

RECONNAISSANCE OF THE LITTLE VALLEY LANDSLIDE, DRAPER, UTAH: EVIDENCE FOR POSSIBLE LATE HOLOCENE, EARTHQUAKE- INDUCED REACTIVATION OF A LARGE PRE-EXISTING LANDSLIDE

by
Francis X. Ashland



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Cover photo: Upper part of the Little Valley landslide, Draper.

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ABSTRACT

Using geomorphic analysis, and radiocarbon ages from a consultant's landslide investigation, I developed a partial movement history for the Little Valley landslide in Draper, Utah, and an approach for recognizing earthquake-induced reactivation in pre-existing slides in the Wasatch Front. The landslide is a large, prehistoric, dormant debris slide, parts of which are undergoing or proposed for residential development. The presence of rotated blocks with deformed and faulted latest Pleistocene-Holocene sag pond sediments and local troughs with latest Pleistocene-Holocene alluvium allowed dating of movement episodes and periods of dormancy.

The age of graben-fill sediments in the head of the landslide ($>29,120$ ^{14}C yr B.P.) indicates that the slide had formed prior to the onset of Late Pleistocene Lake Bonneville. A latest Pleistocene movement episode (estimated at about 17,000 cal yr B.P.) is suggested based on the preservation (lack of erosion) of the foot of the landslide that extends about 360 feet (110 m) downslope of the Bonneville shoreline and overridden shoreline sediments at the toe of the slide. The youngest dated movement episode (4700 cal yr. B.P.) is based on the age of the base of a colluvial wedge associated with an antithetic, sag-pond-bounding fault that offsets organic silt (loess or sag-pond sediments) in the head of the landslide. This movement overlaps in time with surface-faulting event W on the Salt Lake City segment of the Wasatch fault zone. The movement occurred during a dry period of the Holocene, supporting a possible seismic origin.

INTRODUCTION

Previous researchers (Keaton and others, 1987; Solomon and others, 2004) have recognized the potential for earthquake-induced landslides in the Wasatch Front despite that few, if any, landslides have been identified as being directly triggered by earthquakes. Harp and Jibson (1995, 1996) reported that the most common types of landslides triggered by the 1994 magnitude 6.7 Northridge earthquake in southern California were highly disrupted, shallow falls and slides of rocks and debris. These included many very small landslides as little as 1 to 2 meters in width. The lack of readily apparent earthquake-induced landslides in the Wasatch Front may be, in part, due to the difficulty of recognizing these types of landslides, and particularly the very small ones, in the geologic record.

Harp and Jibson (1996) indicated that larger, deeper coherent landslides caused by the 1994 Northridge earthquake were relatively rare and consisted mostly of reactivated pre-existing slides. Utah's best-documented landslide of this type is the Springdale landslide in the southwestern part of the state (Jibson and Harp, 1996) that was triggered by the 1992 magnitude 5.8 St. George earthquake. In the Wasatch Front, no mapped landslide, excluding liquefaction-induced lateral spreads (Hylland and Lowe, 1998; Harty and Lowe, 2003), has been documented as having been triggered or reactivated by a prehistoric major earthquake. Movement of most large landslides in northern Utah likely occurs in response to climatically controlled factors such as the rise in ground-water

levels during wet periods, although earthquakes may be a significant additional factor. The number of recently reactivated pre-existing landslides due to wet periods in the last two decades suggests that many northern Utah landslides are dormant (inactive for at least a year but with the potential to reactivate) and have low factors of safety (Ashland, 2003).

The Little Valley landslide is one of the largest prehistoric slides in Salt Lake County. Residential development exists on the lower part of the landslide and the slide is similar to other Wasatch Front landslides upon which residential development has occurred or is proposed. Due to its proximity to the Wasatch fault zone and other factors, the landslide is also a potential candidate for a slide that may have been reactivated, at least locally, by large earthquakes.

LITTLE VALLEY LANDSLIDE

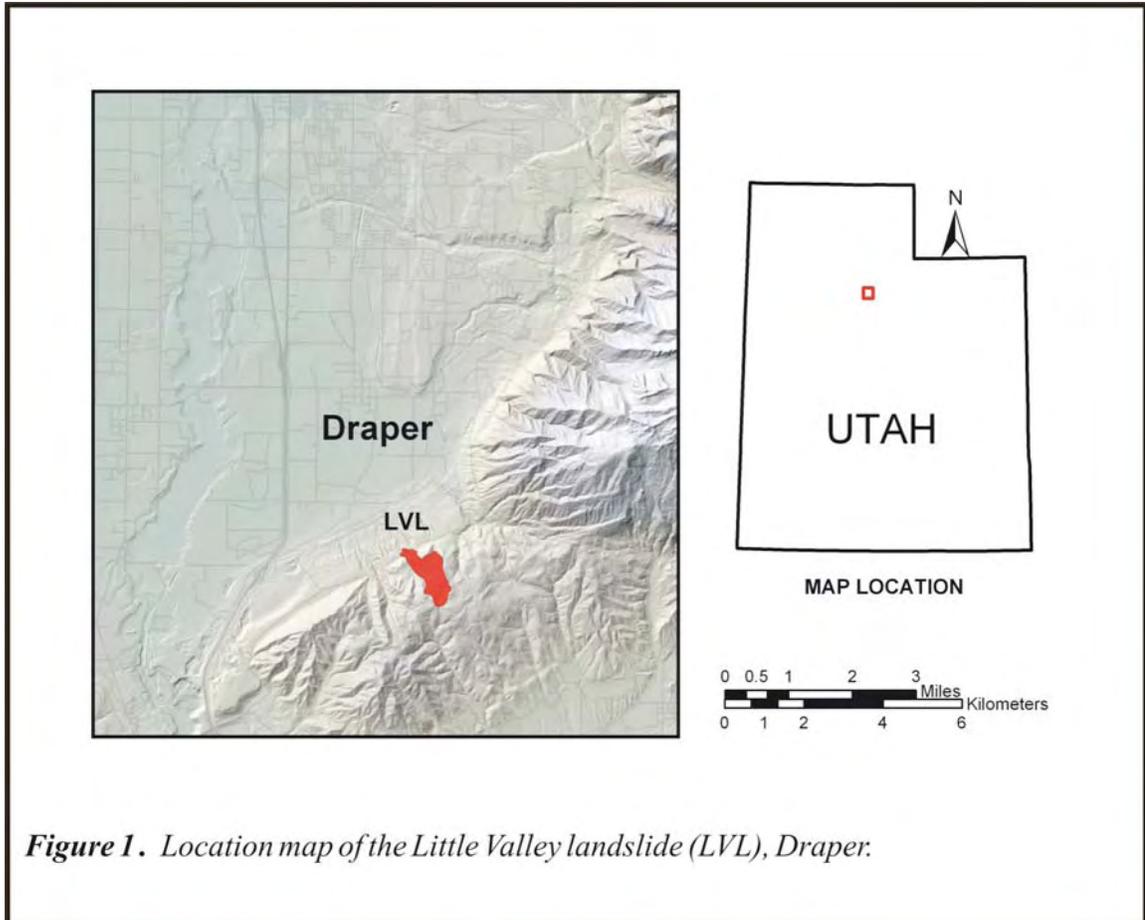
Introduction

The Little Valley landslide in Draper is the largest landslide in southern Salt Lake County (figure 1). The landslide consists of several stacked lobes, possibly suggesting different episodes of movement, and rotational block slides in the head and along the right (northeastern) flank. The landslide's topographic and geologic setting, proximity to the Wasatch fault zone, and characteristics suggest a potential vulnerability to earthquake-induced movement. Wong and others (2002) predicted peak horizontal accelerations resulting from a Salt Lake City segment, Wasatch fault magnitude 7 scenario earthquake to reach 0.7-0.8 g in the vicinity of the landslide. Thus, the landslide, or parts of it, may have been episodically reactivated by earthquakes. Geomorphic characteristics and landslide evaluations by consultants also made this landslide a reasonable candidate to test whether earthquake-induced movement could be recognized in large Wasatch Front landslides.

Landslide Description and Geology

Biek (2005) mapped the Little Valley landslide as extending about 5,800 feet (1,770 m) between the ridgeline and Bonneville-level bench on the north slope of the Traverse Mountains (also see the mapping of Van Horn, 1975) (figures 1 and 2). The landslide varies in width reaching a maximum of about 1,800 feet (550 m) in the Little Valley area. The landslide consists of several stacked lobes that suggest multiple episodes of movement or overriding by upslope parts of the landslide mass atop downslope parts during the main episode of movement. Two prominent rotational landslide blocks exist; one in the eastern part of the head and one along the east flank of the slide. Each is characterized by a back-tilted surface partly buried by pond deposits. Ephemeral sag ponds still occupy the upslope parts of the rotated blocks.

The Little Valley landslide overlies and is surrounded on the east and south by deeply weathered and altered Tertiary volcanic rocks (Biek, 2005). Highly fractured, intensely



brecciated, and locally pulverized orthoquartzite of the Pennsylvanian-Mississippian Oquirrh Group abut the landslide on the west and flank the lowermost part of the slide. Late Pleistocene lacustrine gravels deposited during the Bonneville lake cycle underlie the lowermost foot of the landslide. Landslide debris is a heterogeneous mix of coarse material that includes large blocks of volcanic rock. Thus, the landslide is a prehistoric, deep-seated, dormant debris slide.

Movement History

Geomorphic evidence and radiocarbon ages of both deformed and undeformed soils on the Little Valley landslide suggest episodic movement since the Late Pleistocene. Tilted and displaced graben-fill sediments in the head of the landslide are older than

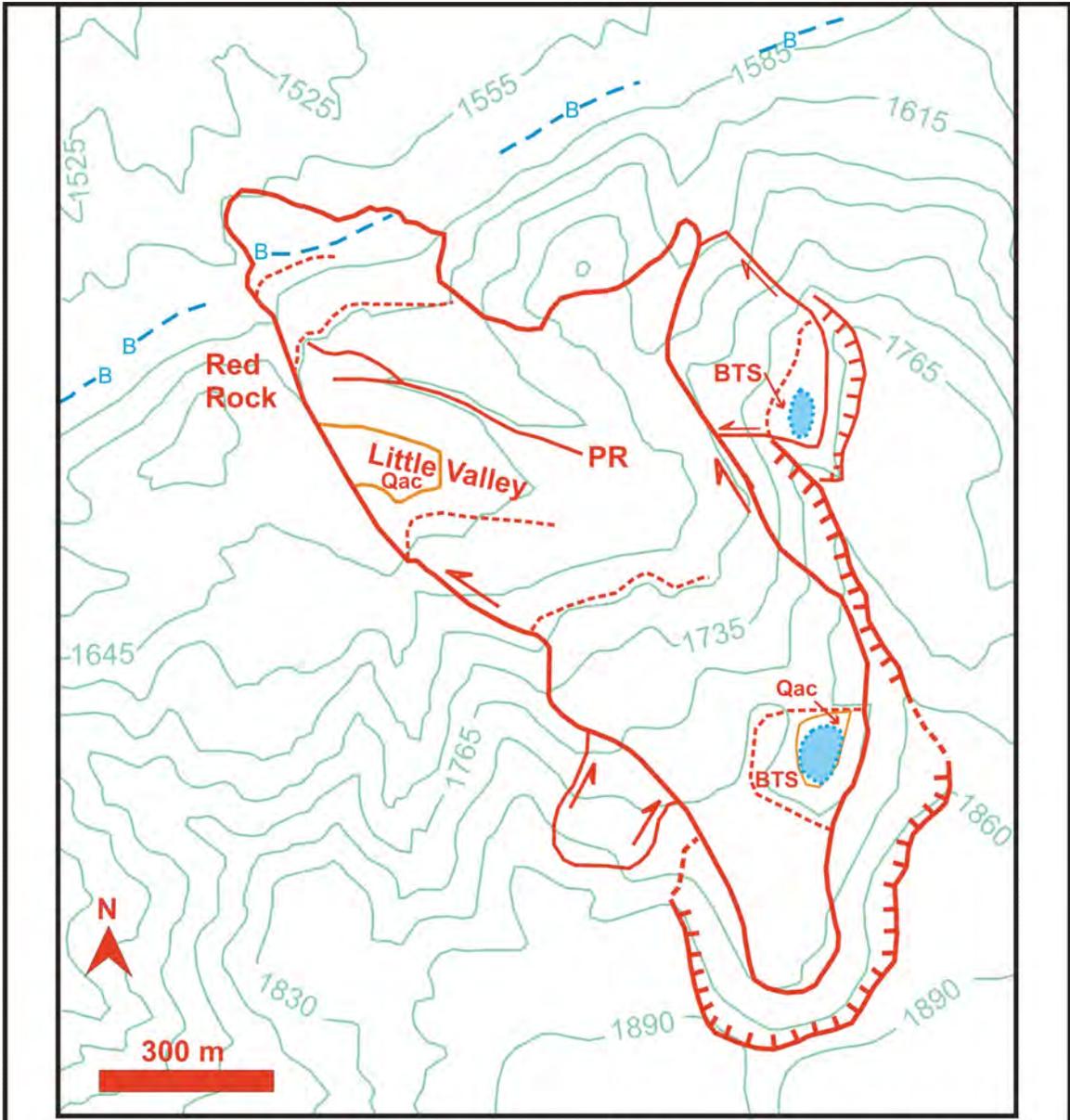


Figure 2. Map of the Little Valley landslide (modified from Biek, 2005). Little Valley occupies the lower central and western part of the landslide. A large northwest-trending pressure ridge (PR) bounds Little Valley on the northeast. Two rotational blocks with back-tilted surfaces (BTS) are present in the head and along the east flank. Sag ponds occupy the upslope sides of the back-tilted surfaces. Biek (2005) mapped alluvium and colluvium (Qac) in lower Little Valley and the upper sag pond area in the head of the landslide. Dashed lines show crest lines of the back-tilted surfaces. Dashed lines in lower and central part of landslide show the base of steep slopes that are likely thrust systems of separate lobes that may have formed during separate episodes of movement or were contemporaneous overriding events. Biek (2005) tentatively mapped the Bonneville shoreline (B) across the lowermost part of the landslide, which overrides Bonneville highstand shoreline deposits by at least 110 meters, suggesting a movement episode at about 17 ka. The original formation and movement of the landslide predates 29,120 ¹⁴C yr B.P. The most recent movement in the head of the landslide occurred about 4700 cal yr B.P.

29,120 ¹⁴C yr B.P. (Intermountain GeoEnvironmental Services, 2003) indicating that the Little Valley landslide initially formed prior to Lake Bonneville (dated at about 28,000 to 12,000 ¹⁴C years B.P.) and the established chronology of surface faulting on the Wasatch fault zone (Lund, 2005). Thus, a seismic origin cannot be established for the landslide, since the oldest documented surface-faulting event on the Wasatch fault zone is about 17 to 20 ka.

Exactly how the original landslide formed is unknown, but the present slide mass may have grown from gradual accumulation of landslide debris from local landsliding along the flanks of the original canyon that the slide now occupies, in combination with retrogressive enlargement. At some point these processes would have broadened the canyon and resulted in a large enough accumulation of landslide debris at a steep enough slope to initiate generally northwestward movement (the current movement direction) of the accumulated debris. Landsliding involved not only shallow slope materials, such as colluvium and accumulated landslide debris, but also the underlying weathered and fractured volcanic rock units. I infer that movement of the rotational blocks in the head and flanks of the landslide occurs in response to movement downslope, and is specifically due to the removal of lateral support as downslope movement of the accumulated landslide debris evacuates parts of the slide.

Biek (2005) mapped the foot of the landslide as extending at least 360 feet (110 m) beyond the Bonneville highstand shoreline, but also showed the shoreline across the lowermost part of the slide. These relationships suggest that a major episode of movement is contemporaneous with the latter part of the Bonneville shoreline lake stage that existed until 16.8 ka. Given the inferred rate of erosion of the nearby Steep Mountain area during the Lake Bonneville highstand, the present foot of the landslide that extends downslope of the Bonneville shoreline is probably not older than 17 ka, otherwise it would have likely been removed by wave erosion. Trenches excavated in the foot of the landslide exposed Lake Bonneville highstand shoreline deposits both overridden by and deposited on landslide debris (figure 3), further indicating an age estimate of 17 ka for the major movement episode.

Radiocarbon ages of apparently undeformed alluvium in Little Valley (figure 2) in the lower and western main body of the landslide (Intermountain GeoEnvironmental Services, 2003) date at about 12.5 to 13.0 ka. Whereas this may suggest stability, at least in the lower part of the slide, during the latest Pleistocene, movement that did not cause ground deformation in the Little Valley alluvium cannot be precluded.

The geomorphic characteristics of the two rotational blocks, one in the eastern part of the head and one on the east flank (figures 2, 4, and 5), suggest more recent (Holocene) movement. The blocks are defined by back-tilted surfaces (BTS on figures 2 and 4) that are partly covered on the upslope side by sag pond sediments. The rotational block in the head of the slide is also characterized by a beheaded drainage that is severed at the intersection of the crest of the back-tilted surface. The drainage exists only downslope of the crest, but is absent upslope and shows no relationship to the existing topography on or upslope of the back-tilted surface. Ephemeral sag ponds on the landslide are apparently



Figure 3. Photographs of trench exposures documenting movement of the Little Valley landslide about 17 ka. (A) Exposure in westernmost of three trenches excavated by Intermountain GeoEnvironmental Services near the toe of the landslide. Well-sorted, rounded gravels are likely Lake Bonneville highstand sediments (Qlb) overlying sheared rock (Qmso, older landslide deposits). Younger landslide deposits (Qmsy) or colluvium (Qc) derived from landslide deposits overlies the lacustrine gravels. Rock hammer is about 1.3 feet (0.4 m) long. (B) Exposure in middle trench of either Lake Bonneville highstand sediments (Qlb) or alluvial-fan deposits (Qafb) graded to the Bonneville shoreline overridden by landslide deposits (Qmsy). Dashed line is approximate thrust. Arrows show movement direction of landslide.

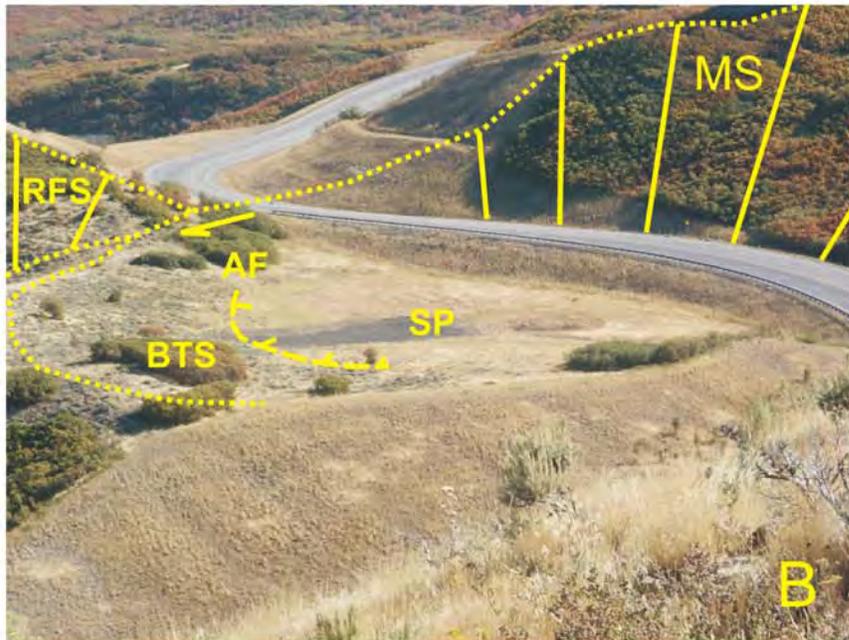


Figure 4 . Photographs of upper sag pond area in the Little Valley landslide, Draper. Sag pond sits on a rotational block in the head of the landslide that has been deformed by stretching. (A) View to the east-northeast of upper part of landslide and sag pond area. (B) Detail showing trench location (area of bare gray soil) on northwest side of sag pond (SP). Also shown are main scarp (MS), right-flank scarp (RFS), back-tilted surface (BTS), and approximate location of antithetic fault (AF). Curvature on antithetic fault is assumed based on observed curvature of back-tilted surface.



Figure 5. Photographs of sag pond area along the east flank of the Little Valley landslide, Draper. (A) View to the south-southeast of the sag pond area, southern part of the main scarp, and back-tilted surface (foreground). (B) View to the northeast of east-flank rotational block (arrow).

the result of water that perches atop the backtilted surfaces and have not yet been captured by downstream drainages, suggesting a Holocene age.

Trenching across the back-tilted surface downslope of the upper sag pond in the rotational block in the head of the landslide (figures 2 and 6) conducted as part of a consultant's geologic study (Intermountain GeoEnvironmental Services, 2003) revealed an antithetic (landslide-related) fault. The antithetic fault likely accommodates stretching of the rotational block and bounds clay-rich graben-fill sediments between the structure and the main scarp. The graben-fill sediments are juxtaposed across a wide fault zone (figure 4) against rotated Tertiary volcanic rock, indicating that the total offset on the antithetic fault exceeds the depth of the trench (about 13.5 feet [4.1 m]). Based on a trench log in the Intermountain GeoEnvironmental Services (2003) report, the total offset along the fault is greater than 18.4 feet (5.6 m) and the net vertical displacement is more than 14.4 feet (4.4 m). As stated above, the age of graben-fill sediments (radiocarbon age older than 29,120 ^{14}C yr B.P.) indicates the graben formed prior to Lake Bonneville. Tilting and faulting of these sediments may be associated with the movement episode that overrode latest Pleistocene Lake Bonneville highstand shoreline deposits, but is poorly constrained and conceivably could be older. No colluvial wedges are apparent between the graben-fill sediments and the fault zone in the lower two-thirds of the trench, but these may be obscured by fault zone deformation. Their absence possibly also suggests offset along the fault at an extremely slow and perhaps nearly continuous rate so that an upslope-facing (antithetic) scarp did not form during this period of movement (Ferrelli and others, 2002). If offset along the antithetic fault occurred at an extremely slow rate, the maximum antithetic scarp height may have measured only a fraction of an inch (millimeters) in height at any one time, insufficient for a colluvial wedge to form. Deposition into the graben would have been solely from erosion of the slowly growing main scarp.

The most recent movement on the antithetic fault offsets organic silt (loess and/or pond sediments) and formed an upslope-facing (antithetic) scarp (now buried). The base of a colluvial wedge (figure 6) yielded an age of about 4,700 cal yr B.P. (4,555-4,860 cal yr B.P.) (Intermountain GeoEnvironmental Services, 2003). This age represents a maximum limiting age for the onset of colluvial-wedge deposition. Therefore, an episode of landslide scarp formation likely occurred at this location shortly before this time. This episode marks an apparently abrupt change from extremely slow and possibly continuous movement on the structure to movement more typical for Wasatch Front landslides in which measurable offset on the antithetic fault resulted in an upslope-facing (antithetic) scarp. The net vertical displacement caused by the most recent movement on the fault is about 3 feet (1 m). The age of this scarp-forming movement episode postdates by about 600 years the estimated mean age of a documented mid-Holocene large earthquake on the Salt Lake City segment of the Wasatch fault zone (event W) estimated to have occurred at about 5300 cal yr B.P. (Lund, 2005), but could be contemporaneous if the uncertainty in the age estimates is considered. Thus, the possibility exists that the most recent documented movement episode was triggered by a Wasatch fault zone surface-faulting earthquake.

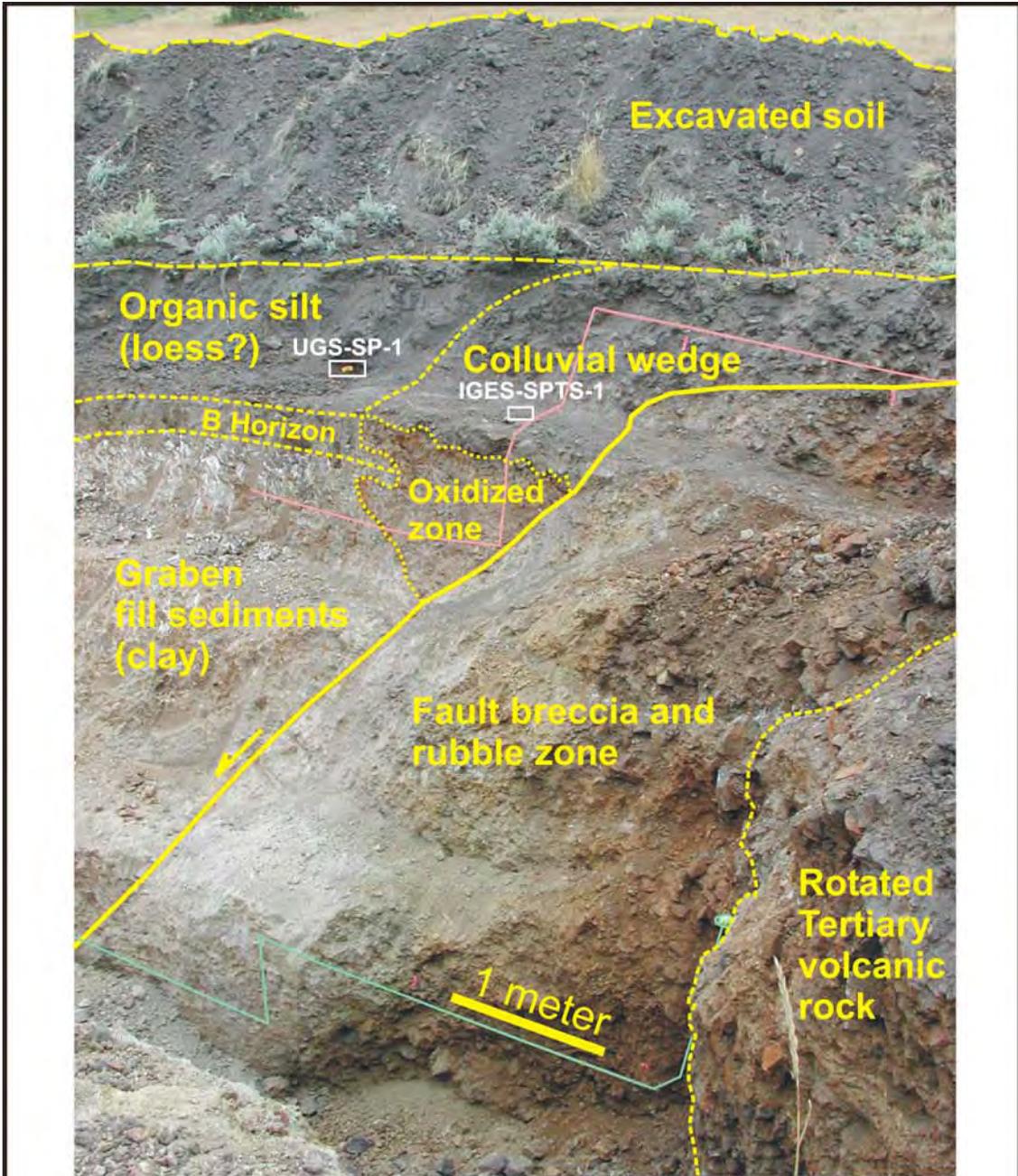


Figure 6. Photolog of antithetic fault zone in a trench across the northwestern part of the upper sag pond in the Little Valley landslide, Draper. Trench was excavated by Intermountain GeoEnvironmental Services (IGES) as part of a landslide evaluation for a proposed subdivision downslope of the area (IGES, 2003). A single colluvial wedge exists at the top of the antithetic scarp fault zone. Soils at the base of the wedge (IGES SPTS-1) range in age from 4555 to 4860 cal yr B.P. constraining the timing of the most recent offset along the scarp as slightly older. This age range overlaps with the estimated timing of surface-faulting event W on the Salt Lake City segment of the Wasatch fault zone (4550 to 6050 cal yr B.P.) allowing the possibility that landslide movement was triggered by event W. Pink and green lines are level lines.

Some corroborating data support a seismic origin for this movement episode. The age of the movement episodes falls within a dry period of the Holocene (figure 7) that occurred between about 6,000 and 4,000 ^{14}C yr B.P. (Murchison, 1989). Ground-water levels sufficient to trigger landslide movement under static conditions were less likely to occur during this extended regional dry period. In addition, the apparent increase in the movement rate of the antithetic fault appears compatible with earthquake triggering. This increase may have been caused by a reduction in shear strength resulting from earthquake-induced displacement of the landslide mass, possibly subsequent to a gradual reduction during periods of extremely slow movement (or creep) prior to that time, or to excess pore pressures developed during earthquake ground shaking.

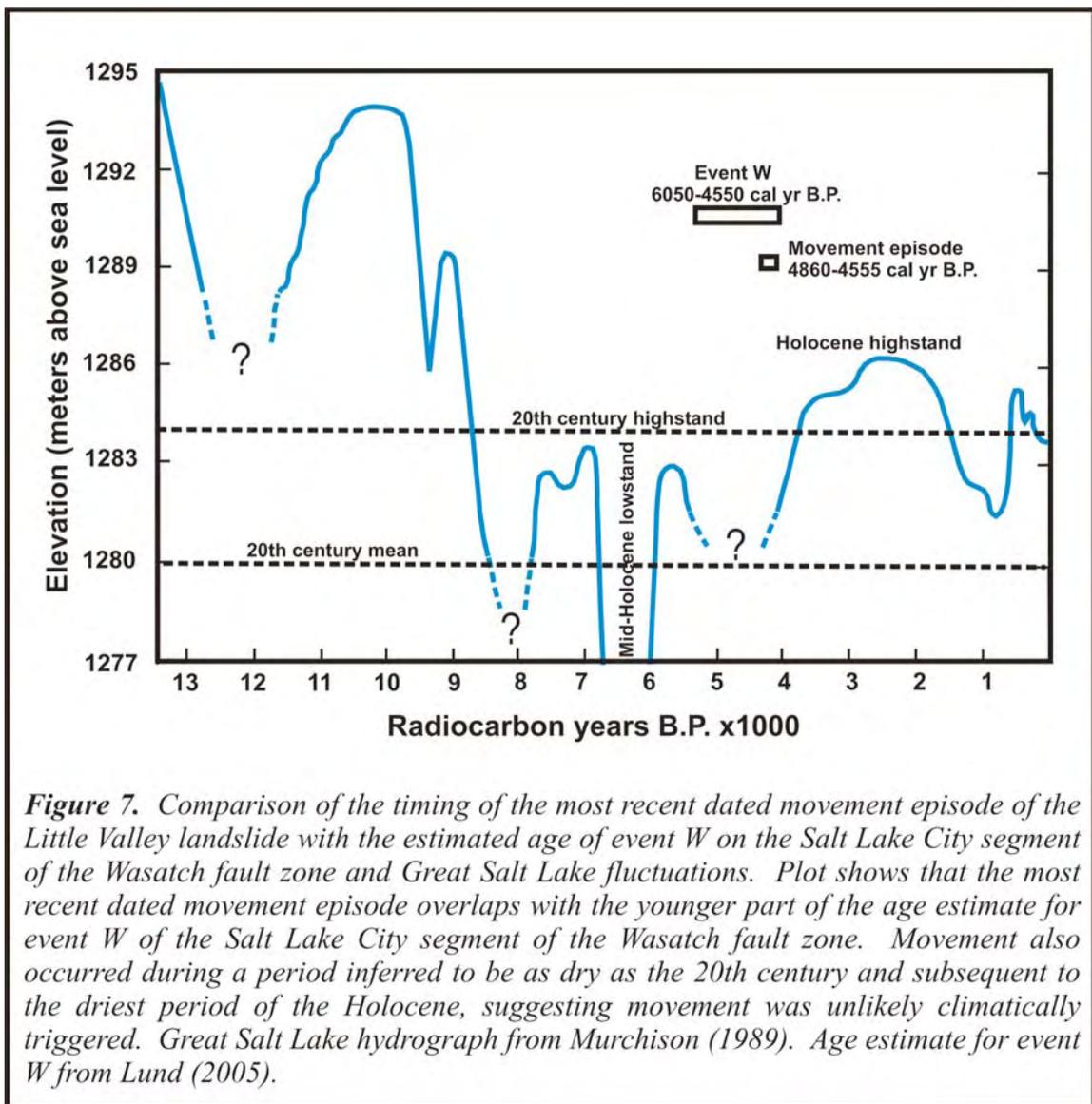


Figure 7. Comparison of the timing of the most recent dated movement episode of the Little Valley landslide with the estimated age of event W on the Salt Lake City segment of the Wasatch fault zone and Great Salt Lake fluctuations. Plot shows that the most recent dated movement episode overlaps with the younger part of the age estimate for event W of the Salt Lake City segment of the Wasatch fault zone. Movement also occurred during a period inferred to be as dry as the 20th century and subsequent to the driest period of the Holocene, suggesting movement was unlikely climatically triggered. Great Salt Lake hydrograph from Murchison (1989). Age estimate for event W from Lund (2005).

THE FEASIBILITY OF RECOGNIZING EARTHQUAKE-INDUCED MOVEMENT OF LARGE WASATCH FRONT LANDSLIDES

This study demonstrates the feasibility of documenting the movement history of large landslides by careful geomorphic analysis and the use of traditional paleoseismic methods such as trenching and radiocarbon dating. This study benefited from data obtained by a consultant's coincidental geologic study of the Little Valley landslide (Intermountain GeoEnvironmental Services, 2003).

The success in establishing a preliminary movement history of the landslide was due in part to the geomorphic characteristics of this particular landslide that provided opportunities to locate datable paleosols and colluvial wedges. Specifically, the presence of organic-rich graben fill and silt in the sag pond area in the head of the landslide and alluvium in Little Valley allowed radiocarbon dating of both movement episodes and periods of stability. In the absence of these geomorphic characteristics, establishing the age of landslide movement has proven challenging, including on other nearby landslides in the Draper area. A paucity of organic deposits exists in the debris of the Little Valley landslide as well as in other nearby slides in Tertiary volcanic rocks. In addition, where one of these landslides has overridden Lake Bonneville highstand shoreline deposits, a datable paleosol was absent, perhaps due to erosion of the topsoil by persistent and strong winds that currently characterize the area and have likely been present in the geologic past.

Access to the best available sites is a critical factor to successfully dating landslides. The trench across the sag pond area in the head of the landslide (figure 2) was limited in extent due to landowner concerns about disturbance to the pond. In addition, the existence of a road at the base of the main scarp prohibited trenching where the best colluvial wedges may be preserved documenting a more complete record of landslide movement in the upper part of the slide. A test-pit log (Delta Geotechnical Consultants, 1997) from the area currently beneath the road at the base of the main scarp indicates that three episodes of movement were evident and suggests that soil A horizons (paleosols) were offset by the main scarp. Thus, the one Holocene event documented by the Intermountain GeoEnvironmental Services (2003) trench (figure 4) may be only one of several Holocene movement episodes. Ashland (2002) recognized that in structurally complex landslides, individual landslide deformation features, such as the antithetic fault in figures 4 and 6, are not consistently active despite movement of the overall slide. Thus, the reactivation of the antithetic scarp may not have occurred with every movement episode of the landslide, but rather coincided with episodes that caused significant stretching of the head block.

Other opportunities exist for dating possible Holocene movement episodes of the Little Valley landslide and nearby slides that overlap with the documented chronology of the Wasatch fault zone. The best remaining site is the main scarp and sag pond area of the rotational block along the east flank of the landslide (figures 2 and 5). The area is currently undeveloped; however, access to the site is difficult, possibly requiring

construction of a temporary access road. Despite the access challenges, the possible favorable geologic conditions include:

- organic-rich sag pond sediments,
- progressively tilted and/or faulted sediments in the rotational block,
- colluvial wedges and buried paleosols at the base of the main scarp, and
- possible antithetic faults and colluvial wedges.

One limitation of this area is the uncertainty of the relation between movement of the main landslide and this east-flank rotational block. Biek (2005) interpreted the east-flank rotational block as a separate landslide of uncertain age. However, the landslide likely developed in part by evacuation of its toe due to movement of the main body of the Little Valley landslide and in part by subsequent downcutting of an unnamed drainage. Thus, movement of this block likely represents enlargement of the Little Valley landslide along its flank caused by removal of lateral support as the main slide evacuated the region downslope of the block.

DISCUSSION

The earthquake-induced reactivation of pre-existing landslides as deep, coherent slides is a significant threat in the Wasatch Front given the large number of landslides in the area and the increasing development on prehistoric landslides. Recent research (Ashland, 2003; Christenson and Ashland, 2006) suggests that many Wasatch Front landslides likely have low factors of safety as indicated by the reactivation of a number of pre-existing landslides during wet periods in the past 20 years. If many or most of the Wasatch Front landslides have marginal stability, then earthquake-induced reactivation likely has occurred in many slides. The demonstrated vulnerability of Wasatch Front landslides to movement triggered by a rise in ground-water levels associated with wet periods suggests that most movement episodes in recurrently moving slides are likely climatically controlled rather than earthquake induced. Separating out earthquake-induced movement episodes from the overall movement history of a landslide, i.e., demonstrating the seismic origin of a movement episode (Jibson, 1996), poses a significant challenge.

This evaluation of the Little Valley landslide demonstrated the feasibility of determining, at least in part, the movement history of a landslide, using traditional paleoseismic methods and geomorphic analysis. Nearly ideal geomorphic conditions, including local sag ponds and structural troughs (Little Valley) that contained datable organic-rich sediments, provided opportunities to date deformation and movement episodes. Whereas I interpret a possible seismic origin for a mid-Holocene movement episode dated at about 4.7 ka, the dating of both the landslide and earthquakes is not accurate enough to definitively correlate the movement episode with the surface-faulting event. The likelihood that the movement episode was earthquake triggered would increase if movement episodes of the same age were identified at other nearby landslides, although such evidence could also support a climatic cause. A seismic origin would be

better supported where multiple landslides were identified as having occurred during a dry period (see figure 7), or other evidence of a seismic origin, such as contemporaneous liquefaction, was identified.

Characterizing the likelihood of deep, coherent landslides being triggered by major Wasatch Front earthquakes requires detailed study to determine the susceptibility and movement behavior of some representative slides. The susceptibility to earthquake-induced movement of an individual landslide could be better demonstrated if multiple episodes of movement correlated with surface-faulting events on the Wasatch fault zone. In addition, the dormancy of a particular landslide during a documented surface-faulting event on a nearby fault segment has implications for the control of other factors on whether earthquake-induced movement occurs. Such factors include ground-water levels, landslide boundary and geometry constraints (the geometric freedom of movement and available driving force under static conditions), possible temporal changes in shear strength (thixotropic hardening), and variations in ground accelerations generated by surface-faulting earthquakes on an individual fault segment.

This evaluation of the Little Valley landslide was limited, and complete documentation of the movement history would require additional trenching of favorable structures such as the main scarp zone. Observations from historically active slides indicate that offset on the main scarp generally occurs with movement of large landslides, except where the total movement is minimal (several centimeters or less). Thus, the main scarp zones likely document a more complete record of a landslide's movement history than internal deformation features in the landslide mass, such as the antithetic fault exposed in the Intermountain GeoEnvironmental Services (2003) sag pond trench, particularly given the uncertainty of movement on any specific internal deformation feature during each movement episode (Ashland, 2002). With more complete documentation of the landslide's movement history, a better correlation with Wasatch fault zone surface-faulting earthquakes may become apparent.

Movement episodes that fall between the documented ages of Wasatch fault zone surface-faulting earthquakes do not necessarily preclude a seismic origin, but require other corroborating evidence to support one. Keefer (1984) indicated that the minimum magnitude to trigger soil and rock block slides and rotational slides (magnitude 4.5-5.0) is less than the magnitude estimated for a Wasatch fault zone surface-faulting earthquake. Thus, Wasatch Front landslides may have been triggered or reactivated by earthquakes of smaller magnitude than those of the documented surface-faulting events. Multiple lines of evidence that might support the conclusion that a landslide episode was triggered by a non-surface-faulting earthquake include similar-age movement episodes from several landslides, movement during prehistoric dry periods, and evidence for liquefaction coincident with landsliding.

SUMMARY

I developed a partial movement history for the Little Valley landslide, one of the largest prehistoric slides in the Salt Lake City metropolitan area, using geomorphic analysis and radiocarbon ages obtained as part of a consultant's landslide investigation (Intermountain GeoEnvironmental Services, 2003). Establishment of this movement history was possible due to some ideal geomorphic characteristics of this particular landslide, including the presence of rotated blocks with deformed and displaced latest Pleistocene-Holocene sag pond sediments, and local troughs on the landslide with latest Pleistocene-Holocene alluvium, that allowed dating of movement episodes and periods of dormancy. Other areas of the slide were characterized by barren landslide debris with no opportunities for radiocarbon dating. A radiocarbon age obtained from the base of a colluvial wedge on the hanging-wall side of an antithetic fault in the upper sag pond area in the head of the landslide indicated a movement episode about 4.7 ka. This age overlaps with the estimated age range of surface-faulting event W on the Salt Lake City segment of the Wasatch fault zone. Whereas the radiocarbon age alone is not conclusive proof of a seismic origin, the movement episode corresponds with a dry period in the Holocene (Murchison, 1989), suggesting movement was unlikely triggered by climatic conditions. However, given the inferred low factors of safety of many Wasatch Front landslides (Ashland, 2003; Christenson and Ashland, 2006), multiple lines of evidence are needed to confidently demonstrate a seismic origin for any specific movement episode.

ACKNOWLEDGMENTS

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REFERENCES

- Ashland, F.X., 2002, Recurrent movement of the East Capitol Boulevard-City Creek landslide, Salt Lake City, Utah [abs.]: Association of Engineering Geologists 45th Annual Meeting, AEG News, v. 45, Program with Abstracts, p. 54.
- Ashland, F.X., 2003, Characteristics, causes, and implications of the 1998 Wasatch Front landslides, Utah: Utah Geological Survey Special Study 105, 49 p.
- Biek, R.F., 2005, Geologic map of the Lehi quadrangle and part of the Timpanogos Cave quadrangle, Salt Lake and Utah Counties, Utah: Utah Geological Survey Map 210, scale 1:24,000.
- Christenson, G.E., and Ashland, F.X., 2006, Assessing the stability of landslides – overview of lessons learned from historical landslides in Utah, *in* Proceedings for the

- 40th Symposium on Engineering Geology and Geotechnical Engineering: Logan, Utah State University, 17 p.
- Delta Geotechnical Consultants, 1997, Geotechnical study – proposed Traverse Ridge Road alignment 2, Draper, Utah: Salt Lake City, unpublished consultant’s report, 24 p.
- Ferrelli, Luca, Michetti, A.M., Serva, Leonello, and Vittorio, Eutizio, 2002, Stratigraphic evidence of coseismic faulting and aseismic fault creep from exploratory trenches at Mt. Etna volcano (Sicily, Italy), *in* Etensohn, F.R., Rast, N., and Brett, C.E., editors, Ancient seismites: Geological Society of America Special Paper 359, p. 49-62.
- Harp, E.L. and Jibson, R.W., 1995, Inventory of landslides triggered by the 1994 Northridge, California earthquake: U.S. Geological Survey Open-File Report 95-213, 17 p., 2 plates.
- 1996, Landslides triggered by the 1994 Northridge, California, earthquake: Bulletin of the Seismological Society of America. v. 86, no. 1B, p. S319-S332.
- Harty, K.M., and Lowe, Mike, 2003, Geologic evaluation and hazard potential of liquefaction-induced landslides along the Wasatch Front: Utah Geological Survey Special Study 104, 40 p.
- Hylland, M.D., and Lowe, Mike, 1998, Characteristics, timing, and hazard potential of liquefaction-induced landsliding in the Farmington Siding landslide complex, Davis County, Utah: Utah Geological Survey Special Study 95, 38 p.
- Intermountain GeoEnvironmental Services, 2003, South Mountain Phase 11 Plat B – Paul Shupe Condo property, Draper, Utah: Salt Lake City, Utah, unpublished consultant’s report, 19 p.
- Jibson, R.W., 1996, Using landslides for paleoseismic analysis, *in* McCalpin, J.P., editor, Paleoseismology: New York, Academic Press, p. 397-438.
- Jibson, R.W., and Harp, E.L., 1996, The Springdale, Utah landslide – an extraordinary event: Environmental & Engineering Geoscience, v. II, no. 2, p. 137-150.
- Keaton, J.R., Anderson, L.R., Topham, D.E., and Rathbun, D.J., 1987, Earthquake-induced landslide potential in and development of a seismic slope stability map of the urban corridor of Davis and Salt Lake Counties: Salt Lake City, Dames & Moore and Utah State University Department of Civil and Environmental Engineering, unpublished Final Technical Report for the U.S. Geological Survey, 47 p., 4 plates, scale 1:48,000.
- Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, no. 4, p. 406-421.
- Lund, W.R., 2005, Consensus preferred recurrence-interval and vertical slip-rate estimates – review of Utah paleoseismic-trenching data by the Utah Quaternary Fault Parameters Working Group: Utah Geological Survey Bulletin 134, 109 p.
- Murchison, S.B., 1989, Fluctuation history of the Great Salt Lake, Utah, during the last 13,000 years: Salt Lake City, University of Utah, Department of Geography, Limnogeotectonics Laboratory Technical Report 89-2, 137 p.
- Solomon, B.J., Storey, N., Wong, I., Silva, W., Gregor, N., Wright, D., and McDonald, G., 2004, Earthquake-hazards scenario for a M7 earthquake on the Salt Lake City segment of the Wasatch fault zone, Utah: Utah Geological Survey Special Study 111DM, 59 p.

- Van Horn, R., 1975, Unevaluated reconnaissance geologic maps of Salt Lake and Davis Counties, west of the Wasatch Front, Utah: U.S. Geological Survey Open-File Report 75-616, scale 1:48,000.
- Wong, I., Silva, W., Olig, S., Thomas, P., Wright, D., Ashland, F., Gregor, N., Pechmann, J., Dober, M., Christenson, G., and Gerth, R., 2002, Earthquake scenario and probabilistic ground shaking maps for the Salt Lake City, Utah, metropolitan area: Utah Geological Survey Miscellaneous Publication 02-5, 50 p., 9 plates, scale 1:75,000.