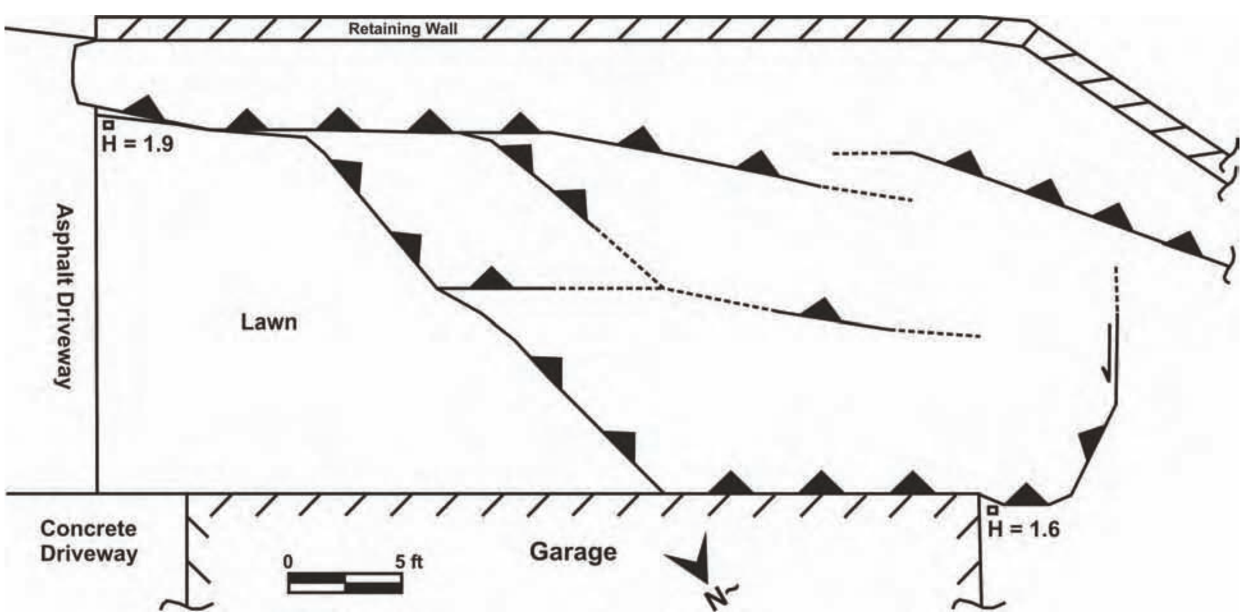

Figure 7. *Detailed sketch (plan view) of toe thrust system in backyard at 6023 N. Creekside Drive. Squares indicate height of folds (in feet). Triangles on upthrown side of thrusts. Dashed lines indicate decreasing offset toward thrust tip. Mapped on January 26, 2007.*

walk. This landslide possibly occupied the site of a previous shallow landslide observed in 2001 along the cut slope at the northeast corner of the lot (Earthtec, 2001c).

The second small, shallow slide directly northwest of the slide described above was solely in a cut and/or fill (upper part) slope below the driveway that diagonally crossed the lower part of lot 21. The main scarp of the landslide abutted the northeast edge of the driveway. Main-scarp offset damaged the pavement and severed a drainpipe (figure 5C). A guardrail post and small rock wall along the edge of the driveway were displaced downslope on the head of the landslide. Movement at the toe of the landslide displaced a second small rock wall at the base of the cut slope, pushing one boulder onto the sidewalk. Buried utilities (gas and electric lines) connecting to the house upslope crossed the cut slope near the east flank of the landslide.

The upper shallow slide consisted of two distinct parts separated by a concrete retaining wall. A toe thrust system below the wall consisted of two major thrusts and one minor thrust above which the sod and topsoil in the backyard were folded (figures 6A, 6B, and 7). The frontal thrust in the system was in contact with the upslope wall of an attached garage. Landscaping curbstones were displaced and tilted where the toe thrust intercepted them. The height of the fold atop the frontal toe thrust was less than a foot. A second major thrust was only a few feet directly below the wall and extended to the northwest beyond the limits of the frontal toe thrust. On the southeast edge of the toe, the downslope edge of both thrusts merged and the combined height of the folds above each thrust was about two feet. The toe thrust system abruptly ended at the southeast end of the retaining wall and the edge of the asphalt driveway (figures 6A and 7). To the northwest, the second thrust paralleled the retaining wall and crossed a small landscaped garden area where other curbstones were tilted. An arcuate minor thrust was between the two major thrusts. A small splay fault connected it to the frontal thrust.

Upslope of the retaining wall, the upper slide consisted of a zone of scarps and ground cracks. Locally, the uppermost (main) scarp was not necessarily the scarp with the greatest offset (figure 6D). The northwestward extension of the main scarp zone onto the adjacent lot (figure 6C) and beyond any well-defined toe features in the landscaped areas upslope of, or adjacent to, the house is problematic, suggesting the scarps were not caused solely by small local landsliding upslope of the house at 6023 N. Creekside Drive. Instead, the scarps may be due to movement of the deep-seated landslide and a shallower, but unconfirmed, slide within the main slide with a toe near Creekside Drive (see queried surface of rupture in figure 4).

The concrete retaining wall between the scarps and the toe thrust system remained mostly undamaged throughout 2005 with only a single high-angle crack near the center of the thrust system. The integrity of the retaining wall suggests that (1) it was either displaced uniformly downslope atop underlying thrusts associated with the small shallow upper slide, or (2) uniform movement (yielding) of the wall at a rate faster than the movement of the garage associated with deep-seated landsliding was the cause of the thrusts in the backyard. In support of the latter case, the thrusts and folds exist mostly between the retaining wall and the attached garage (figure 7). Thus, the toe thrust system may be the result of shortening between the retaining wall and the garage caused by a faster movement rate of the wall relative to the garage. Therefore, a separable upper, small shallow slide may not exist, but rather, all the landslide deformation features upslope of the house may reflect deep-seated movement and differential movement rates in the upper part of the slide.

Ground-deformation features that defined the perimeter of the Creekside Drive landslide in 2005 were limited to three clusters of en echelon right-stepping cracks along the left flank (figure 8) and the main scarp zone. The three separate clusters of cracks defining the left flank of the slide were:

1. a right-stepping shear crack zone in the northwest part of the lawn at 6023 N. Creekside Drive that offset landscaping curbstones (figure 8B),

2. en echelon cracks in the lower driveway at 6023 N. Creekside Drive (figure 8C), and

3. right-stepping cracks in and abutting (to the north) Creekside Drive (figure 8D, 8E).

By 2006, features defining the upper left flank of the landslide were better developed and included a continuous shear crack on lot 20 that joined the main scarp zone (figure 8A).

The clusters of cracks were each separated from the next by a right step indicating left-lateral shear along the flank consistent with deep-seated landsliding. In June 2005, the main scarp zone consisted of several discontinuous scarps that ranged between 2.3 and 3.4 feet high, and ground fissures, both transverse and longitudinal, downslope of the scarps. The main scarp height was somewhat enigmatic because it exceeded the magnitude of other ground deformation associated with the main slide, suggesting that most of the offset and ground deformation was attributable to movement of either the upper shallow slide or an undetected slide in the upper part of the Creekside Drive landslide (see queried surface of rupture in figure 4).

The toe of the Creekside Drive landslide was poorly defined on the lower, locally thickly vegetated slope abutting Gordon Creek. The basal surface of rupture of the landslide appeared to splay, forming a system of thrusts that intercepted the ground in several locations where shallow soils were folded or oversteepened on the downslope side of the slope.

Lot 20/21 Landslide

A small companion slide occurred along the property line between lots 20 and 21 directly northwest of the Creekside Drive landslide, mostly on a natural slope covered by deciduous trees. On lot 21 (the 6023 N. Creekside Drive property), the southeastern part of the slide displaced a rock wall on the upslope side of the lower driveway. The main scarp of the landslide crossed a natural slope upslope of the driveway and Creekside Drive. The head of the landslide (figure 9A) was characterized by relatively shallow, displaced earth blocks that were locally backtilted. Small trees on the blocks were displaced, rotated, or toppled. A steep scarp bounded the upper part of the west flank of the landslide that locally exceeded 10 feet in height. Table 3 summarizes the approximate dimensions, relief, and average slope of the slide. On the southeast side of the landslide a

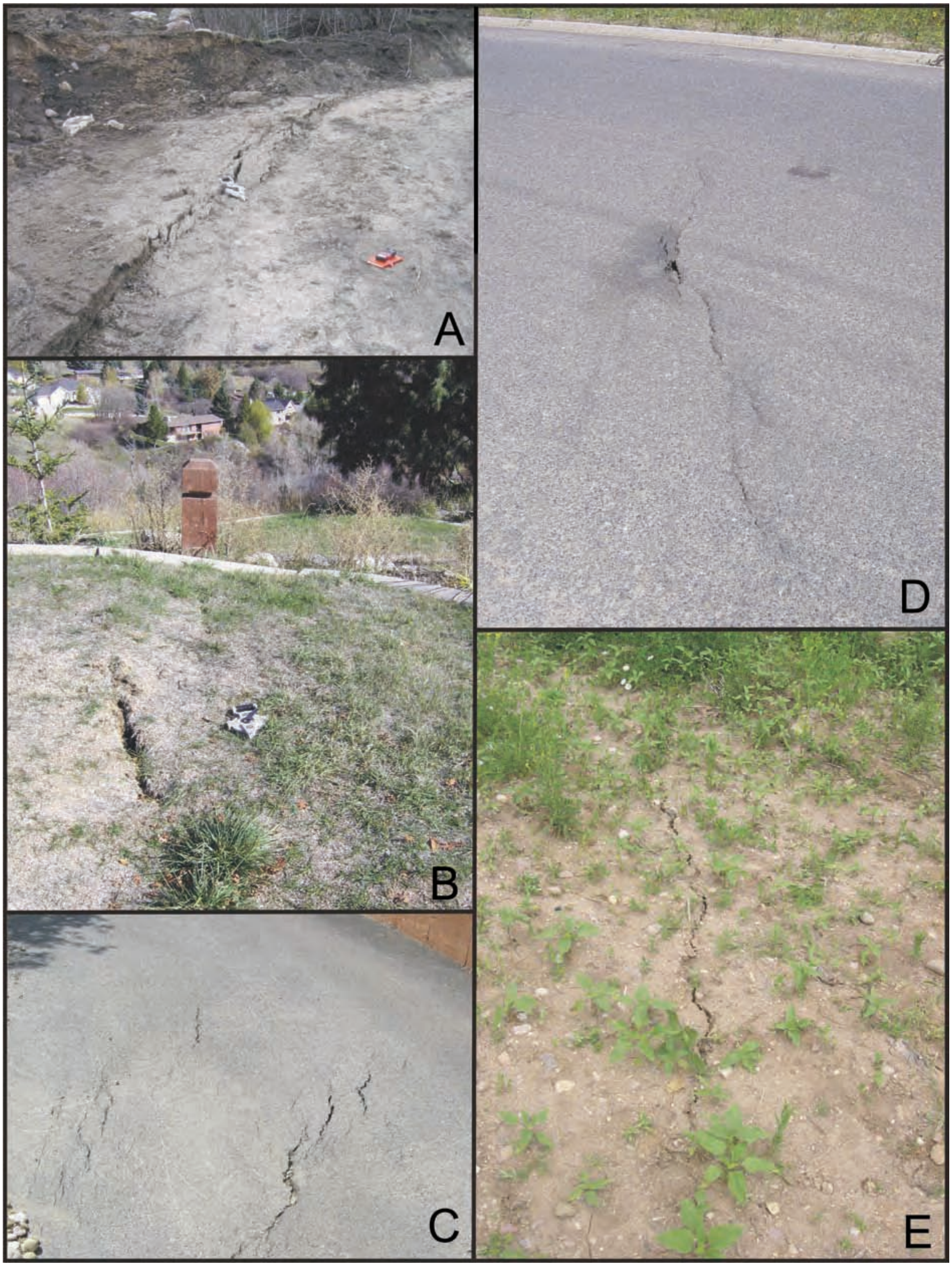

Figure 8. *Ground-deformation features defining the left flank of Creekside Drive landslide. (A) View upslope (to southwest) of left-lateral shear crack on lot 20. (B) View downslope (to northeast) of right-stepping ground cracks in lawn north of house at 6023 N. Creekside Drive. (C) View to southeast of en echelon, right-stepping cracks in lower driveway at 6023 N. Creekside Drive. Note two parallel crack zones. (D) View downslope (to north) of road crack in Creekside Drive. (E) View downslope (to north) of ground crack in fill on western part of lot 1 (6006 W. Creekside Drive).*

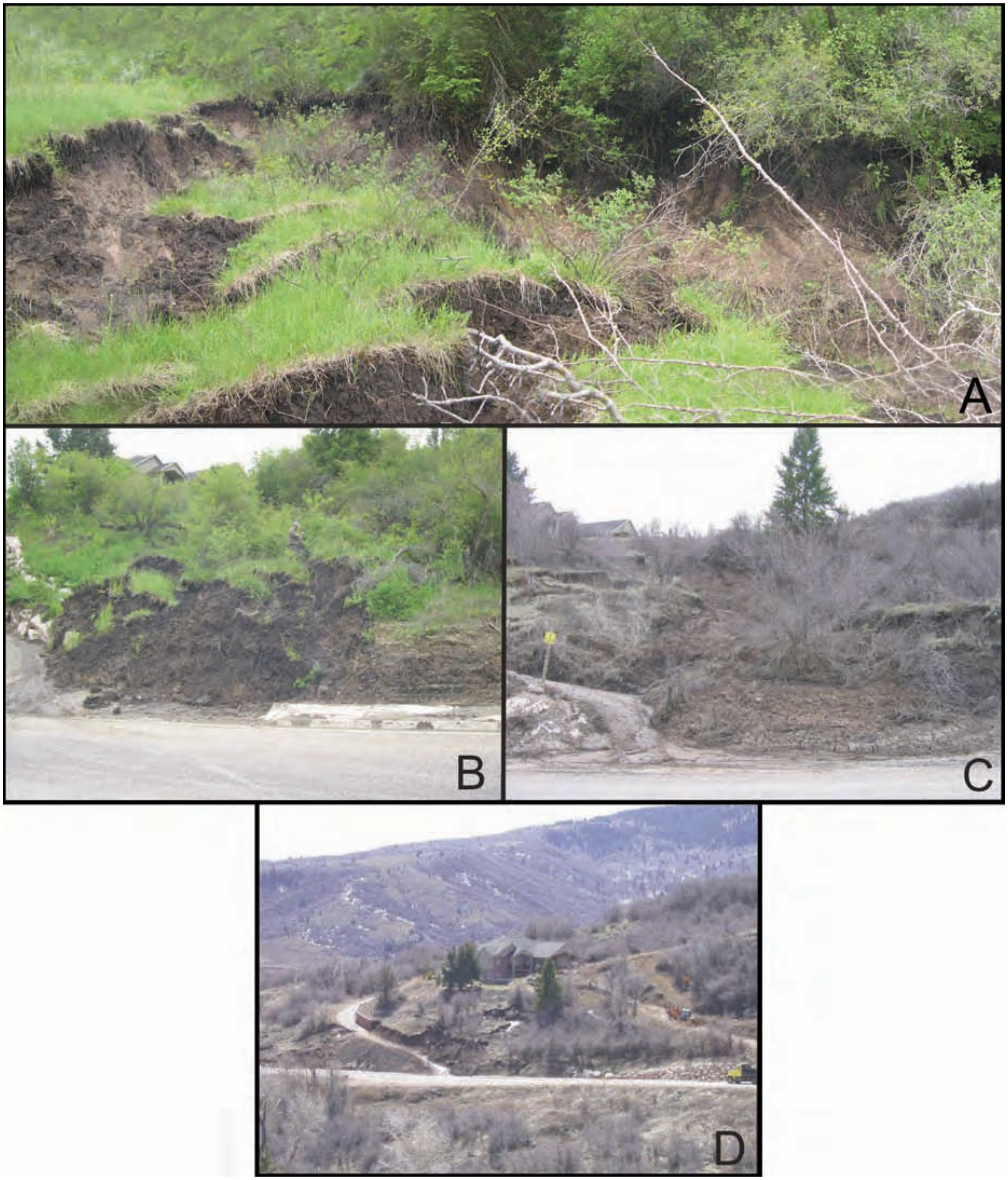

Figure 9. Landslide near boundary between lots 20 and 21 directly northwest of the Creekside Drive landslide. (A) View to the southwest of landslide head in June 2005. Note that upper part of the slide is in a natural slope. Displaced and rotated soil blocks and toppled trees in foreground. (B) View to southwest of landslide toe in June 2005. (C) View to southwest of toe in April 2006. Lower part of landslide had changed to an earth flow by 2006. Note displaced soil on lower driveway. (D) View to south of landslide in January 2007. Abandoned house at 6023 N. Creekside Drive (lot 21) in background.

small scarp extended eastward upslope of the displaced part of the rock wall along the edge of the driveway.

Other Small Landslides Along Creekside Drive

Two other small landslides occurred along the southwest side of Creekside Drive in 2005, one near the boundary between lots 17 and 18, and another east of River View Circle abutting lots 29 and 30 (figures 2 and 10). Table 3 summarizes the approximate dimensions, relief, and average slope of the slides. Near the lot 17/18 boundary, a very small landslide (figure 10A) occurred in a cut slope above a utility box. The main scarp on June 8 was about 3 to 5 feet high. As with most of the roadside landslides along Creekside Drive, the head of the slide extended upslope of the crest of the cut slope. This landslide formed at the northwest edge of a larger landslide identified in 2006 (see Lot 18 landslide below).

Another area of shallow landsliding (figure 10B, 10C) occurred in a cut slope on the southwest side of Creekside Drive east of River View Circle abutting parts of lots 29 and 30. Most of the landsliding was in a cut slope, but the main scarp(s) extended into flatter natural slopes above the crest of the cut slope. The area of landsliding consisted of two small abutting slides that shared a common boundary. The western landslide was the smaller of the two slides. The combined width of this area of landsliding was about 145 feet (table 3). The toe of the landslide was in the ditch upslope of the sidewalk. Movement at the toe of the landslide had displaced the cover of a water-meter box several inches.

Table 3. *Approximate dimensions, relief, and average slope of the other small 2005 landslides.*

Landslide	Length (ft)	Width (ft)	Relief (ft)	Slope (%)
Lot 29/30	65[a]	144[b]	17[c]	27[c]
Lot 20/21	110[a]	30-87[bd]; 45[c]	34[c]	31[c]
Lot 18 cut slope	29[a]	16[c]	13[c]	45[c]

[a]Horizontal distance between head and toe
[b]Toe
[c]Head
[d]Smaller width in 2005

Figure 10. *Other small landslides along Creekside Drive. (A) View to the south of small cut-slope landslide along northwestern Creekside Drive. (B) and (C) Main scarp zone of small landslide area east of River View Circle. Lower part of landslide was in cut slope, but main scarp crossed the natural slope upslope of the crest of the cut slope. The landslide consisted of two small abutting slides. Photographs taken in June 2005.*

2006 Landslides

In addition to the landslides described above, six other landslides were identified in 2006. Two of the slides, the Cascade Drive and Lot 18 landslides, were large enough to affect parts of one or more lots. Four small slides included two in cut slopes and two in embankment fills. Table 4 summarizes the approximate dimensions, relief, and average slope of some of the slides. In addition, a rock wall at 6067 N. Creekside Drive failed in April (figure 11).

Table 4. Approximate dimensions, relief, and average slope of some of the 2006 landslides.

Landslide	Length (ft)	Width (ft)	Relief (ft)	Slope (%)
Cascade Drive	160[a]	170[b]	47[c]	29[c]
Lot 18	155[a]	210[d]	35[e]	23[e]
Wasatch Drive embankment	92[a,f]	31[b]	24[f]	31[g]
Wasatch Drive cut slope	32[a]	30[d]	12[b]	36[b]

[a]Horizontal distance between head and toe
[b]Head
[c]Crown
[d]Toe
[e]Estimated from topographic map
[f]Composite of upper slide and flow
[g]Upper slide only

Cascade Drive Landslide

By late April 2006, a moderate-size landslide was affecting lots 192 and 193 north of Gordon Creek on the southwest side of Cascade Drive, and threatened a house at 5813 Cascade Drive on the northwestern of the two lots (lot 193) (figures 12 and 13). However, most of the slide occupied the vacant southeastern lot (lot 192). The landslide was approximately square-shaped in plan view, roughly 170 feet wide at its head and about 160 feet long. A detailed topographic map provided by Mr. David Simon (Simon-Bymaster Inc., written communication, December 2006) shows the local relief to be about 47 feet, indicating an average slope of about 29 percent (table 4).

Well-defined ground-deformation features consisted of a main scarp, flanks, and local toe folds (figure 13). On April 21, 2006, the main-scarp offset ranged from about 2 to 5 feet, increasing toward the west and the southeast corner of the house at 5813 Cascade Drive (figure 13A, 13B).

The main scarp extended beneath part of a curved concrete driveway on the east side of the house. Offset on the main scarp had left the slab partly suspended above the ground surface about 2.4 feet. By early May, jacks had been placed underneath the driveway slab by the homeowner to support it (figure 13E). Both the west and east flanks of the landslide were well defined and could be traced from the main scarp to near Gordon Creek. In the lower slope, the flanks had positive relief relative to the surrounding slope (the ground was higher on the slide side of the flank). Local relief across the flank ranged from about 1 to 4 feet and was highest on the east flank of the slide (figure 13D). Near the southeast corner of the slide, landslide deposits overthrust flood-plain deposits along Gordon Creek (figure 13C). The toe was exposed for about 50 feet in this area between the east flank and Gordon Creek. Along the west side of the toe, shallow sliding had occurred into the creek, possibly due to local oversteepening.

Lot 18 Landslide

Another landslide occurred in 2006 on the north part of vacant lot 18 southwest of Creekside Drive. The boundary of the landslide was well defined by ground-deformation features, including a main scarp and toe. The landslide was a partial reactivation of a large, rotational, deep-seated slide that forms a large amphitheater occupied by lots 17 and 18 (figures 14 and 15). The 2006 landslide formed between the sidewalk along the southwest edge of Creekside Drive and the crest of the slope that fronts the lot on the northeast. Table 4 summarizes the approximate dimensions, relief, and average slope of the slide.

Ground-deformation features consisted of a continuous main scarp, toe, and right-flank shear zone (figure 16). Additional features included irregular ground cracks and small scarps that extended to the southeast of the slide's right flank. The main scarp was arcuate in shape and concave to the northeast. The scarp reached a maximum height of about 4.3 feet, but where it crossed a dirt access road (figure 16B) it was only about 1.5 feet high. At the main scarp crossing of the access road, a minor antithetic scarp defined a small graben that was about 7 feet wide (figure 16C). Directly to the west, the main scarp formed a zone of two parallel northeast-facing scarps that were between 2 and 2.5 feet high. On the right side of the landslide, the toe of the landslide consisted of two stacked low-amplitude folds indicating that the surface of rupture splayed into two closely spaced thrusts. The lower fold occurred along the edge of the sidewalk and was less than a foot high (figure 16A). A second fold occurred near the base of a local steep slope less than 3 feet upslope of the lower fold. The two folds merged together to the southeast. On the northwest side of the slide, the toe was less distinct, and was poorly defined by a slight oversteepening at the base of a cut slope along the road. A well-defined right-flank shear trended roughly perpendicular to Creekside Drive between the toe and the main scarp.

Other Small Landslides

Four other small landslides were identified in 2006 (figure 17). The smallest occurred in a small driveway cut slope at 6067 N. Creekside Drive (lot 19) (figure 17A). The small rotational earth slide displaced material several feet onto the driveway and formed a scarp several feet high. A second landslide resulted from the partial failure of an embankment fill on the downslope (north) side of the lower access road on lot 20 (figure 17B). Two other small landslides occurred near the intersection of Creekside Drive and Wasatch Drive. The first, a small complex earth slide-earth flow formed in a southeast-facing embankment (figure 17C, table 4) consisting of fill from local soils and Norwood Tuff debris. The landslide was about 31 feet wide at its head, but narrowed downslope (table 4). On the lower east side, a narrow, earthflow lobe extended 38 feet downslope from the remainder of the slide. Another small slide (figure 17D, table 4) occurred

Figure 11. *Rock-wall failure in April 2006 at 6067 N. Creekside Drive. (A) View to the west of rock-wall failure in backyard. (B) View to the east of part of the failure southeast of house.*

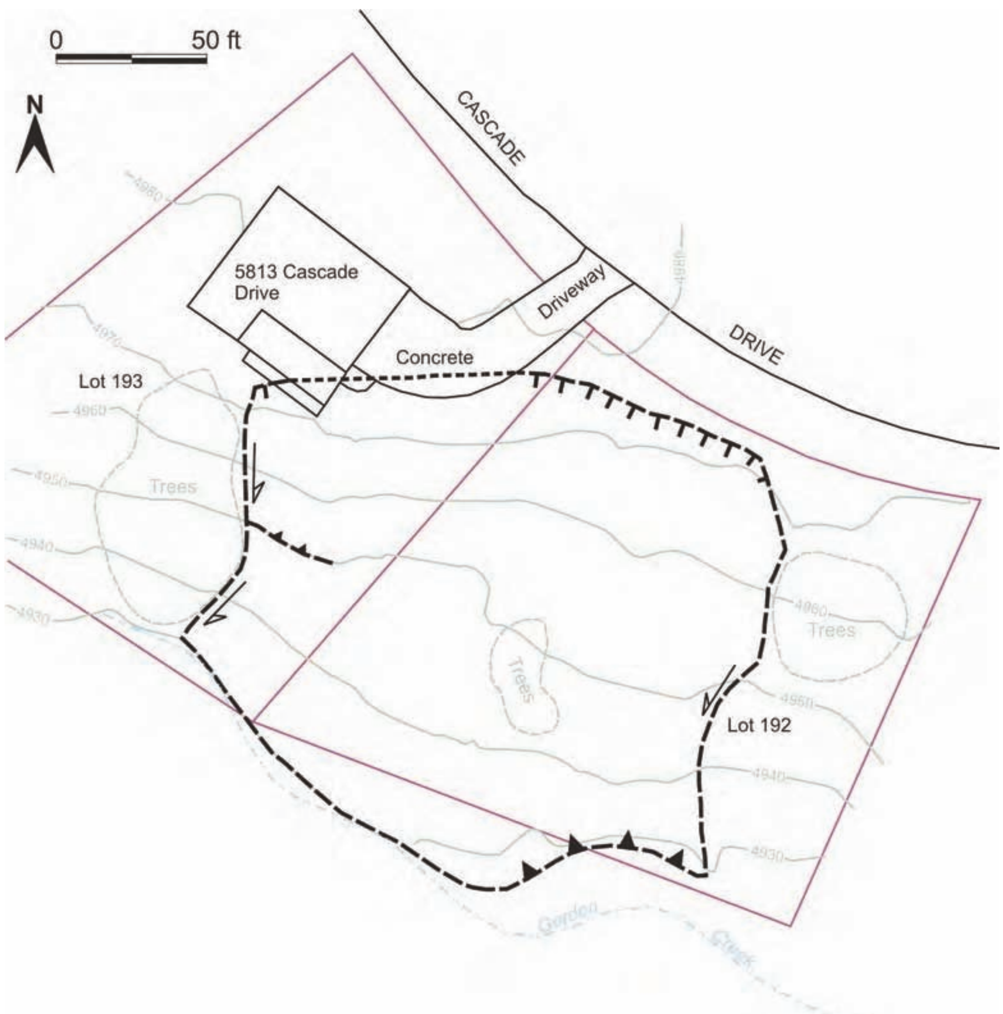

Figure 12. *The Cascade Drive landslide in April 2006. Hachured line is main scarp. Short dashed line is estimated location of scarp beneath concrete driveway and other slabs. Triangles show toe or internal thrust where observed. Most internal deformation features not mapped.*

Figure 13. *Ground-deformation features and damage caused by movement of the Cascade Drive landslide, lots 192 and 193 (5813 Cascade Drive). (A) Main-scarp offset left part of concrete driveway slab suspended about 2.4 feet above ground. (B) View to the northwest of main-scarp offset, about 5 feet, at the southeast corner of house at 5813 Cascade Drive. (C) View to the north of the toe of the landslide on lot 192. Landslide debris is thrust atop the Gordon Creek flood plain. (D) View to the northwest of the left (east) flank of landslide on lot 192. (E) Jacks used to support suspended concrete driveway slab in May 2006.*

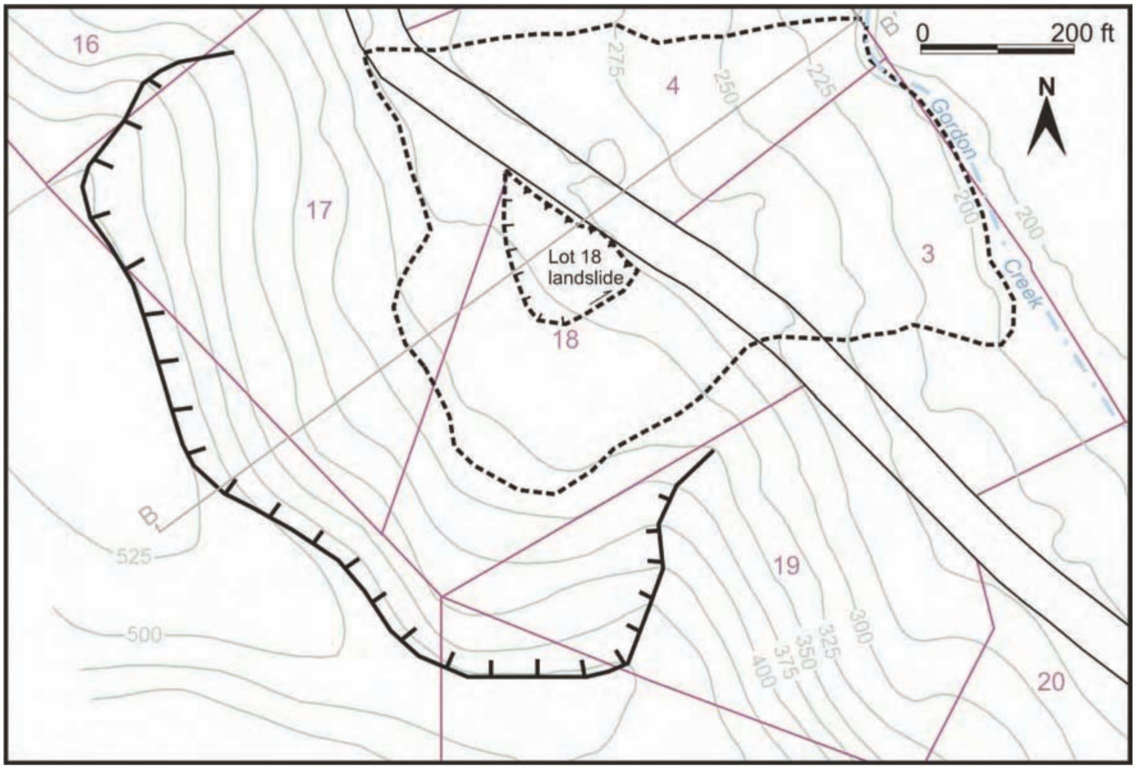

Figure 14. *Lot 18 area showing probable pre-existing landslide and the Lot 18 slide. Solid hachured line is the main scarp of the large, deep-seated pre-existing landslide. Dashed line is the approximate boundary of the pre-existing landslide deposit. Triangles and hachures show toe and main scarp of the 2006 Lot 18 landslide, respectively. Arrow indicates movement direction along right flank of slide. Flat area south of lot "18" label is back-tilted surface with a sag pond in the southeast corner (see figure 16D). Line of geologic cross section (figure 15) shown by B-B'.*

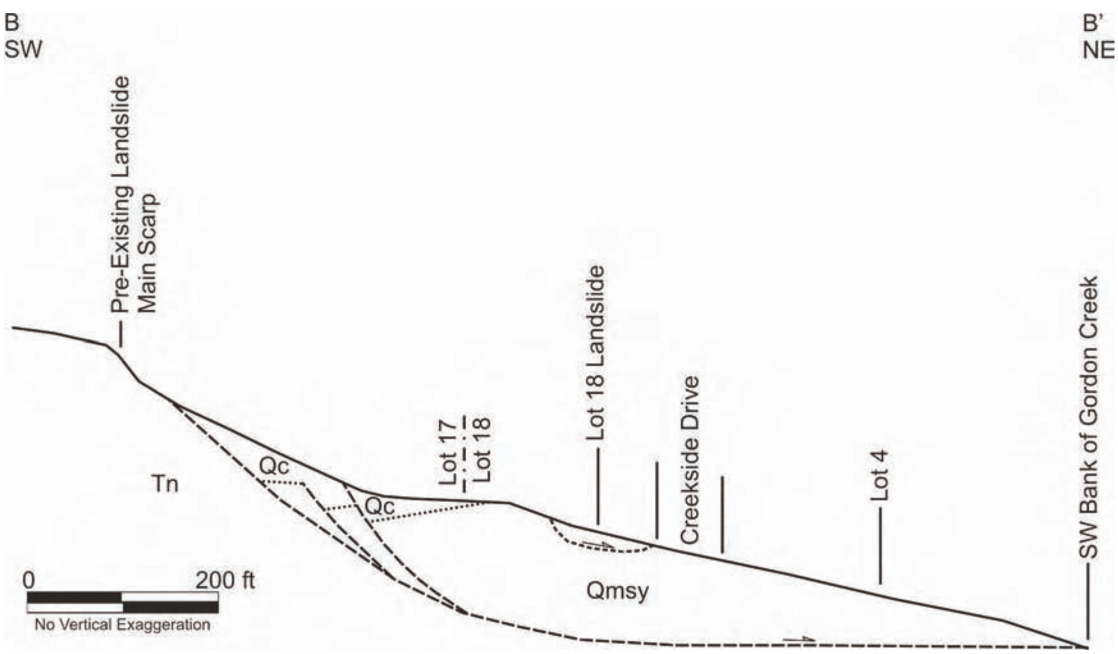

Figure 15. *Geologic cross section showing relationship between the Lot 18 landslide and the large, pre-existing, deep-seated slide (Qmsy). Short dashed line shows probable geometry of Lot 18 landslide. Long dashed lines show possible geometry of deep-seated landslide. Dotted line shows possible offset in colluvium (Qc) from movement of large slide. Landslide likely overlies weathered Norwood Tuff (Tn).*

Figure 16. *Ground-deformation features in and abutting the Lot 18 landslide. (A) Folded shallow soils at toe of landslide. (B) Offset of access road by main scarp. Scarp height ranged between 1.3 and 1.6 feet near road. (C) View to the northeast of small graben where head of slide crosses access road. Graben is about 7.1 feet wide. (D) View to the east of back-tilted surface on large, deep-seated, pre-existing landslide southeast of Lot 18 slide.*

directly downslope of the embankment failure in a cut slope along Wasatch Drive. The landslide was defined by a small main scarp that was about a foot high.

Changes to 2005 Landslides

Renewed or accelerated movement of the 2005 slides in 2006 resulted in some changes in landslide size and the extent of ground deformation. Minor movement of the large Creekside Drive landslide resulted in increased ground deformation that better defined the left flank of the slide. However, the right flank of the slide remained poorly defined by the end of 2006. Minor movement of the Southern Sewer-Line landslide (Ashland, 2006) caused additional offset on the main scarp, but no apparent change in size. In 2006, the Northern Sewer-Line landslide expanded in size to the north and most of the activity appeared to occur in the northern part the slide. Of the small shallow slides, the Lot 20/21 landslide changed the most dramatically, expanding to the southeast above the driveway at 6023 N. Creekside Drive and transitioning from an earth slide in 2005 to a complex earth slide-earth flow in 2006 (figure 9C). Displacement from movement in 2006 resulted in encroachment of the slide onto the driveway and Creekside Drive. The earth-flow deposits that encroached onto Creekside Drive were cleared and temporarily stored in a pile on the north edge of the road. Minor earth flow also occurred on the northwest side of the small shallow landslide beneath the driveway (figure 5D).

LANDSLIDE MOVEMENT HISTORY

Most of the landslide movement in 2005 preceded our initial site visit on June 8. Local residents and contractors indicated that movement initiated earlier in the year, roughly coincident with the end of the snowmelt in the area. In early June 2005, the UGS installed survey stakes to measure landslide movement and ground deformation across the main scarps of the three largest slides (figures 2 and 18; see figure 18B and Ashland [2006] for 2005 movement data at the two slides abutting the sewer line). In addition, measurement points were established at other sites, such as across ground cracks and sidewalk gaps, to measure ground deformation and deformation to pavement areas, but little or no ground deformation was documented at these stations in the second half of 2005. However, the stations across the main scarps documented additional minor movement between June 2005 and late December 2006 at two of the slides (figure 18A, 18B).

In October 2005, the UGS installed survey points along the center lines of Creekside Drive and River View Circle as well as in a few select locations, in order to more precisely measure landslide movement in 2006 and better define the

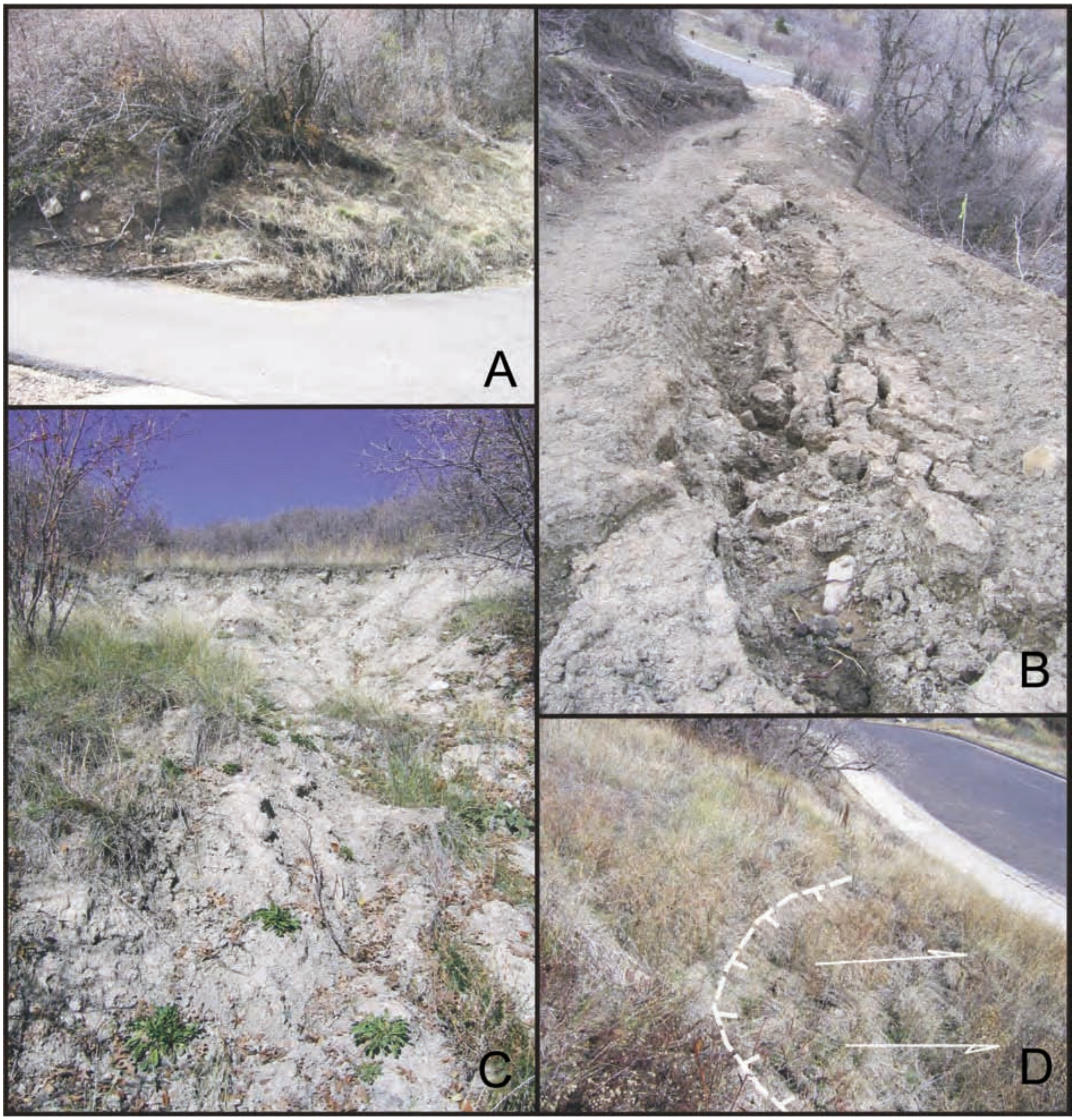

Figure 17. *Other small landslides in 2006. (A) View to the west of a small slide in a driveway cut slope at 6067 N. Creekside Drive. (B) View to the northwest of the head of an embankment failure in the lower part of the access road on lot 20. (C) View upslope (to the north) of landslide in an embankment near Wasatch Drive. (D) View to the east of the head of a small slide in cut slope along Wasatch Drive. Dashed hachure line is approximate main scarp. Arrows show approximate movement direction.*

boundaries of the Creekside Drive landslide (figure 19). Detailed movement monitoring using a survey-grade Global Positioning System (GPS) device provided information on the total movement amounts of two of the three largest 2005 landslides (the Creekside Drive and Southern Sewer-Line slides), defined movement distribution and patterns, and provided constraints on the boundaries of the Creekside Drive slide.

2005 Movement

Nearly continuous minor movement (stretching) was measured across the main scarp upslope of the house at 6023 N. Creekside Drive between June 14 and October 12 (figure 18A). The apparent lack of movement between June 10 and 14 (first two measurements on the plot) is likely an artifact of the detection limit, or resolution, of our measurement technique over a short four-day time span. The plot suggests that movement may have suspended for a short time in late June before resuming, but the detection limit issue may also be the cause for the downward deflection in the curve during that time period that spanned only eight days. Figure 18B shows continuous minor movement of the Southern Sewer-Line landslide in 2005 similar to the movement of the Creekside Drive landslide. However, movement of the Northern Sewer-Line landslide suspended in late June 2005 (Ashland, 2006).

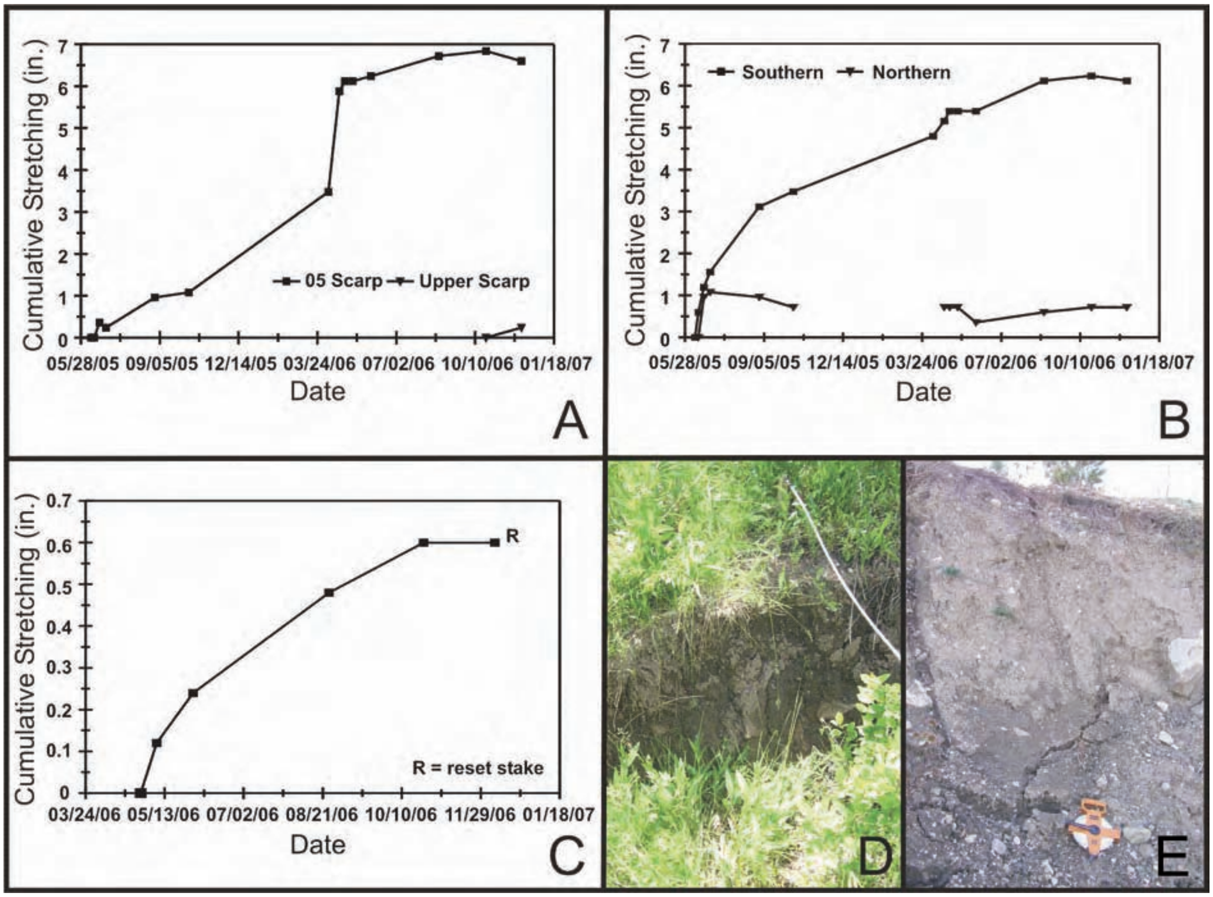

Figure 18. *Plots showing cumulative stretching (movement) across main-scarp zones of three of the Creekside Drive-area landslides. (A) Cumulative stretching across main-scarp zone of the Creekside Drive landslide. Plot shows nearly continuous movement between June 10, 2005, and December 28, 2006. Note the rapid acceleration in the rate of movement in April 2006 coincident with the end of snowmelt. Scarp spanned by stake station shown in D. By 2006, another scarp had formed upslope. Lower curve shows stretching across upper scarp in late 2006. (B) Cumulative stretching across main-scarp zones of the Southern Sewer-Line and Northern Sewer-Line landslides. Plot shows continuous movement of the Southern Sewer-Line landslide for measurement period, but movement of the Northern Sewer-Line landslide suspended by late June 2005. Fresh ground crack at base of main scarp of the Southern Sewer-Line landslide (E) confirms continued main-scarp offset in late 2005. (C) Plot showing continuous stretching across main-scarp zone of the Cascade Drive landslide between April 28 and October 24, 2006. Movement may have suspended in late 2006.*

2006 Movement

Renewed, but minor, movement of the three large 2005 landslides occurred in 2006. The results of UGS landslide monitoring of the Creekside Drive and Southern Sewer-Line landslides using GPS survey techniques indicated that movement in 2006 initiated, or the rate of movement accelerated, sometime between early January and early April and movement lasted until about early May. The maximum total movement of the Creekside Drive and Southern Sewer-Line landslides was only 2.8 and 2.4 inches (7 and 6 cm), respectively, by June 23, 2006 (figure 19). Observations also indicated local movement and some enlargement of the Northern Sewer-Line landslide in 2006. Figure 18A shows that about 5.5 inches of stretching occurred across the main scarp of the Creekside Drive landslide in 2006, most occurring before May. The large amount of movement measured across the main scarp may be due to the composite nature of the scarp, the result of both movement of the entire landslide and local movement of an upper shallower slide (see discussion above). UGS stake measurements across the main scarp of the Southern Sewer-Line landslide indicated about 2.6 inches of movement in 2006, about 1.9 inches occurring before May (figure 18B).

The UGS began monitoring the two largest 2006 landslides (the Lot 18 and Cascade Drive slides) on April 28, 2006, after all or most, respectively, of the 2006 movement had already occurred. Minor movement of the Cascade Drive landslide continued through October 2006 (figure 18C), but no additional movement was detected at the Lot 18 slide after April 28.

BUILDING AND PAVEMENT DISTRESS

The Creekside Drive and Cascade Drive landslides directly affected developed residential lots, causing most of the damage, the former also impacting Creekside Drive and buried utilities. Minor irregular road cracks observed in late 2006 on Cascade Drive may also be due to landsliding. Landsliding also affected two separate dirt access roads to lots 18 and 20.

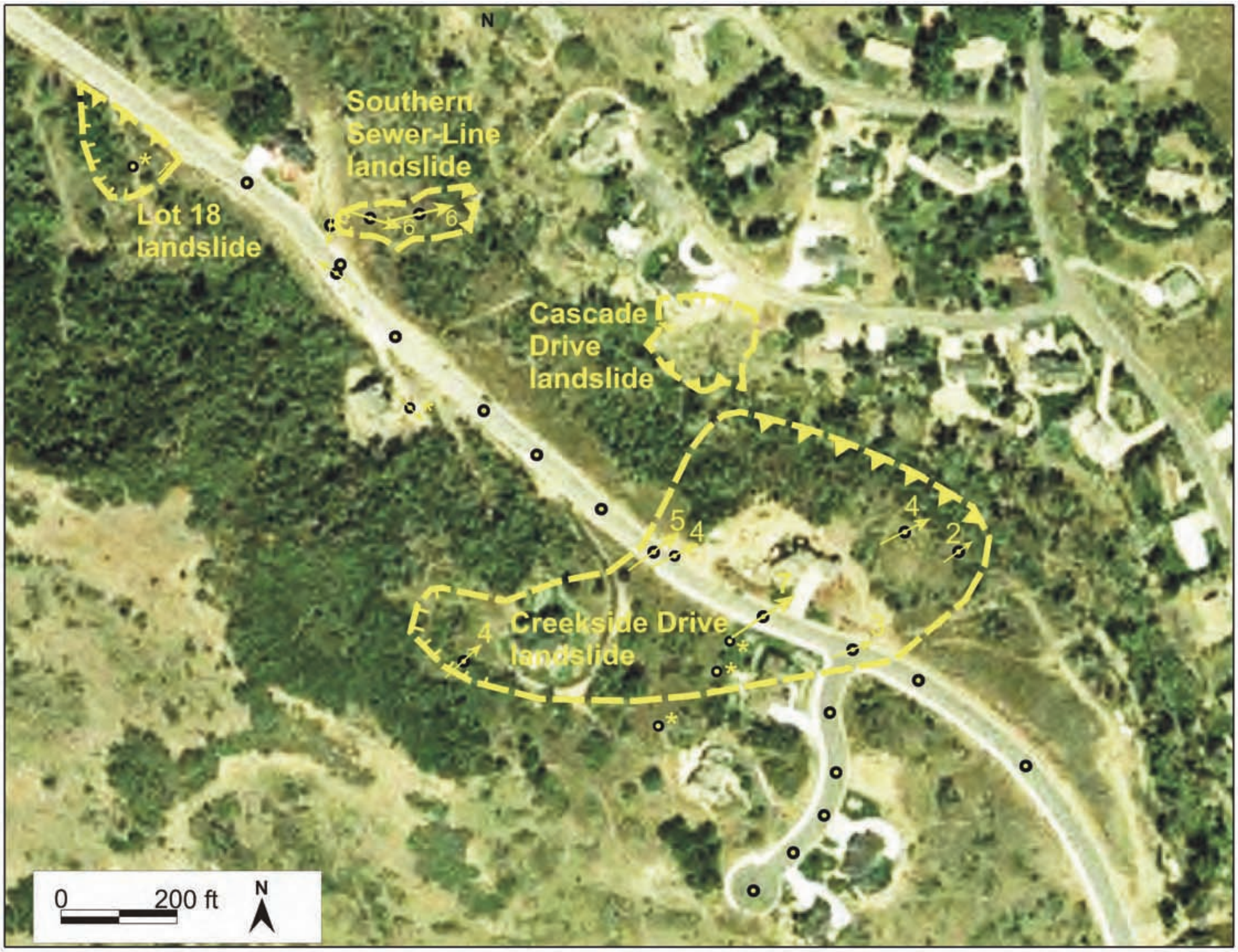

Figure 19. *Results of landslide movement monitoring using a survey-grade Global Positioning System device. Arrows show movement directions. Movement amounts shown in centimeters for period between November 1, 2005, and June 23, 2006. Asterisks indicate survey points installed in April 2006 after most movement had already occurred.*

Building and pavement distress caused by the Creekside Drive landslide included damage to houses, patios, sidewalks, driveways, and roads. The most severe damage occurred to the house at 6023 N. Creekside Drive, but houses at 5983 N. River View Circle (lot 23; figure 3) and 6006 W. Creekside Drive (lot 1) were also damaged, based on exterior inspection.

Damage at 6023 N. Creekside Drive

By mid-June 2005, damage to the house at 6023 N. Creekside Drive was severe, and partly limited the use of the property (figure 20). Cracks were pervasive in both the interior and exterior of the house. Most of the damage to the house was outside the limits of where the backyard shallow toe thrust system was in contact with the attached garage and thus was likely due to ground deformation caused by deep-seated landsliding, specifically stretching in the head of the Creekside Drive landslide. By April 2006, the damage to the house had become so severe that the house was voluntarily abandoned. Figure 20B shows the distortion to the attached garage and abutting part of the house by ongoing movement in 2006.

Damage at 5983 N. River View Circle

By June 2005, damage had also occurred to the house at 5983 N. River View Circle (figure 21). Damage included buckling of a back porch and attached walkway (figure 21A), including rotation and cracking of the porch posts (figure 21B) and cracks in the northwestern wall (figure 21D). By late April 2006, a separation gap was well developed along the northeast edge of the house (figure 21C).

Damage at 6006 W. Creekside Drive

In 2005, building and pavement distress at 6006 W. Creekside Drive consisted of some local patio damage and minor foundation-wall cracking. The patio damage consist-

Figure 20. *Damage to house at 6023 N. Creekside Drive. (A) View to the south of sheared (tilted) porch posts on west corner of house. (B) View to the northwest of distortion to attached garage by late 2006. Rectangles added to show distortion. (C) View to the east-southeast of interior damage to wall and doorframe in basement of house. (D) View to the northeast of separation (left of mat) and garage floor/foundation wall crack.*

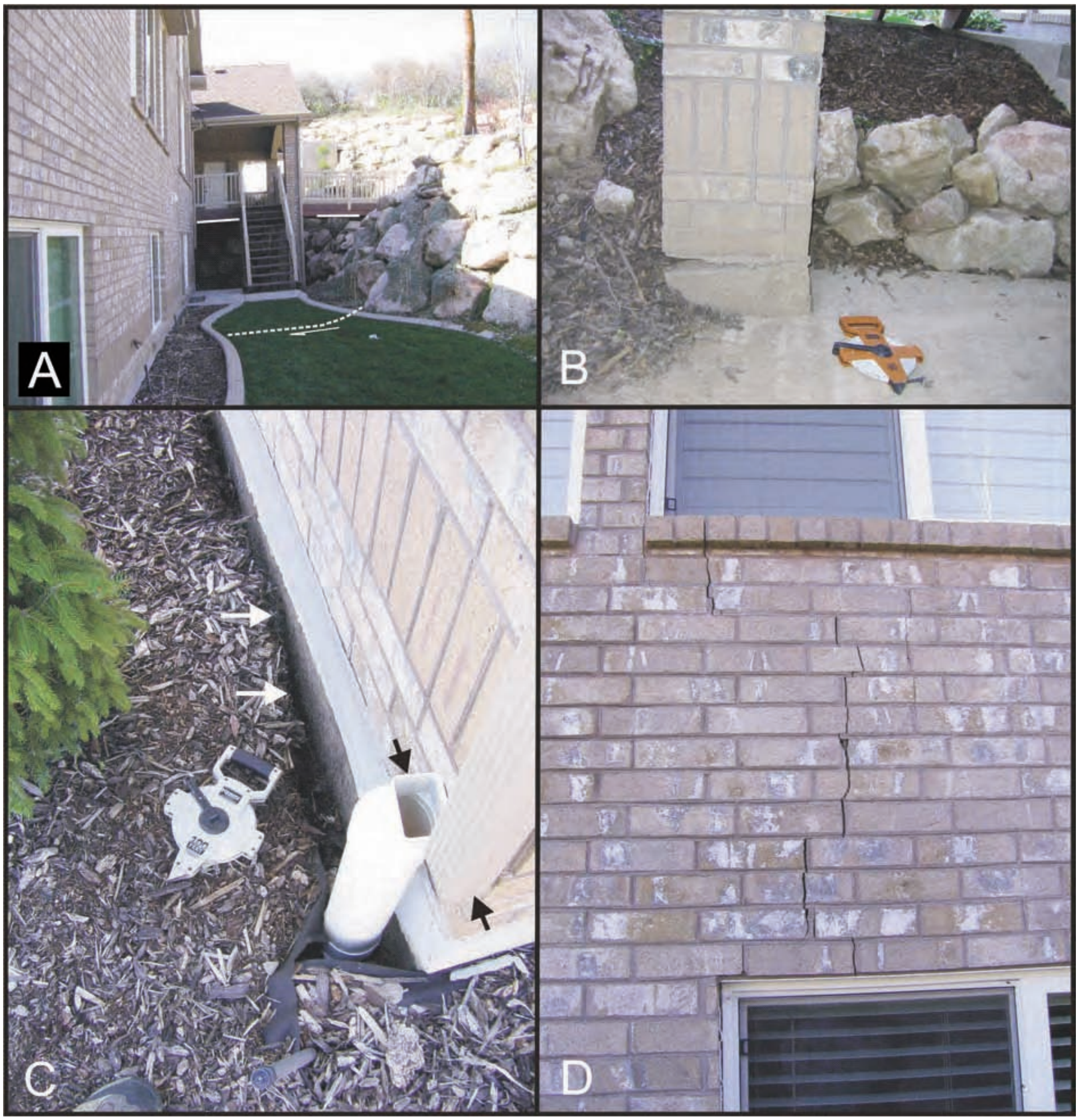

Figure 21. *Damage to house at 5983 N. River View Circle. (A) Buckling of back porch and walkway due to landslide movement. Solid white lines added to help visualize porch deformation. Dashed line shows approximate right flank of the Creekside Drive landslide. Arrow indicates movement direction. (B) Rotation and cracking of porch support column. (C) Gap (white arrows) between soil and northeast wall of house. Note offset of downspout drainpipe and inlet pipe (black arrows) in late April 2006. Both were connected in August 2005. (D) Cracking in northwest wall of house, likely where right flank of slide intercepts it.*

***Figure 22**. Pavement distress caused by movement of the Creekside Drive landslide. (A) Transverse cracks in upper part of driveway at 6023 N. Creekside Drive. (B) Road damage at intersection of Creekside Drive and River View Circle. See text for additional information. (C) Detail view of sidewalk damage on B and gap between sod and sidewalk (arrows). (D) Driveway damage at 6023 N. Creekside Drive near the intersection of the left flank of the Creekside Drive landslide and the main scarp of the small slide in cut slope.*

ed of crushing of the patio slabs on the downslope side of porch posts. The damage suggests downslope movement of the posts relative to the patio. In addition, some minor hairline cracking was noted on the north-side foundation wall.

Pavement Distress and Ground Deformation

Pavement distress consisted of mostly cracking of asphalt road and driveway surfaces, and concrete driveways, sidewalks, and curb and gutter elements (figure 22). Most of this occurred on and directly abutting the Creekside Drive landslide. Additional cracking outside the limits of the main landslide, particularly in the River View Circle area, may be due to expansive soils.

A distinct pattern of sidewalk and pavement deformation was observed at the intersection of River View Circle and Creekside Drive. At this intersection, the sidewalk on the west side of River View Circle makes a right-angle bend from northeast-trending River View Circle to northwest-trending Creekside Drive (figure 22B). The sidewalk at this bend was characterized by open sidewalk-panel separations (in a radial pattern) and transverse separations between the sidewalk and sod (to the southwest) (figure 22C), and local crushing. In the road, the pavement was slightly heaved and included a portion that was backthrust to the southwest onto the concrete gutter element (figure 22B). By 2006, small diagonal road cracks had appeared near the intersection of River View Circle and Creekside Drive, possibly indicating incipient deformation along the right-flank shear zone, which likely crosses the intersection (figure 3). Upslope and southwest of the 5983 N. River View Circle property, the right flank of the pre-existing Creekside Drive landslide was defined by a northeast-trending, down-to-the-northwest scarp with several feet of offset. Ground cracking and possible, but equivocal, minor offset at the base of the scarp suggested this boundary feature was reactivated in 2006 by minor movement of the landslide.

Possible Damage Due to Expansive Soils

Expansive soils may also be the cause of some of the damage observed on developed lots on and abutting the landslides, such as damage to patios and movement of porch posts, excluding the porch-post damage at 6023 N. Creekside Drive (figure 20A) and 5983 N. River View Circle (figure 21B), which are too severe to be attributed to this cause. Most of the crack and damage patterns observed suggest a component of downslope-directed movement. Heave caused by expansive soils may also result in downslope-directed movement of soil and building elements and differentiating this mechanism from initial landslide-related damage is problematic without subsurface investigations and instrumentation, or until landslide features become better developed as additional movement occurs.

CAUSES AND IMPLICATIONS TO LANDSLIDE STABILITY

Movement of the Creekside Drive area landslides in 2005 initiated during a wetter-than-normal period and after most snow at this elevation (approximately 5000 feet) had melted. Thus, rising ground-water levels in the underlying landslide deposits likely triggered the movement in 2005. Independent monitoring by the UGS of other landslides in the Norwood Tuff near the intersection of State Routes 167 and 226, several miles to the north, showed a large percentage (approaching 100 percent) of the monitored landslides, including a very large landslide near the Snowbasin ski resort (the Green Pond landslide), reactivated in 2005. Ground-water-level data provided by the Utah Department of Transportation for the Green Pond landslide showed that peak seasonal ground-water levels in two wells in 2005 were the highest and second highest recorded since measurements began in 2000. Movement amounts of these landslides ranged from inches to feet, and at some landslides movement continued throughout 2005. Thus, the landsliding in the Creekside Drive area was coincident and similar in overall behavior with the landsliding in the Norwood Tuff elsewhere in western Morgan County and the abutting part of Weber County.

One implication from these measurements and observations is that a large percentage of the pre-existing landslide inventory in western Morgan County is likely marginally stable and subject to recurrent movement. In addition, some of the landslides in the area may be continuously moving at very slow, imperceptible rates even during dry periods. The near-universal reactivation of landslides in the monitored area also suggests that base ground-water levels were near instability threshold levels (Ashland, 2003) prior to the onset of the snowmelt in 2005.

Given the excess precipitation in the area in 2005 (6.4 inches of excess precipitation between September 2004 and August 2005 at the National Weather Service Huntsville station), ground-water levels in landslide deposits in the Creekside Drive area likely remained high (shallow) at the end of 2005. Continued movement of at least two of the landslides throughout the latter part of 2005 suggests sustained high ground-water levels.

By March 1, 2006, cumulative precipitation for the period between September 2005 and February 2006 was only slightly above normal (105 percent) and excess precipitation was about 0.6 inch. Thus, peak seasonal ground-water levels in the Creekside Drive area landslides in 2006 may have been slightly less than or about the same as levels in 2005. Slightly lower ground-water levels are suggested by only minor movement of the two large Creekside Drive area landslides. However, the formation of new landslides in 2006 and inferred movement amounts of a foot or more at these slides prior to late April suggest slightly higher ground-water levels. Due to the lack of ground-water-level data spanning the 2005-06 period, the actual ground-water fluctuation during this period and specifically the relative height of the peak seasonal ground-water level in 2005 and 2006 remains uncertain.

IMPLICATIONS TO FUTURE SAFE DEVELOPMENT

Active landsliding in 2005 and 2006 in western Morgan County and the adjoining part of Weber County reveal the inherent marginal stability of pre-existing landslides in the

Norwood Tuff. In the Creekside Drive area, landsliding consisted of both total and partial reactivation of pre-existing slides, and the formation of new slides in cut slopes and embankments. The latter (new slides) illustrate the destabilizing effects of hillside modifications, specifically cuts and fills, on already marginally stable slopes. Movement of the largest landslide, the Creekside Drive slide, was due to the reactivation of a large pre-existing slide underlying all or parts of at least five, and perhaps as many as seven, lots in the Highlands West subdivision.

The rapidity of damaging landsliding in the Creekside Drive area following residential development also indicates the marginal stability of the pre-existing landslides. A conditional-use permit was issued for the house at 6023 N. Creekside Drive and a site-specific geotechnical investigation performed in 2001, only four years prior to damaging landsliding. The house at 6023 N. Creekside Drive was occupied for only four years before being abandoned in 2006 due to landslide damage. Shallow landslides that formed in cut slopes along Creekside Drive occurred even more rapidly; several had formed by 2001 (Earthtec, 2001d).

The short time between development and landsliding was previously documented in 2001 at the Frontier Drive landslide (Ashland, 2001). The Frontier Drive landslide, about a mile northeast of Creekside Drive, was a partial reactivation of a large pre-existing slide in lacustrine deposits derived from the underlying and surrounding Norwood Tuff. At Frontier Drive, damaging landsliding initiated only a few years (less than four) after residential development. In 2006, part of the 2001 landslide reactivated again and enlarged to the north, damaging landscaped areas of two lots and a buried culinary water line. Thus, two damaging landslides occurred in a five-year period, and in less than nine years following the start of development.

Significant landslide damage occurred in the Creekside Drive area despite both subdivision-wide and lot-specific, predevelopment, geotechnical and geologic studies. The current losses likely exceed $1 million including the pre-slide appraised value of the abandoned house at 6023 N. Creekside Drive ($600K). The losses indicate a failure to adequately identify, characterize, and mitigate landslide hazards in the Highlands West subdivision and adjacent areas (Cascade Drive). If the initial recommendation of Goode (1972) to avoid development on the "unstable" lots had been followed, losses would have been greatly reduced. The geologist who conducted the predevelopment investigations for the Highlands West subdivision (Kaliser, 1996, 1999) was also perhaps the first geologist to map landslides in the area and monitor landslide movement (Kaliser, 1972). Some of the general recommendations made by Kaliser (1972) included (1) avoidance, (2) excavation and replacement of landslide debris, and (3) mechanical stabilization (engineered retaining walls, buttresses, etc.).

Avoidance was the primary recommendation of Goode (1972) for the identified "unstable" lots. Nevertheless, neither avoidance nor the other two stabilization options listed above were recommended in the predevelopment geologic (Kaliser, 1996, 1999) and geotechnical (Earthtec, 1996, 1999, 2001d) reports for any lot. Instead, deep (pier) foundations were recommended on lots with recognized landslide conditions (higher hazard?), in addition to foundation and land drains at some sites (Earthtec, 1999). Most cuts (and fills) have 2:1 (50%) slopes as recommended by Earthtec (1999, 2001d), less conservative than Kaliser's (1972) recommendation for flatter 3:1 (33%) cut slopes within the boundaries of mapped landslides, and despite documentation of historical landslides along cut slopes (Goode, 1972). To subsequently mitigate small, shallow landslides in cut slopes and settlement behind rock walls in 2001, Earthtec (2001d) recommended land drains, although the effectiveness of such drains in low-permeability clay soils as identified in the geotechnical studies (Earthtec 1996, 1999) is questionable. In fact, the two sewer-line landslides appear to be localized along land drains and excavations for drain pipes (Ashland, 2006).

The primary shortcoming of the predevelopment studies was inadequate recognition and characterization of the likelihood of reactivation of the deep-seated Creekside Drive landslide. No discussion of this possibility appears in any of the predevelopment reports including Goode (1972), whereas concern for local slope stability is repeatedly discussed (Earthtec 2001b, 2001c, 2001d). The lack of adequate characterization may be related to inadequate geologic mapping (Goode, 1972; Kaliser, 1972, 1996, 1999) and a reliance on shallow test pits rather than deep boreholes for subsurface investigation (Earthtec, 1996, 1999). As shown in figures 3 and 12 (this study), topography-based landslide mapping provides an adequate basis for estimating the boundaries of the Creekside Drive landslide, which reactivated in 2005, and the large prehistoric landslide encompassing the Lot 18 landslide. Such mapping is prerequisite for defining adequate subsurface investigations, characterizing landslide stability, and effectively mitigating the hazard. Test pits performed in the subsurface investigations for the predevelopment studies (Earthtec, 1996, 1999) are much shallower than the 58-foot depth (beneath Creekside Drive) of the Creekside Drive landslide. Thus, critical information needed to define the subsurface landslide geometry and characterize groundwater conditions and the shear strength of the basal surface of rupture zone was lacking.

The lessons learned from the damaging landslides in 2005 and 2006 in the Creekside Drive area that are prerequisite for future safe development include the following:

1. Pre-existing landslides in the area are inherently marginally stable and subject to future total and partial reactivation. Some of these landslides may be active and continuously moving at extremely slow to very slow rates.

2. Reactivation of any of the large pre-existing landslides in the area can result in large losses and pose a significant challenge to stabilize.

3. Cut slopes in the landslide deposits quickly result in shallow landslides.

4. Traditional hillside modifications associated with residential development destabilize slopes and promote landsliding shortly following development.

5. Land drains do not effectively stabilize local slopes or pre-existing, clay-rich landslides.

6. Avoidance, mechanical stabilization, and possibly closely regulated mass grading appear to be the best approaches for safe development.

FUTURE HAZARD

By the end of 2006, movement had either suspended or slowed to an extremely slow rate at all of the Creekside Drive-area landslides. Based on UGS monitoring since 2001 of other nearby landslides in the Norwood Tuff, future movement of at least some of the Creekside Drive landslides is likely. Most of the future seasonal movement will likely occur in the months of March and April, but movement may continue throughout the calendar year at some slides during wet years. The likelihood of renewed movement or acceleration in the rate of movement increases with wetter-than-normal precipitation, particularly for the period between September and February (Ashland, 2003); however, movement cannot be ruled out even during periods of near-normal precipitation. Movement of the Frontier Drive landslide in 2001 occurred despite drier-than-normal precipitation between September 2000 and February 2001, following residential development upslope of the slide. A future prolonged drought may cause the Creekside Drive-area landslides to become dormant (no movement for over a year); however, a single wet period may reactivate the slides. Future movement amounts are difficult to predict. In 2006, total seasonal movement of monitored landslides in the Norwood Tuff ranged from a few inches to over 23 feet. Ultimately, some form of mechanical stabilization will be required to prevent future movement of the Creekside Drive-area landslides.

ACKNOWLEDGMENTS

Michael Kirschbaum, Greg McDonald, Ashley Elliott, and Richard Giraud (all current or former UGS personnel) assisted with the fieldwork. Greg McDonald performed landslide monitoring using a survey-grade Global Positioning System device between November 2005 and June 2006. Lucas Shaw (UGS) provided assistance in creating several of the figures in this report. David Simon (SBI) provided information on the Highlands West subdivision. Austin Rowser (Morgan County Engineer) provided periodic updates on landslide-related occurrences in the area and the results of the Cotton, Shires and Associates, Inc. subsurface investigations. The cooperation of the local property owners is graciously appreciated.

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