

RECONNAISSANCE OF THE DRAPER HEIGHTS LANDSLIDE AND OTHER POSSIBLE EARTH- QUAKE-INDUCED, SHALLOW, DISRUPTED SOIL AND ROCK SLIDES IN DRAPER, UTAH

by
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Cover photo: Residential development at the base of Steep Mountain, Draper.

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ABSTRACT

Earthquake-induced landslides, with the exception of liquefaction-induced lateral spreads, have not been recognized in the Salt Lake City metropolitan area. This study assesses the feasibility of identifying such earthquake-induced landslides, given the documented latest Pleistocene to present surface-faulting chronology for the Wasatch fault zone and mapped hillslope areas with moderate to high potential for shallow, disrupted slides. Previous researchers mapped a high earthquake-induced shallow landslide hazard on the northwest slope of Steep Mountain, but did not identify any earthquake-triggered slides.

This study identifies the Draper Heights landslide as a possible earthquake-induced, shallow, disrupted soil slide, one of the most common landslide types triggered by the 1994 Northridge earthquake. Other nearby flat-bottomed scars upslope of cone-shaped deposits are also possible earthquake-induced, shallow, disrupted soil slides. Limited opportunities exist for radiocarbon and cosmogenic dating of the slides. The Draper Heights landslide postdates the Bonneville shoreline (younger than 16,800 cal yr B.P.) and thus overlaps in age with the documented surface-faulting chronology of the Wasatch fault zone. Slope-stability analysis, however, suggests that this and other possible landslides on the northwest slope of Steep Mountain may be triggered by earthquakes of smaller magnitude than surface-faulting events.

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. Keefer (1984) listed disrupted soil and rock slides and falls as the most common types of landslides caused by earthquakes. Harp and Jibson (1995, 1996) noted that the majority of landslides caused by the 1994 magnitude 6.7 Northridge earthquake in southern California were these types of slides and observed that disrupted slides were generally shallow. 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, particularly the very small ones, in the geologic record and differentiating them from non-earthquake-induced landslides.

Steep Mountain (figures 1 and 2) is an area previously recognized as having the potential for shallow, earthquake-induced landslides (Keaton and others, 1987), but to date, prehistoric earthquake-induced landslides have not been identified in the area. The one mapped landslide (Van Horn, 1975; Biek, 2005b) in the northwest slope of the mountain, referred to herein as the Draper Heights landslide (figure 1), is a shallow, disrupted soil slide and thus, the type most likely to be caused by an earthquake.

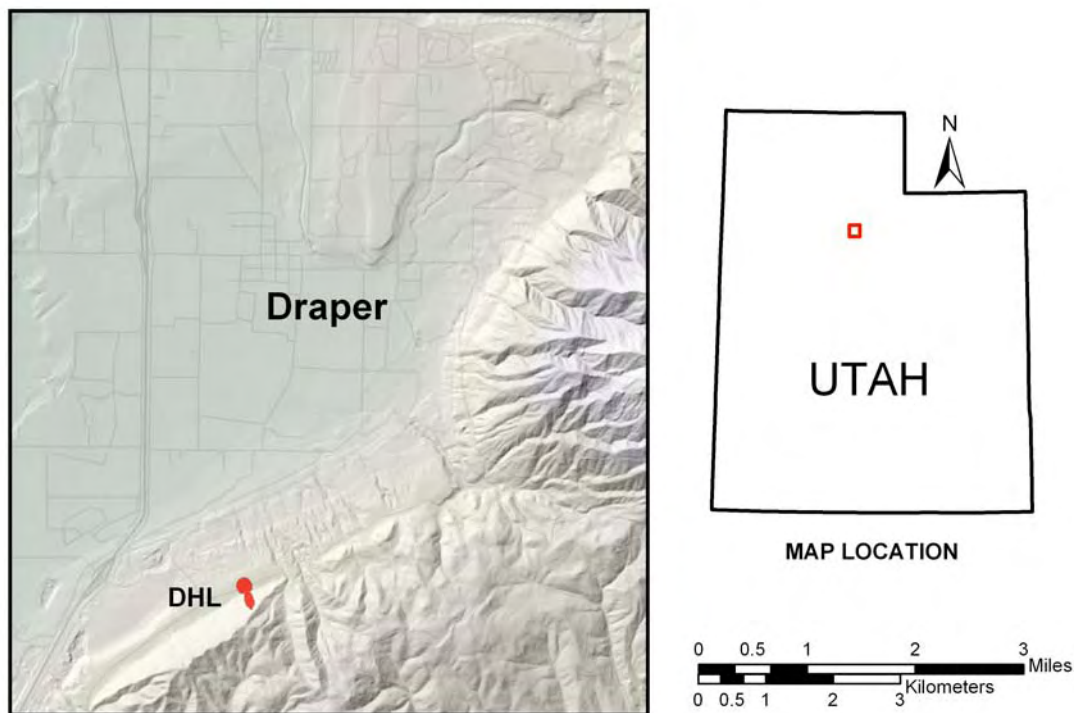


Figure 1. Location of the Draper Heights landslide (DHL) and Steep Mountain.

DRAPER HEIGHTS LANDSLIDE AND SEISMIC STABILITY OF THE STEEP MOUNTAIN NORTHWEST SLOPE

Introduction

Keaton and others (1987) recognized a significant potential for earthquake-induced landsliding in the Steep Mountain area, but did not identify prehistoric landslides that may have been triggered by large earthquakes. Geomorphic characteristics have been recognized during ongoing landslide research (including this study) and mapping by the Utah Geological Survey (Biek, 2005a, 2005b) as suggesting a susceptibility of the northwest slope of the mountain to earthquake-induced landsliding. Recent residential development at the base of Steep Mountain in Draper (figure 2) increases the vulnerability of this community to earthquake-induced landsliding. As part of this study, I:

- evaluated the possibility that the Draper Heights landslide on the northwest slope of Steep Mountain is an earthquake-induced slide,
- assessed the feasibility of dating the landslide and correlating it with a documented surface-faulting event on the nearby Wasatch fault zone,

- evaluated the potential for future earthquake-induced landslides on the Steep Mountain northwest slope using the ground motion estimates of Frankel and others (1996), and
- mapped and evaluated other possible shallow, disrupted slides in the vicinity of Steep Mountain.



Figure 2. Residential development along the base of Steep Mountain. Keaton and others (1987) mapped a high earthquake-induced landslide potential in the northwest slope prior to any development at the base of the mountain. (A) View of houses at the base of the northwest-facing slope in an area characterized by hummocks, and wavy ridges and swales. Biek (2005a, 2005b) interpreted the latter as evidence of creep (the extremely slow downslope movement) of variably thick colluvium on the slope. These areas may be near the threshold of failure and also extremely vulnerable to earthquake-induced landsliding. (B) View showing the proximity of houses to the northwest slope of Steep Mountain. Average slope is about 66 percent. (C) Detail showing proximity of houses to an area characterized by hummocks. Setback of houses from base of slope is inadequate to protect them from landsliding of the scale of the Draper Heights landslide. (D) View of the undeveloped western part of the Steep Mountain area showing the land that was (in the developed eastern part of Steep Mountain) available for building setback to reduce the risk from earthquake-induced landsliding.

Physiography and Geology of Steep Mountain

Steep Mountain is an east-northeast trending ridge that reaches a maximum elevation of about 6180 feet (1884 m) in the southern part of the Salt Lake City metropolitan area. The local relief between a prominent bench underlain by Bonneville shoreline deposits and the ridge crest reaches a maximum of about 1020 feet (311 m) and the average slope is relatively uniform, ranging between about 65 and 67 percent (33° to 34°). Recent residential development has occurred at the base of the eastern part of the mountain (figure 2) despite the vulnerability to landsliding.

Steep Mountain is underlain by highly fractured, intensely brecciated, or locally pulverized orthoquartzite and calcareous sandstone of the Upper Pennsylvanian Bingham Mine Formation of the Oquirrh Group (Biek, 2005a, 2005b). A variably thick veneer of colluvium and local alluvium overlies the fractured and easily eroded Bingham Mine Formation rocks on most of the northwest slope of Steep Mountain. The colluvium is likely thickest in the lower slope, possibly including landslide debris from shallow disrupted slides, and in local broad swales. Due primarily to the poor rock-mass quality of the underlying Bingham Mine Formation rocks, the colluvium is generally well sorted in grain size consisting mostly of sand- and fine-gravel-sized particles. Cobble-sized fragments generally represent the maximum particle size in the colluvium. Based on this texture and the angular fragment shape, the colluvium is likely cohesionless, well drained, and has a relatively high friction angle.

The present northwest slope of Steep Mountain formed as the result of wave erosion by glacial Lake Bonneville at its highest level. Oviatt and others (1992) estimated that the highest level of Lake Bonneville lasted about 1000 years, between about 15,500 and 14,500 ¹⁴C years B.P. (~18,000-16,800 cal yr B.P.). During this time, the northwest slope of Steep Mountain retreated southward due to erosion, resulting in the existing slope that is likely considerably steeper than the slope that existed prior to Lake Bonneville. A wave-cut bench in Bingham Mine Formation rocks extends as much as 1700 feet (520 m) north of the base of the northwest slope of Steep Mountain, indicating a maximum erosion rate of about 1.4 to 1.7 feet per year (43-52 cm/yr) during occupation of the Bonneville shoreline.

Following the catastrophic Bonneville flood at approximately 14,500 radiocarbon years ago (16,800 cal yr B.P.), the lake was lowered about 340 feet (104 m) to the Provo shoreline, and sediments deposited at the highest (Bonneville shoreline) level at the base of Steep Mountain became subaerially exposed. Since that time, physical weathering of the slope rocks formed local colluvium. Erosion occurred during intense rainstorms and rapid snowmelt forming local swales and gullies in the slope. Alluvial fans formed at the base of the slope below these swales and gullies. Biek (2005a) mapped a nearly continuous belt of alluvial-fan deposits at the base of the northwest slope along the western part of Steep Mountain.

Draper Heights Landslide

The Draper Heights landslide is a shallow, disrupted, complex debris slide-flow near the east end of Steep Mountain (figure 3). The landslide consists of a nearly circular deposit at the base of the slope that overlies Lake Bonneville highstand shoreline sediments. The deposit is approximately 800 feet (240 m) in diameter and about 20 to 30 feet (6-9 m) thick near the base of the slope. The source area of the debris slide is a zone that locally exceeds 400 feet (120 m) wide and extends about 900 feet (270 m) to the south between the base of the slope and the ridgeline. The local relief upslope of the deposit is about 620 feet (190 m) or about 390 feet (120 m) less than the maximum local relief farther to the west. The average slope directly west of the slide is about 65 percent.

Based solely on landslide type (shallow, disrupted slide), the Draper Heights landslide may be an earthquake-induced landslide. Harp and Jibson (1996) documented that this type of slide and falls were the most common types of landslides triggered by the 1994 Northridge earthquake. Jibson (1996) summarized the characteristics of slope materials that are particularly susceptible to earthquake-induced landsliding to include weathered, sheared, and intensely fractured and jointed rock, all of which describe the condition of the Bingham Mine Formation rocks that underlie the north slope of Steep Mountain (Biek, 2005a, 2005b). The nearly circular shape and smoothness of the deposit suggest that the landslide occurred as a single event and that slide debris traveled relatively rapidly downslope as a flow.

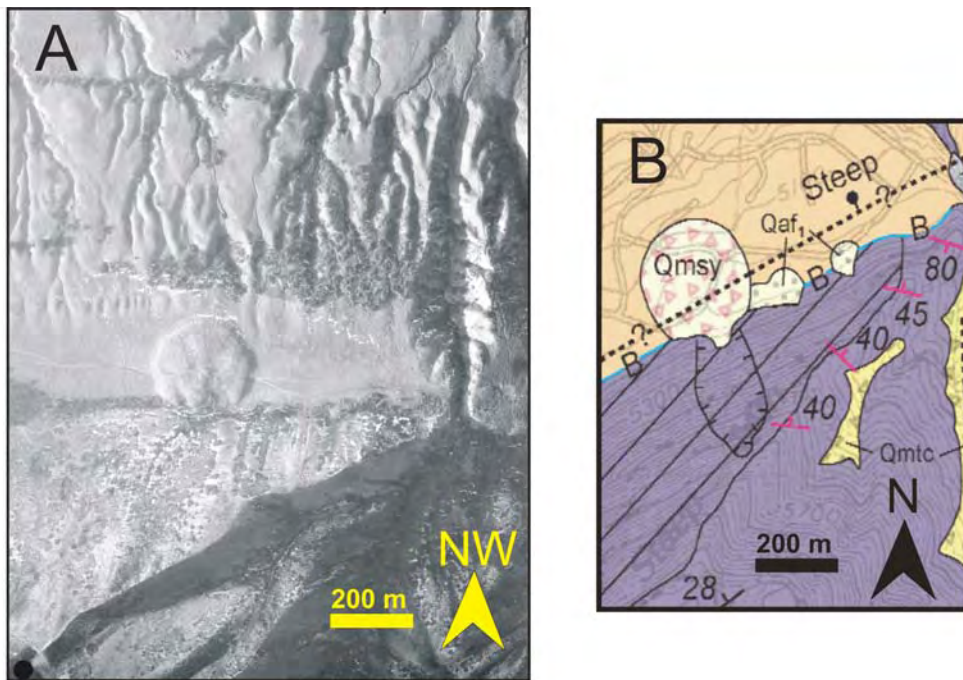


Figure 3. Aerial photograph (A) and geologic map (B) of the Draper Heights landslide (Qmsy). Aerial photograph taken prior to residential development along the base of Steep Mountain. Geologic map from Biek (2005b); showing the Bonneville shoreline (letters "B").

Feasibility of Dating the Landslide

The Draper Heights landslide overlies Bonneville shoreline sediments that were deposited about 15,500 to 14,500 ^{14}C years B.P. (~18,000-16,800 cal yr B.P.). Thus, the landslide is latest Pleistocene or younger and overlaps in age with the documented chronology of the Salt Lake City segment of the Wasatch fault zone (Lund, 2005). Obtaining an age estimate of the landslide may be possible using either radiocarbon or cosmogenic dating, or both, although the potential is limited.

Radiocarbon dating of the landslide may be possible if a buried paleosol developed on Bonneville shoreline sediments underlies the deposit. Limited, if any, opportunities exist to obtain this sample from foundation excavations within the limits of the landslide deposit because most of the residential lots have already been developed. However, a borehole could be drilled on public property such as a street. Recovery of a buried paleosol could be attempted using continuous sampling methods near the estimated depth of the base of the deposit. However, preliminary evidence suggests that a buried paleosol may not be present atop the underlying Bonneville shoreline sediments. A trench where the toe of the nearby Potato Hill landslide overrides Bonneville shoreline sediments did not encounter a buried paleosol. Strong winds that are characteristic of the area may strip organic sediments as rapidly as they form, preventing soil development.

Cosmogenic dating of either surface sediments on the deposit or in the source area may also be possible. Residential development over most of the deposit limits opportunity for cosmogenic dating because surface sediments are disturbed and buried. Cosmogenic dating of surface soils in the source area scar may be possible, but further reconnaissance of the area is necessary to determine if areas exist where colluvial processes have not buried or modified the original slide scar.

Other Possible Earthquake-Induced, Shallow, Disrupted Slides

Based on the earthquake-induced-landslide-potential mapping of Keaton and others (1987), a search was made for other possible shallow, disrupted slides in the vicinity of the Draper Heights landslide. Given the poor rock-mass condition of the Bingham Mine Formation rocks and the moderate to high earthquake-induced landslide potential of most of the nearby slopes, the Draper Heights landslide is likely not unique. Whereas Biek (2005a, 2005b) did not map any additional landslides in the vicinity of the Draper Heights landslide, AMEC Earth & Environmental (2003) mapped a shallow, disrupted rockslide/fall on the east side of a narrow spur underlain by shattered Bingham Mine Formation orthoquartzite about 1.1 miles (1.8 km) to the east. In addition, four nearby flat-bottomed scars and cone-shaped deposits are possible shallow, disrupted soil slides.

Three of the four scars occur in close proximity on slopes underlain by intensely fractured and faulted (as indicated by numerous slickensides) Bingham Mine Formation orthoquartzite (figure 4). The fourth is underlain by both Tertiary volcanic rocks and Bingham Mine Formation orthoquartzite. The scars are characteristically flat-bottomed and differ significantly from nearby V-shaped drainages formed by fluvial erosion that

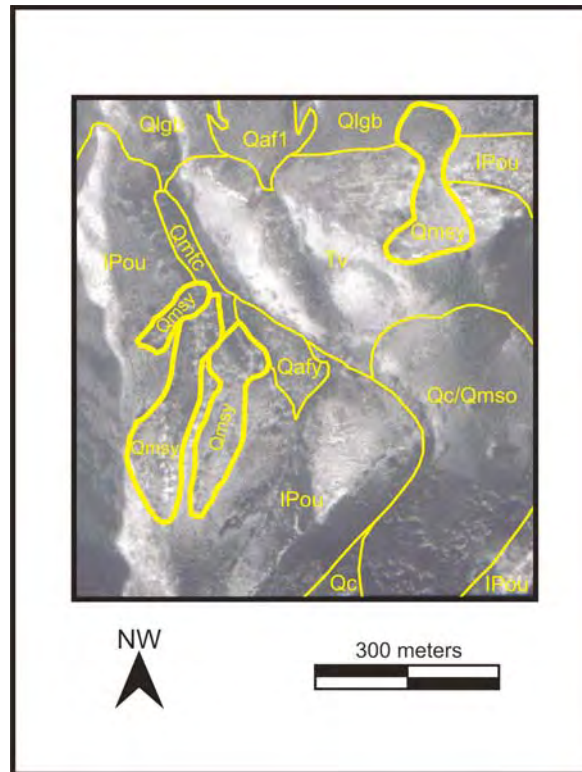


Figure 4. Map showing four possible shallow, disrupted landslides (Qmsy) defined by shallow, flat-bottomed scars and cone-shaped deposits. Three of the landslides are in colluvium underlain by Bingham Mine Formation orthoquartzite. The fourth is underlain by both Tertiary volcanic rocks (Tv) and Bingham Mine Formation orthoquartzite (IPou). Draper Heights landslide is about 0.75 miles (1.2 km) west of these landslides.

have alluvial fans at their base. The scars are occupied by short oak trees. The upslope part of each of the scars is characterized by an abrupt, step-like, downslope-facing scarp that suggests a landslide origin. At the base of the easternmost scar, a cone-shaped deposit has a local slope of 25° . None of the deposits below the scars are incised by drainages, in contrast to the incised alluvial fan at the base of the V-shaped drainage directly to the east.

Dating of these possible landslides is feasible using the methods described for the Draper Heights landslide. The deposits at the base of the three closely spaced scars are undeveloped and accessible from a nearby road. Their likely shallow depth allows for excavation to their base with a backhoe, and the possibility of identifying a landslide origin of deposits and finding a buried paleosol that dates them. Cosmogenic dating of the landslides is also feasible, but some of the limitations discussed for cosmogenic dating of the Draper Heights landslide likely also apply at these slides.

Seismic Slope Stability of the Northwest Slope of Steep Mountain

I re-evaluated the slope stability of the northwest slope of Steep Mountain using the ground-motion estimates of Frankel and others (1996) and the limit-equilibrium infinite-slope stability equation of Jibson and others (2000). Keaton and others (1987) used a fixed friction angle and concluded a high earthquake-induced potential where a calculated ground acceleration (0.13 g) with an exceedance probability of 50 percent in a 100-year time period exceeded the critical acceleration under dry conditions.

Keaton and others (1987) estimated the friction angles of geologic materials in the Wasatch Front because of the regional nature of their study and the lack of shear-strength data. However, a back-calculated, slope-specific, minimum friction angle of 34° was obtained for the northwest slope of Steep Mountain that is 4° higher than the value assumed in the Keaton and others (1987) study. The back-calculated minimum friction angle (34°) falls near the mean for loose sands of Holtz and Kovacs (1981) and thus is representative, as a minimum value, of the cohesionless slope colluvium and highly fractured Bingham Mine Formation orthoquartzite. Factors of safety were then calculated using the limit-equilibrium infinite-slope stability equation of Jibson and others (2000) for each 4° interval for friction angles ranging between 34° and 46°, the latter value being the upper bound reported in Holtz and Kovacs (1981) for cohesionless dense sand. Finally, critical accelerations were calculated and compared to the estimated rock (site class B) ground motions for the site (Frankel and others, 1996).

Figure 5 shows that, depending on the actual friction angle of the slope material assuming dry conditions, a potential for earthquake-induced landslides exists for ground motions with less than the 5 percent in 50-year exceedance probability. If the friction angle is 42° or less, then earthquake-induced landslides are possible for ground accelerations less than the 10 percent in 50-year exceedance probability. Thus, the ground motions capable of triggering shallow, disrupted landslides in the northwest slope of Steep Mountain have a return period of less than 1,000 years and likely less than 500 years.

Summary

Based on the previously recognized potential for earthquake-induced landslides (Keaton and others, 1987), the Steep Mountain area was evaluated to determine whether the type of landslides commonly triggered by major earthquakes exist in the area. The Draper Heights landslide may be an earthquake-induced landslide because it is a shallow, disrupted slide in a hillslope with a high earthquake-induced landslide potential. If such a landslide occurred today elsewhere on the northwest slope of Steep Mountain, it could be catastrophic, causing death and damage to houses due to inadequate building setbacks at the base of the slope.

Other nearby shallow, disrupted slides mapped as part of this study suggest that earthquake-induced landslides may have been triggered in the area and are part of the geologic record that can be identified with careful mapping. Opportunities likely exist,

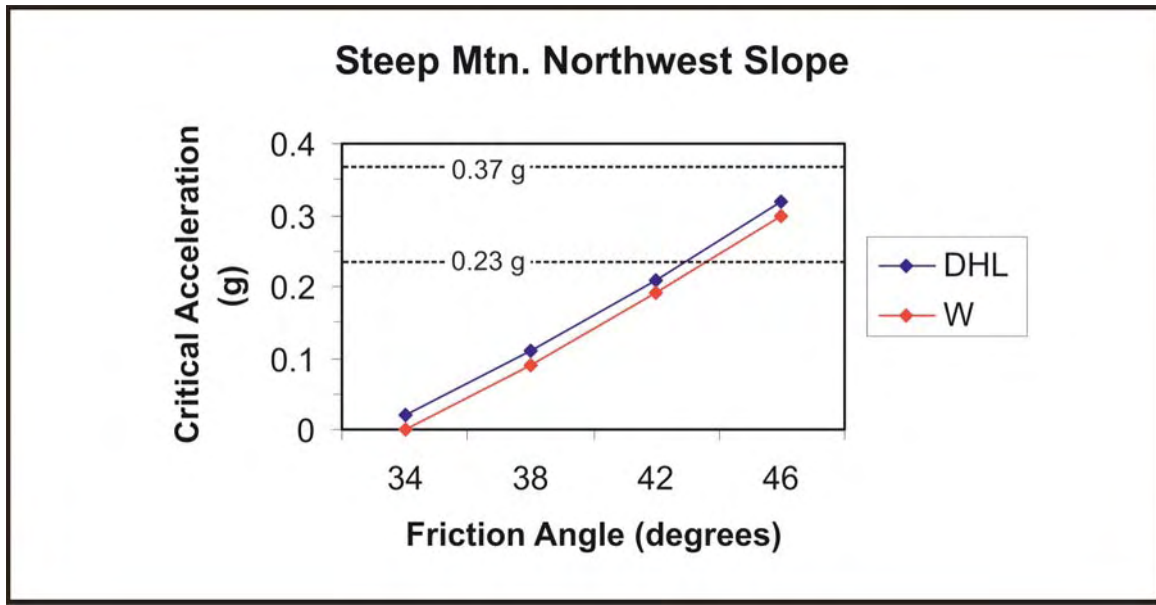


Figure 5. Back-calculated critical accelerations for the northwest slope of Steep Mountain. Range in friction angle is estimated for cohesionless colluvium and intensely fractured Bingham Mine Formation orthoquartzite. Lower bound friction angle (34°) is minimum required for dry slope to remain stable. Most of the back-calculated critical accelerations are below the peak acceleration with a 10 percent probability of exceedance in 50 years (0.23 g) based on site class B conditions (Frankel and others, 1996). All back-calculated critical accelerations are below the peak acceleration with a 5 percent probability of exceedance in 50 years (0.37 g) based on site class B conditions (Frankel and others, 1996). Two profiles used for back-calculations: DHL - profile near Draper Heights landslide and W - profile in steepest part of slope west of slide.

although somewhat limited ones, to date the Draper Heights landslide and other nearby slides. Correlation with documented surface-faulting earthquakes on the Wasatch fault zone could demonstrate that this type of earthquake-induced landsliding is characteristic of the surface-faulting earthquakes in the Wasatch Front. However, slope-stability analysis suggests that shallow, disrupted slides are possible in the Steep Mountain area for ground accelerations much less than those characteristic of a surface-faulting earthquake.

CONCLUSIONS

The Draper Heights landslide on the northwest slope of Steep Mountain is a large, shallow, disrupted slide and may be earthquake-induced. Keaton and others (1987) had mapped the northwest slope as having a high earthquake-induced landslide potential. Scars on similar nearby slopes may be evidence of other earthquake-induced, shallow,

disrupted landslides, suggesting these types of slides, common in the 1994 Northridge earthquake, are possibly part of the geologic record in the Salt Lake City metropolitan area. Dating of these events may provide some proof of their seismic origin; however, slope-stability analysis suggests that earthquakes of smaller magnitude than known surface-faulting events may trigger landslides on the northwest slope of Steep Mountain. A better landslide inventory may reveal more shallow, disrupted slides in the Steep Mountain area, but the absence of such slides may only indicate that most are too small to be preserved in the geologic record. Currently, building setbacks from the base of Steep Mountain are inadequate to protect houses from slides similar to the Draper Heights landslide.

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