When Landslides Are Misinterpreted as Faults: Case Studies from the Western United States

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ABSTRACT

We present several case studies from the western United States where faults are mapped on the basis of geomorphic and structural evidence that is equally likely to indicate landsliding. In some examples, faults have obscured evidence of landslides that utilized fault planes as rupture surfaces. In the Southern California examples, late Pleistocene or Holocene faults are mapped solely based on linear scarps. Such faults are often better explained by landsliding. Similarly, both landslides and faults have been proposed to explain prominent scarps and grabens in the Saddle Mountains of Washington. We note that both faulting and landsliding have been invoked by consultants and reviewers to explain offset Quaternary colluvium in observation pits and linear scarps in a subdivision in central Utah. Several subparallel linear scarps in granitic rock on a ridge top in the Southern California desert have also been mapped as faults. Recent studies, however, show that the features more likely indicate incipient landsliding that grades laterally into fully developed landslides. The Hebgen Lake, Montana, earthquake of 1959 produced landsliding as well as tectonic ground rupture. We suggest that an arcuate scarp that formed north of the primary ground rupture zone, previously interpreted as a fault, was likely produced by reactivation of a 6-mi-wide (9.7 km) landslide. We include a final case study where a combination of normal and thrust faulting mimics landsliding near St. George, Utah. Failure to correctly differentiate between landslides and faults leads to incorrect evaluation of a site's stability as well as incorrect evaluation of seismic hazard and ultimately impacts public health and safety.

INTRODUCTION

We present several case studies from the western United States where faults are mapped on the basis of geomorphic and structural evidence that is equally likely to indicate landsliding (Figure 1). In one example, faulting has obscured evidence of a landslide that utilized a fault plane as a rupture surface. Landslides and faults share many features in common. They both create scarps that can be linear or arcuate, and geologic structures exposed in outcrop or in exploratory trenches can be identical. For example, there is often little apparent difference in the type of ground rupture and geologic structure produced at the toe of large bedrock landslides and thrust faults. Similarly, the structure and displacements produced by normal faults are mimicked by the structure at the head and "graben" areas of landslides (Cotton, 1996). In an unpublished research paper, Cotton (1996) demonstrated that every pattern of tectonic faulting can be produced by landsliding. Figure 2, taken from Cotton (1996), provides examples of the ways in which landslide structures exposed in exploratory trenches can mimic various types of faults.

In all but the last case study, we show that either evidence for landsliding outweighs evidence of previously mapped tectonic faulting or that evidence of landsliding is at least as strong as the evidence of postulated faulting. In the last case study, Warner Ridge, east of St. George, Utah, we describe a situation where slip along two faults mimics the geomorphic features of a large translational landslide.

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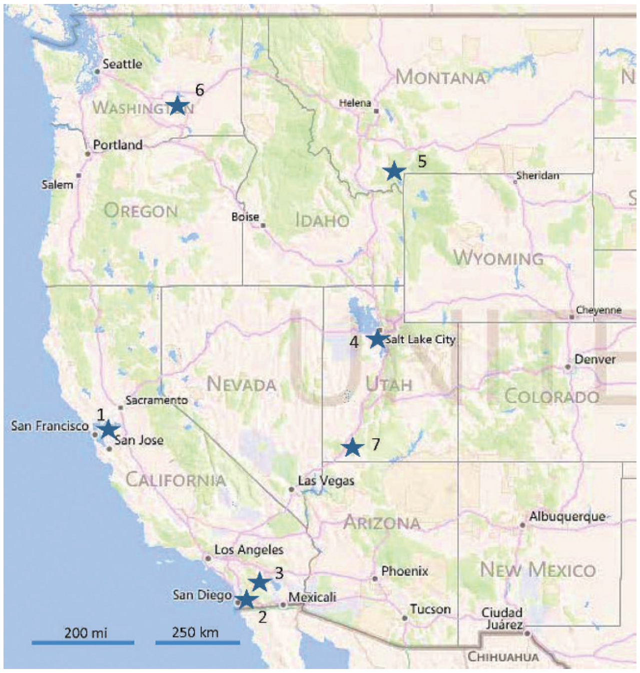

Figure 1. Map showing the western United States and location of case studies discussed in text. 1 = General Electric Test Reactor, Livermore, California; 2 = San Ysidro landslides and faults, San Ysidro, California; 3 = Coyote Ridge, California; 4 = Traverse Mountains, Utah; 5 = Kirkwood Ridge, Montana; 6 = Smyrna Bench, Saddle Mountains, Washington; 7 = Warner Ridge, St. George, Utah. Base map is from ArcGIS Explorer.

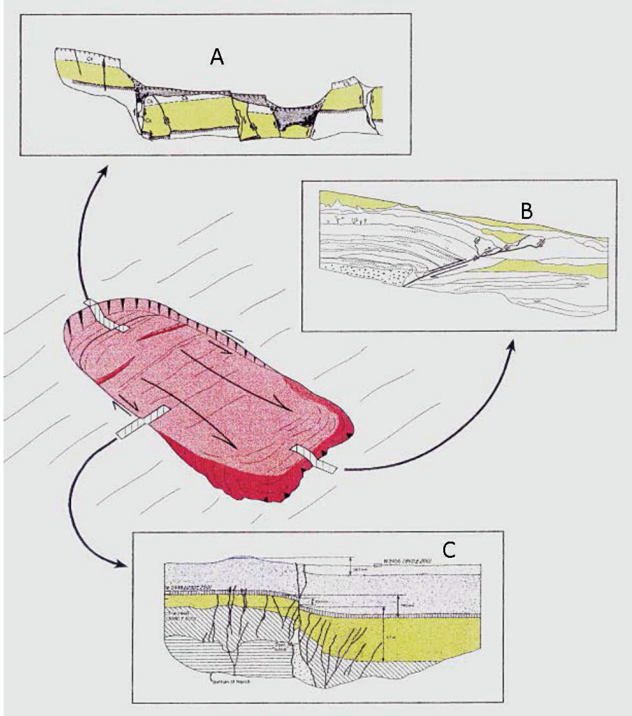

Figure 2. Landslide model and trench locations with structure mimicking faults at right flank, toe, and head. From Cotton (1996). (A) Normal fault. (B) Thrust fault. (C) Strike-slip fault. Reproduced with permission.

THE GENERAL ELECTRIC TEST REACTOR (VALLECITOS ATOMIC LABORATORY), LIVERMORE, CALIFORNIA

In 1957, the General Electric test reactor (GETR), currently the Vallecitos Atomic Laboratory, near Livermore, California, received the first commercial license from the Atomic Energy Commission for a nuclear reactor to produce medical test isotopes. At that time, it was the only source of medical isotopes in the United States. In 1978, the U.S. Geological Survey (USGS) indicated that the reactor was sited on or near faults deemed to be part of the active Verona Fault System (Figure 3). The General Electric Company (GE) then hired a team of consultants to investigate the fault. The GE consultants excavated tens of exploratory trenches, up to 32 ft (10 m) deep, and large-diameter borings that were observed and logged by the USGS, the California Division of Mines and Geology (now the California Geological Survey, CGS), as well as the GE consultants. As a result of the extensive exploration, three reverse-slip surfaces were documented: one uphill about 270 ft (82 m) north of the reactor, and two others downhill, approximately 1,000 ft (303 m) and 2,500 ft (760 m), respectively, south of the reactor (Rice et al., 1979). The USGS interpreted the slip surfaces in the exploratory trenches as thrust faults that were likely active. Roy Shlemon, a GE consultant, dated the age of the thrusts as Holocene, and likely recording a single slip event of at least 15 ft (4.5 m), as reflected by offset soil stratigraphy (Shlemon, 1985). The key stratigraphic marker was a strongly developed buried argillic horizon determined to be approximately 100 k.y. old. The paleosol and the overlying Holocene colluvium and surface organic horizon were displaced (Shlemon, 1985).

During the investigation of the Verona Fault by the CGS, two exploratory trenches were placed along the mapped trace of the fault: one trench several miles north of the reactor and another to the east. These trenches failed to reveal any evidence that the Verona Fault was present to the extent postulated by the USGS. The CGS concluded that the thrust faulting was constrained in both directions away from the postulated landsliding and that, therefore, the Verona Fault was limited to a length of about 3.8 mi (6.3 km). Based on regional mapping and on the unlikely potential for a single, 15 ft (4.5 m) tectonic event occurring on a relatively minor fault, both the GE consultants and the CGS concluded that the thrust-like slip surfaces most likely represented landsliding. A perfect concentric "half-arc" distribution of low-angle

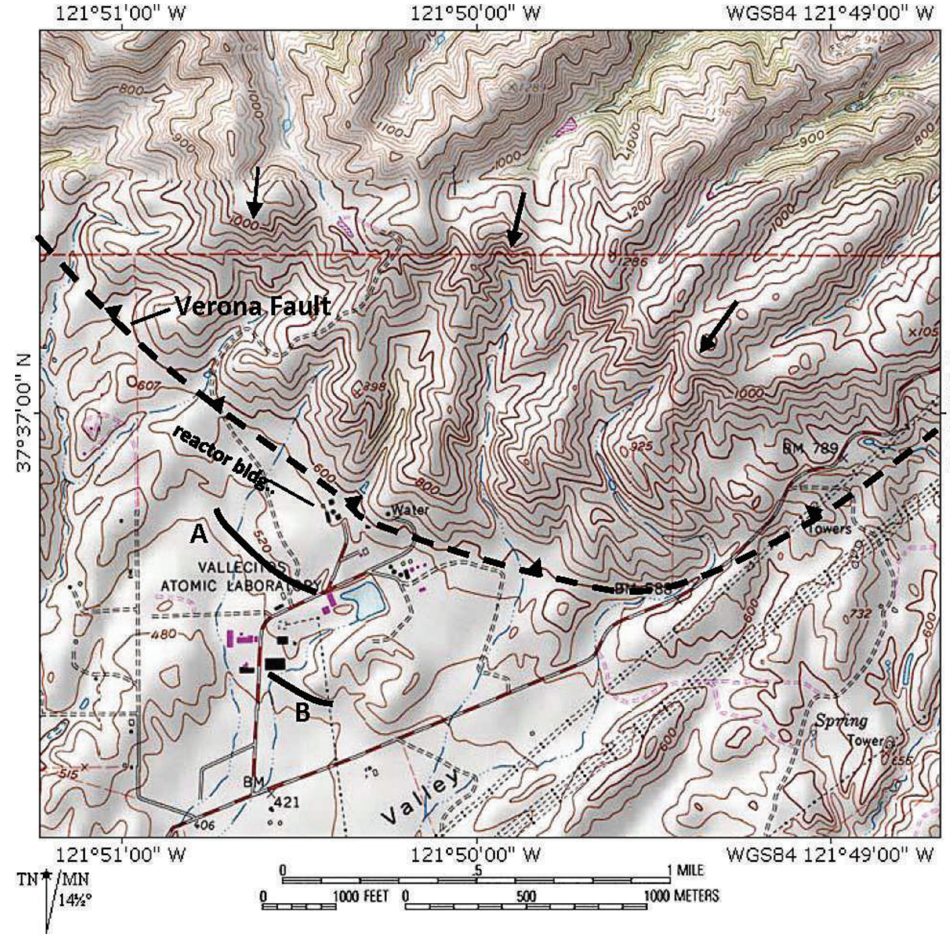

Figure 3. Map of the General Electric Test Reactor site (Vallecitos Atomic Laboratory) and vicinity. Arrows indicate crown of postulated landslide. Heavy black lines south of the Verona Fault labeled A and B are thrust ''faults'' identified by General Electric consultants. Location of faults is after Rice et al. (1979).

slip surfaces defined by trenching southwest of the reactor—a pattern that one would expect to be present at the toe of a landslide—was further evidence of landsliding (Shlemon, personal communication, 2012). The weak link in the GE argument was that, despite the trenching, they could not find an unequivocal head of the expected landslide.

We also believe that site landsliding was a reasonable explanation for the features observed based on the geomorphic evidence, namely, the much-eroded arcuate crown shown on Figure 3 and the lobate toe. All investigators recognized that faults probably occurred both north and south of the reactor building. However, none of the geologists involved pointed out that landslides and faults are not mutually exclusive. Indeed, large landslides and faults can occupy the same space. Landslides may be triggered by nearby fault activity and may use fault planes as failure surfaces.

The battle over the origin and significance of the ''faults'' continued for years. Testimony before multiple review panels ensued; however, the disagreement over the origin of the ''faults'' ultimately resulted in shutdown of the nuclear facility. Currently, the reactor remains in shutdown mode and the site is maintained and monitored by General Electric Hitachi Corporation to allow remnant radiation to safely decay. The argument among the geologists and geotechnical engineers was memorialized in a book that is a must-read for all geotechnical engineers and engineering geologists, *The Atom and the Fault* (Meehan, 1986).

LANDSLIDING AND FAULTING, SAN YSIDRO, CALIFORNIA

San Ysidro, a community of approximately 30,000 people within the City of San Diego, California, lies adjacent to the U.S.-Mexican border (Figure 4). The area is relatively level terrain above the Tijuana River floodplain that straddles the international border just before entering the Pacific Ocean. The low hills east

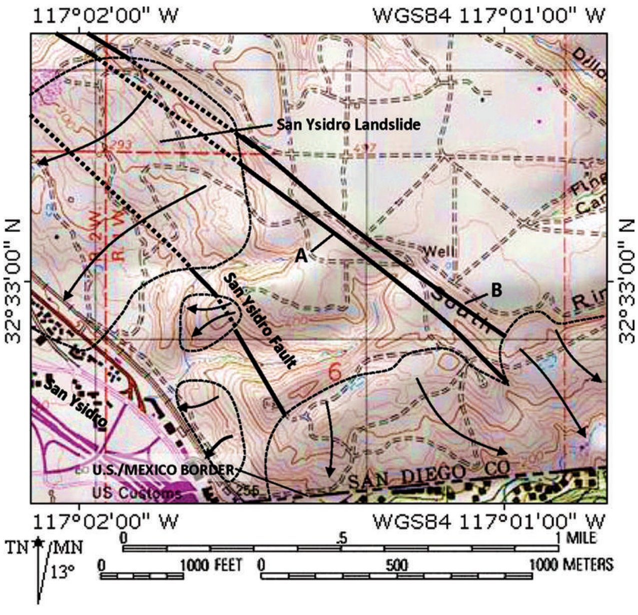

Figure 4. The San Ysidro Fault Zone, San Diego, California. Faults labeled A, B, and the San Ysidro Fault were originally mapped based on prominent lineaments, which we interpret as landslide scarps. Fault locations are after Kennedy and Tan (2008).

of town are underlain by horizontally bedded Tertiary sediments capped by a Lower Pleistocene marine terrace deposit consisting of sandstone and conglomerate. The Tertiary sediments are the Oligocene Otay Formation and the overlying Pliocene San Diego Formation. The Otay Formation is mainly fine gray sandstone and siltstone interbedded with waxy bentonite (smectite) that is present in beds varying from a few inches to 3 or 4 ft (~1 m) thick. The areally extensive marine terrace east of San Ysidro is incised by many steep-sided canyons that form a trellis drainage pattern. Wherever these canyons are incised into the Otay Formation and expose bentonite beds, there are massive landslides, which were first recognized by Hannan (1970).

The San Ysidro Fault Zone (Kennedy and Tan, 2008) consists of several subparallel faults that extend from the U.S.-Mexico border approximately 1.5 mi (2.4 km) into the United States (Figure 4). The main evidence for tectonic faulting consists of several prominent linear scarps and a shear zone observed in a cut slope on the U.S. side of the border. The basis for mapping the San Ysidro Fault, the most westerly of the three faults making up the San Ysidro Fault Zone, is apparently a topographic bench at the head of an unnamed landslide south of the San Ysidro landslide and a northwest-trending lineament east of another small landslide (D in Figure 5).

Kennedy and Tan (2008) also identified two additional faults east of the San Ysidro Fault based on prominent scarps in the Pleistocene marine terrace. The faults are interpreted as continuing northwest approximately 1 mi (1.6 km) to join with the southern portion of the La Nacion Fault. Here we point out that mapping faults in known landslide areas should be done cautiously. Further, in this case, the geomorphic evidence indicates that the inferred faults do not extend beneath the San Ysidro Landslide but rather terminate at the southern edge of the landslide (Figure 5). We also point out that the previously mapped scarps are actually one scarp, with the east and west scarp merging at a sharp bend near their mid-point (Figure 5). The merged scarp thus forms the east side of a prominent linear graben that we interpret as evidence of massive landsliding. A landslide origin for the two scarps was confirmed by a site-specific geotechnical investigation (Hart, 1999) that encountered a basal rupture plane at a depth of 80 ft (24 m) in a large-diameter boring near the landslide toe.

COYOTE RIDGE, SAN DIEGO COUNTY, CALIFORNIA

The informally named "Coyote Ridge faults" are located in the Anza-Borrego Desert of Southern California near the northern end of Coyote Mountain (Figure 1). Coyote Ridge is underlain by highly fractured granitic rocks and characterized by a 1.75-mi-long (2.8 km) zone of scarps, some of which are 30 ft (9 m) high, with intervening alluvium-filled grabens. The scarps are within a 2,000-ft-wide (600 m) zone of en-echelon and subparallel features (Figure 6) topographically descending from the high point of the ridge to the sharp break in slope separating the ridge top and steeper mountain front.

The scarps have been interpreted as minor faults that parallel the adjacent Coyote Canyon Fault, a major active splay of the San Jacinto Fault, by various authors (Sharp, 1967; Theodore and Sharp, 1975; and Janecke and Dorsey, 2008). Sharp (1967) suggested that the scarps may be the result of landsliding but provided no additional explanation. We interpret the scarps as caused by incipient landsliding and attribute failure to a mechanism unique to highly fractured rock, described as follows.

Because the rock exposed in the canyons flanking the west side of the ridge is highly fractured and low-angle faults that could form a basal rupture surface are not evident or suspected, Hart (2008) suggested that failure occurs along interconnecting fracture systems in step-like fashion because of high transient shear stresses produced during earthquakes along the Coyote Creek and San Jacinto Faults. This ongoing process ultimately results in catastrophic slope failure.

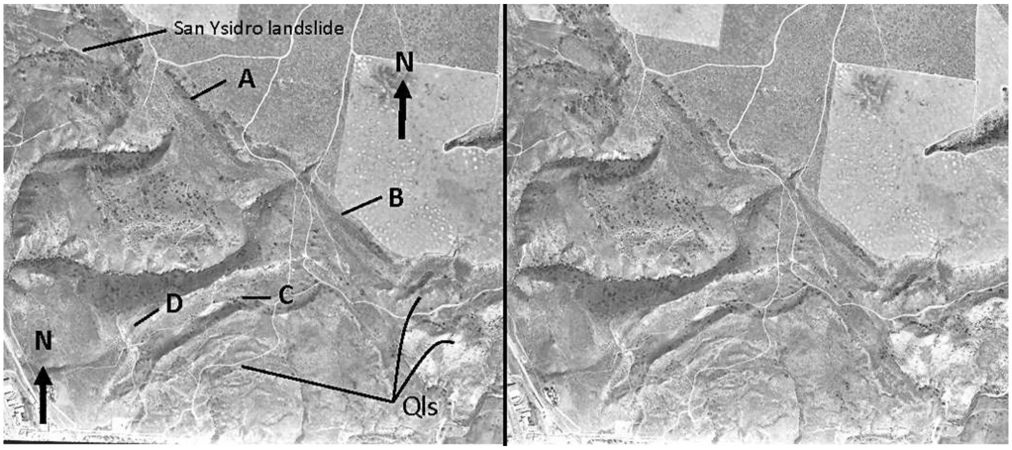

Figure 5. Stereo-pair imagery showing landslide terrain east of San Ysidro. (A–B) Lineaments previously mapped as faults as shown on Figure 4. (C) Graben of large slide with closed drainage at head. (D) Lineament previously interpreted as evidence for faulting. Landslide limits are not shown so that landslide features are not obscured. Qls = landslide. Aerial photograph source: U.S. Department of Agriculture, 1953, AXN 3M, 29, 30.

This is exemplified at the north end of Coyote Ridge, where one of the more prominent scarps merges with the headscarp of a large, fully developed bedrock landslide (Figure 6).

LANDSLIDING VERSUS FAULTING, TRAVERSE MOUNTAINS, UTAH

The Traverse Mountains of central Utah project westward from the Wasatch Range approximately 20 mi (32 km) south of Salt Lake City (Figure 1). The mountains rise to an elevation of approximately 6,000 ft (1,818 m), 1,600 ft (485 m) above the adjacent valley floor. Published geologic maps, chiefly Biek (2005), indicate that rocks making up the range are essentially horizontally bedded Tertiary volcanic rocks overlying Pennsylvanian orthoquartzites and calcareous sandstones.

The Fort Canyon Fault, a segment of the Wasatch Fault, forms the structural boundary between the Wasatch Range and the eastern edge of the Traverse Mountains. This active fault is approximately 2 mi (3.2 km) northeast of an area that is now rapidly urbanizing. Many minor faults in the area are inferred based mainly on strong vegetal and topographic lineaments. We note, however, that much of the area that has already been developed and many areas

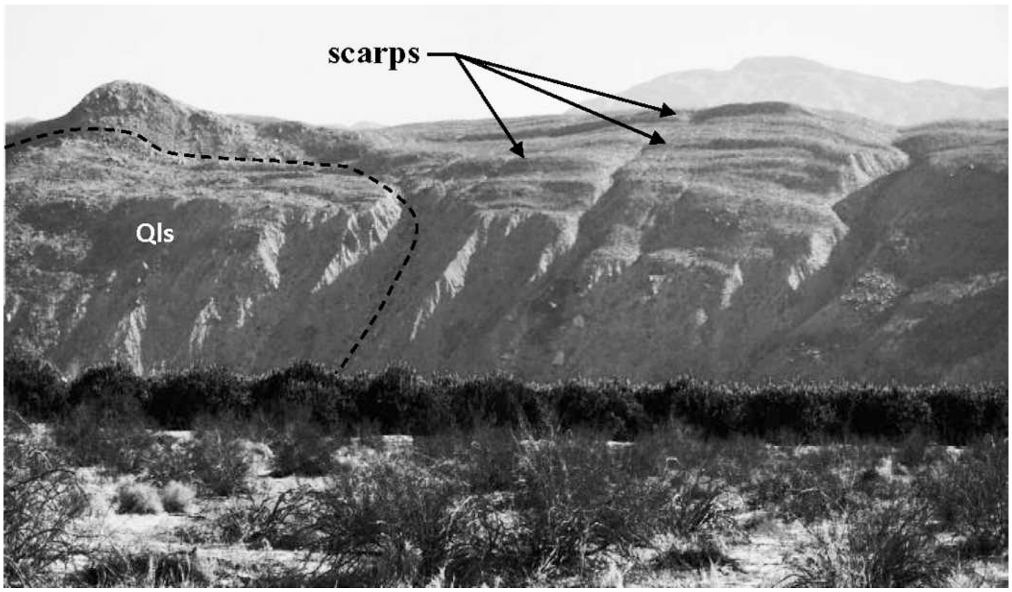

Figure 6. Scarps (indicated by arrows) on the west slope of Coyote Mountain (Coyote Ridge), Anza-Borrego Desert State Park, California, previously interpreted as faults (see text for discussion). Qls = landslide. Photo by Michael W. Hart.

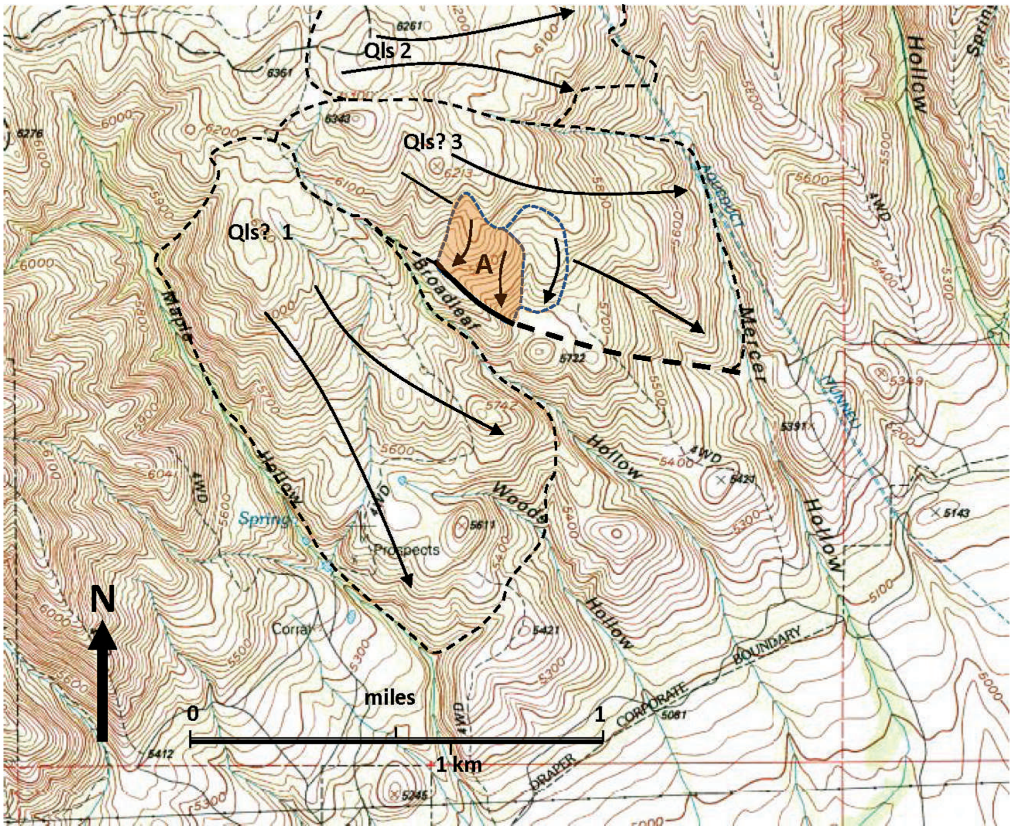

Figure 7. Topographic map of Landslide A, and vicinity, Traverse Mountains (see Figure 1 for location). Qls = landslide, queried where questionable or uncertain. Landslides 1 and 2 are after Biek (2005); landslide 3 is a postulated landslide (this study). Heavy black line is a fault mapped by Biek (2005). Coordinates of center of slide for reference: 40.467536°N, 111.827230°W. Base map is from ArcGIS Explorer. Note the similarity between spacing of contours and topographic benches on all three landslides compared to terrain to the east and west.

proposed for development are underlain by massive landslides (Biek, 2005).

A relatively small landslide (Landslide A, Figure 7) on the southern slope of the mountains and within a proposed residential development has been the subject of intensive geotechnical studies to determine whether scarps and offset Holocene soils are evidence of landsliding or faulting. The western boundary of the landslide, according to the geologic map by Biek (2005), was formed by an approximately 1-mi-long (1.6 km) fault. Evidence for the fault is mainly geomorphic, namely, a strong topographic lineament that forms the western boundary of the landslide.

Exploratory trenches along the trace of the mapped fault exposed what the developer's geotechnical consultant interpreted as a fault contact between colluvium and volcanic bedrock. Even though the published geologic map depicted the fault as forming the western boundary of the landslide, the developer's consultant concluded that the exposure confirmed the existence of an active fault and, accordingly, that there was no evidence of landsliding. The city's geologic consultant disagreed with the developer's consultant, and a third party was called in to act as referee. Several additional trenches were then excavated to determine whether the offset was due to tectonic faulting or to landsliding.

The intent of the additional study was to confirm the existence or absence of landsliding by finding the toe of the slide at an elevation of approximately 5,700 ft (1,730 m). The trenches exposed sheared and brecciated rocks but no evidence of a basal slip surface. The presence of hard volcanic rock prevented use of large-diameter borings to find a possible deeper slip surface.

Nevertheless, based on evidence from other trenches in the body of the postulated landslide, the third party agreed with the city's geologist that the preponderance of structural evidence favored a landslide origin. This conclusion is important because mitigation measures for active faulting are obviously much different than those required for a landslide.

We reviewed aerial photographs to prepare this paper and to identify a plausible reason why the toe of the landslide was not previously discovered. Specifically, the search for conclusive landslide

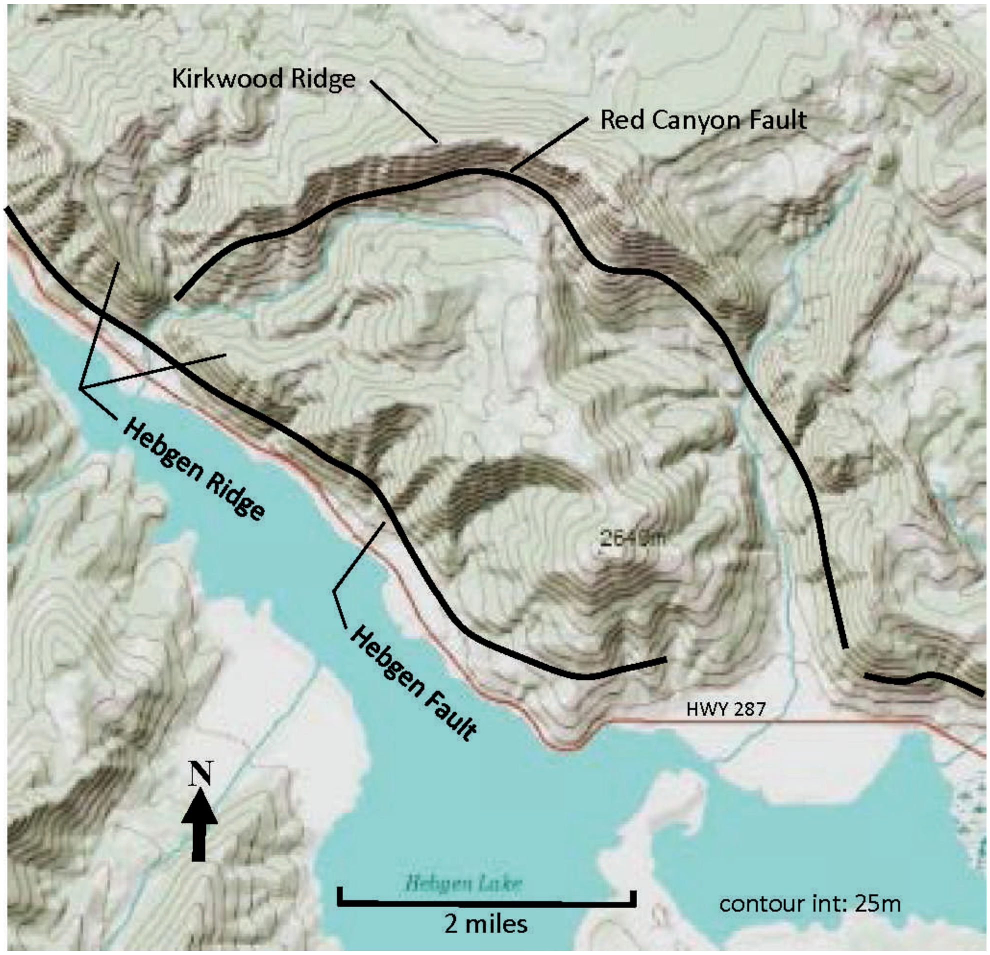

Figure 8. Possible landslide north of Hebgen Lake, Montana. Postulated headscarp is south slope of Kirkwood Ridge. Toe is defined by Hebgen Fault. Center of map: 44.822587°N, 111.229552°W. Topographic base map is from ArcGIS Explorer.

evidence was probably limited to too small an area. The aerial photographs show that the relatively small, poorly defined landslide is more likely a small secondary feature developed on a much larger mass movement (Figure 7), and we interpret the fault mapped by Biek (2005) as a lateral shear that forms the landslide's western flank. The geomorphic evidence that Landslide A lies within a much larger landslide is as follows. First, the larger landslide is characterized by an anomalously low terrain gradient, similar to that of landslides to the west and north mapped by Biek (2005). The low gradient is apparently a consequence of the landslide process, whereby the proximal and medial portions of the landslide are subject to rotation along listric shear surfaces, and thinning is caused by extension. Second, the body of the postulated larger slide is characterized by a series of subdued topographic benches commencing at an elevation of approximately 6,200 ft (1,937 m) and present almost to the landslide toe. Third, a prominent headscarp and colluvium-filled graben can be observed. Evidence of once-ponded drainage, now filled with colluvium, also exists at several other localities within the body of the larger landslide.

In retrospect, a shortcoming of the geotechnical study was the failure to satisfactorily document evidence for tectonic faulting, and if a fault did exist, whether or not it extended beyond the limits of the landslide. This would have helped to determine if the landslide utilized a preexisting fault plane as a slip surface, and if there was evidence for tectonically offset Holocene sediments beyond the mapped limits of landsliding. We point out, however, that such conclusions would be inherently uncertain owing to the poor definition of the landslide boundaries.

KIRKWOOD RIDGE, MONTANA

North of Hebgen Lake, Montana (Figure 1), at the southern end of the Madison Range, there lies an arcuate ridge that rises 3,200 ft (1,000 m) above the lake to an elevation of 9,700 ft (2,940 m). This 7.5-mi-long (12 km) ridge forms what geomorphically

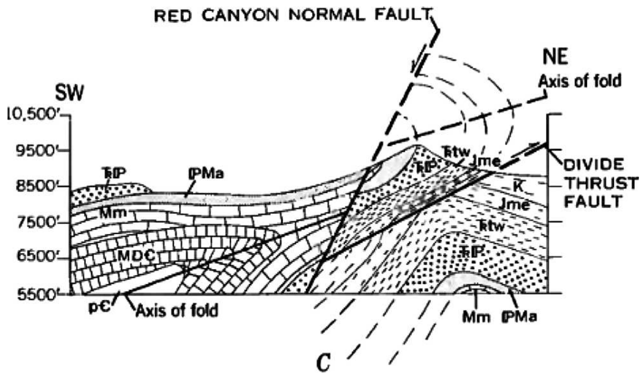

Figure 9. Geologic section through Kirkwood Ridge, Montana, showing southerly dip of Red Canyon Fault and low south dip of Paleozoic strata. IPMa = Amsden Formation; Mm = Madison Group; TrIP = Triassic sediments undivided; MDC = undivided Mississippian, Devonian, and Cambrian sediments. Figure is modified from Fraser et al. (1964).

appears to be the crown of a large landslide (Figure 8). The Red Canyon Fault lies about mid-slope on the southern side of the ridge and parallels the arcuate ridge crest. Ground rupture along this fault and the Hebgen Fault occurred during the 1959 Hebgen Lake earthquake and formed an approximately 10-ft-high (3 m) scarp. The morphology of the terrain south of the scarp, the arcuate Kirkwood Ridge, pattern of ground rupture, and the geologic structure, consisting of Paleozoic sediments dipping at a low angle to the south, all provide circumstantial evidence that the Red Canyon Fault is not a tectonic fault but rather the scarp of a very large landslide, and that the 1959 movement on the Red Canyon Fault was the result of landslide reactivation during the earthquake. Apparently, there was no evidence of thrusting along the north shore of Hebgen Lake during the 1959 earthquake that might be attributed to landslide movement, only down-to-the-south movement along the Hebgen Fault that parallels the lake shore and localized slumping along the lake (Witkind, 1964).

We observed outcrops along Highway 287, which parallels the north shore of Hebgen Lake, and the toe of the postulated landslide and found no conclusive evidence that the 6-mi-wide (9.6 km) feature was the result of landsliding. There are, however, some slope failures in the highway cut, and there is landslide debris in a cut slope behind a commercial building. We found that most sediments exposed in the road cuts consist of undisturbed glacial till and alluvium. Precambrian mica schist exposed in a few locations along the north shore of the lake appears to be intact and dips steeply southwest in a direction consistent with the regional structural trend (Figure 9). A basal rupture zone, if one exists, may lie further up the slope or beneath the surface of Hebgen Lake. We conclude there is insufficient evidence to unequivocally state that the Red Canyon Fault is either a landslide slip surface or a tectonic fault; however, it is our opinion that the geomorphic evidence favors a landslide origin.

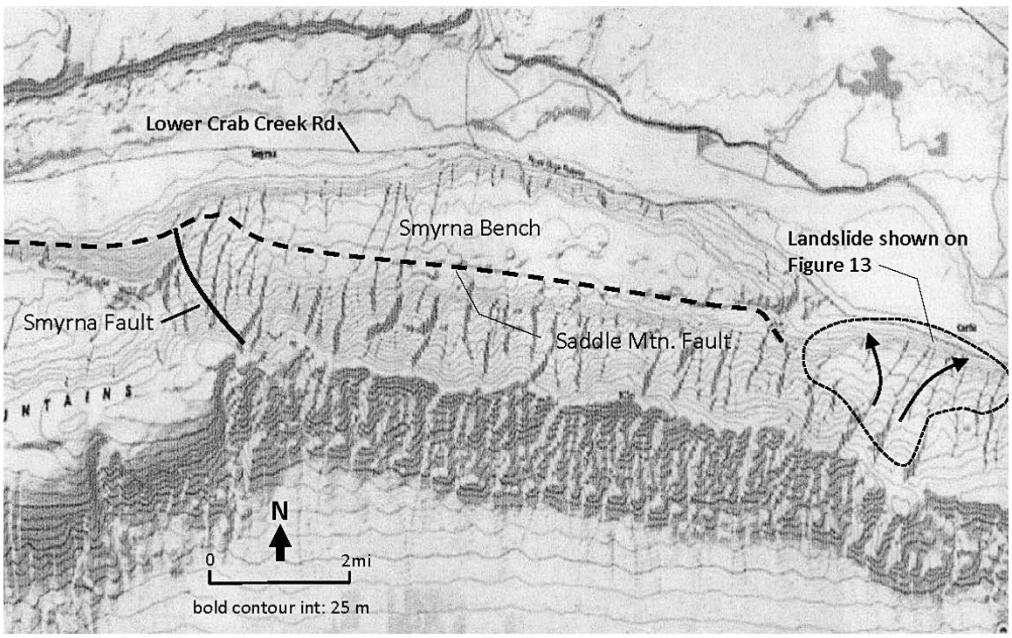

Figure 10. Topographic map of eastern portion of Saddle Mountains. The center of Smyrna Bench is at 46.829840°N, 119.599348°W. The relatively small landslide at the right side of the map is the same as shown on Figure 13. Smaller landsides south of Saddle Mountains Fault and along the toe of Smyrna Bench are not shown for clarity. Fault locations are from Reidel (1988). Topographic base map is from ArcGIS Explorer.

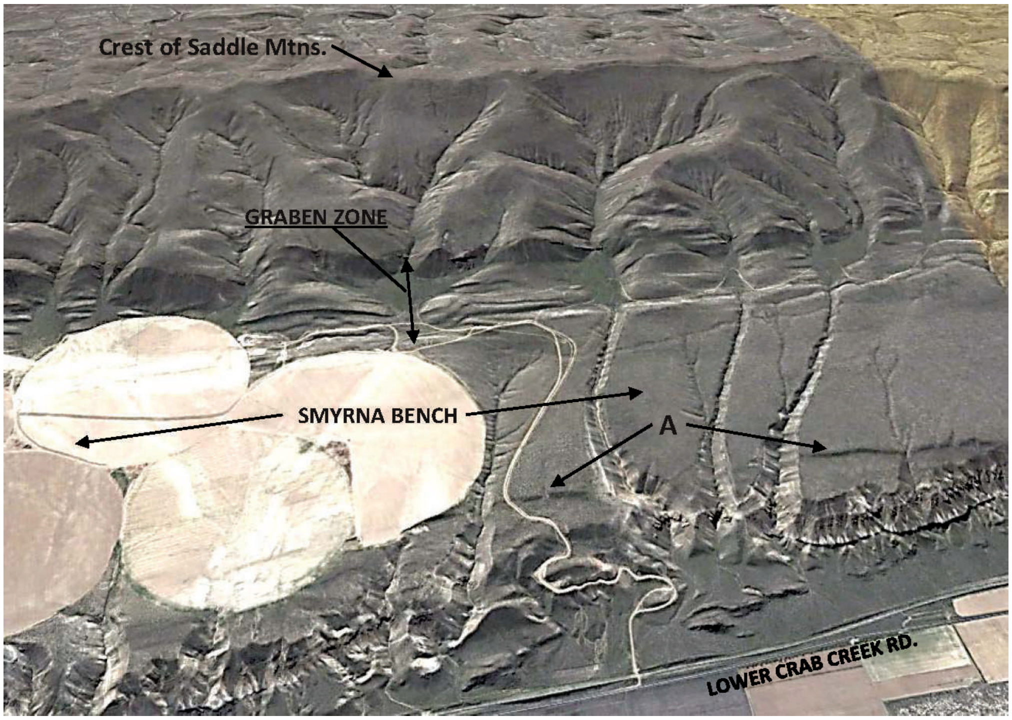

Figure 11. View to south of central portion of Saddle Mountains and Smyrna Bench showing well-developed graben zone with numerous linear scarps. (A) Scarp of incipient secondary landslide. White circular areas are irrigation pivots. Google Earth image.

SMYRNA BENCH, SADDLE MOUNTAINS, WASHINGTON

The Saddle Mountains of south-central Washington (Figure 1) are underlain by Tertiary volcanic rocks and interbedded sediments that have been uplifted into an east-west–striking asymmetrical anticline. On the north side of the mountain range, there is the locally famous Corfu landslide, a large earthflow that formed in thick loess deposits. The topography of the northern slope is dominated by a 1-mi-wide (1.6 km) and 8-mi-long (13 km) topographic surface called the Smyrna Bench. The Saddle Mountain Fault lies at the south edge of the bench near the base of the steep northern range front. According to Reidel (1984), the fault does not extend east of Smyrna Bench (Figure 10). The fault dips 30 to 40 degrees south and is bounded by a 70-ft-thick (20 m) breccia. Reidel (1984), Bingham et al. (1970), and West et al. (1996) map the Saddle Mountain Fault on the southern edge of the bench (Figure 10) coincident with a nearly 8-mi-long (13 km) series of east-west–trending scarps and grabens (Figure 11) that have been variously interpreted as either the result of landsliding (Bingham et al., 1970), or faulting (Reidel, 1984, 1988; West et al., 1996).

Bingham et al. (1970) interpreted the Smyrna Bench as resulting from massive translational landsliding on gently north-dipping beds of the Ringold Formation; however, later studies by Reidel (1984, 1988) do not even address the possibility of landsliding, and West et al. (1996) dismiss the possibility of a landslide origin of Smyrna Bench. They comment on the shears observed during their trenching as follows, "dip-slip movement, therefore, is unlikely to occur along subvertical structures as the result of horizontal block-glide movement" (West et al., 1996, p. 1126). The observation by Cotton (1996) bears repeating here "every pattern of tectonic faulting can be produced by landsliding."

Bingham et al. (1970) cited the following evidence for concluding a landslide origin for the bench.

1. The irregular hills downslope of the scarp are underlain by rocks with inconsistent bedding orientations.
2. A trench excavation conducted during his study exposed a wide zone of broken and sheared basalt along its entire 120 ft (36 m) length.
3. The trenching exposed open cracks an average of 1 ft (0.3 m) in width, with one crack approximately 21 ft (6.4 m) wide.
4. The horizontal displacements observed in the trench were much greater than the total vertical displacements.

To these observations, we add that the well-defined grabens and scarps attributed to faulting do not

Figure 12. Scarp cited as evidence for active faulting east of Smyrna Bench. From West et al. (1996); reprinted with permission.

extend west of the Smyrna Fault at the west end of the bench. In addition, the prominent scarp shown on Figure 12, cited by West et al. (1996) as evidence of a continuation of active faulting east of Smyrna Bench, is actually the scarp of a large incipient landslide as shown on Figure 13. We conclude that the evidence presented by Bingham et al. (1970) for a landslide origin for the Smyrna Bench, in addition to the compelling geomorphic evidence that has been overlooked by previous workers, overwhelmingly favors a landslide origin. We counter the argument that the graben zone is too linear to have been caused by massive translational landsliding by pointing out that many large translational slides have rectilinear headscarps, and, in fact, linear graben formation is a characteristic of translational landsliding.

Further evidence for a likely landslide origin for the bench is the Smyrna Fault Zone, a strike-slip fault mapped by Reidel (1988) that forms the boundary between Smyrna Bench and terrain to the west. The fault is mapped as having a right-lateral sense of slip (the opposite of that which would be created by landsliding), although there is apparently no evidence to support that conclusion.

WARNER RIDGE, ST. GEORGE, UTAH

Warner Ridge is approximately 6 mi (9.6 km) east of Saint George, Utah (Figure 1). The north-trending ridge is underlain by a highly resistant cap rock, the Shinarump Conglomerate Member of the Triassic Chinle Formation. Underlying this unit, the upper red member of the Moenkopi Formation consists of less-resistant sediments. Rocks on the east side of the ridge generally dip to the east, and rocks west of the ridge dip gently to moderately steeply westward to form an asymmetrical anticline. The Washington Fault, a prominent northerly striking normal fault, lies 1,200 ft (365 m) west of the ridge.

We investigated what initially appeared to be a landslide on the face of Warner Ridge (Figure 14). This feature had the geomorphic characteristics of a translational landslide, which included a rectilinear headscarp and an elevated "toe" manifested by low rounded hills interpreted as a zone of thrusting. In addition, a steeply east-dipping thrust fault that fit our model of translational landsliding was found near the base of the hills during a geotechnical study. The geomorphology of the terrain east of the fault is

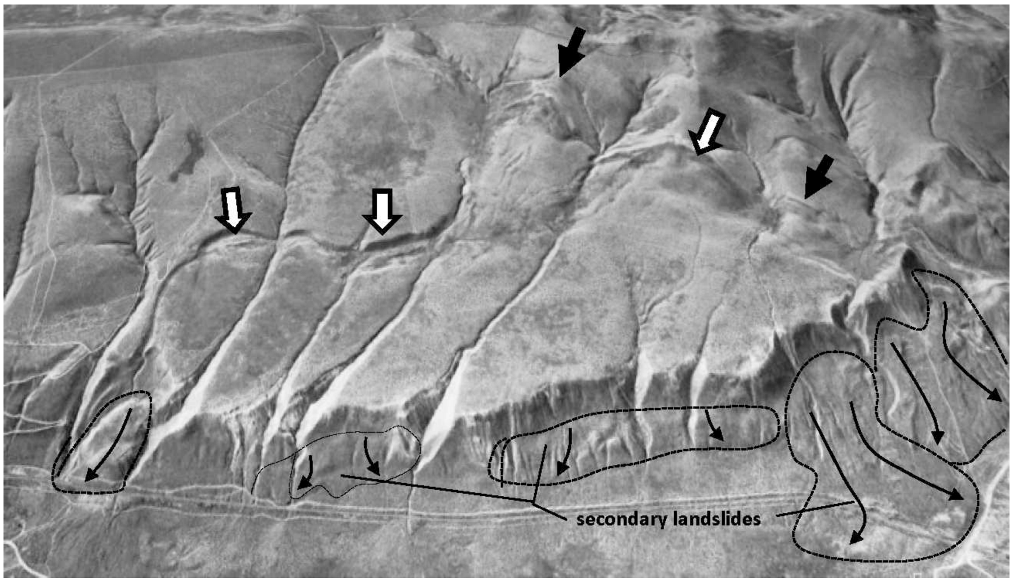

Figure 13. Incipient landslide at the eastern margin of Smyrna Bench. See Figure 10 for location. View to south. Bold black arrows are at the same location as arrows shown in Figure 12. White arrows indicate location of headscarp. Google Earth image.

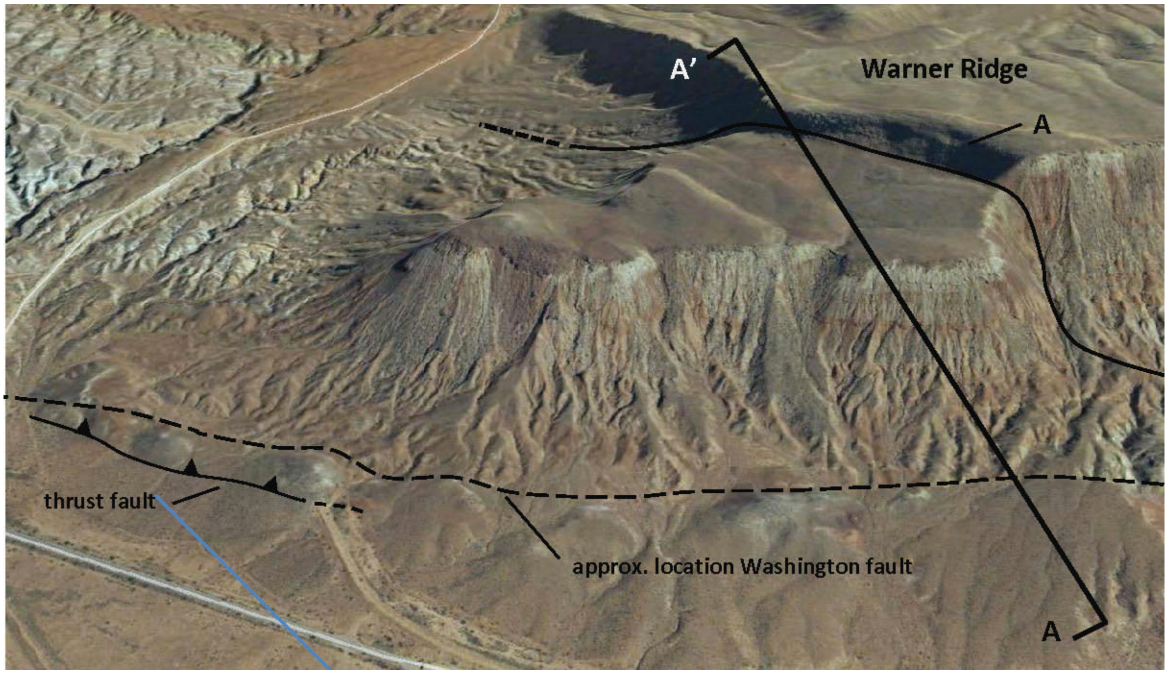

Figure 14. Warner Ridge east of St. George, Utah, showing fault scarp (A) previously interpreted as a landslide scarp and thrust fault found during a site-specific geotechnical investigation. View to east. Structural section A-A′ is shown on Figure 15. Center of image: 37.05201°N, 113.479184°W. Google Earth image.

consistent with a landslide interpretation, and the fact that a thrust fault existed along the western edge of the low hills at the toe of the feature lent additional credence to that interpretation. In fact, the feature resembled several other landsides with similar rectilinear headscarps such as the landslides in San Ysidro (Figures 4 and 5).

In order to test our landsliding hypothesis, we were able to rapidly determine, by examining the exposures along the flanks and toe of the feature, that the apparent landslide headscarp most likely stemmed from normal faulting subparallel to the Washington Fault near the toe of the anomalous geomorphic feature. The nearly continuous exposures of sediments beginning near the toe of slope and ending about halfway up the steep bluff face indicated that there were no secondary shear zones or basal rupture surfaces consistent with a landslide interpretation. The fine, cemented sandstones, limestone, and interbedded clayey shales, although dipping to the west in a direction favorable to landsliding, contained no low-angle shear zones suggestive of large-scale landsliding. In addition, the excellent near-continuous outcrops along the northern flank of the "landslide" revealed no evidence of landslide movement, only many normal faults consistent with the regional tectonic pattern.

We knew that a branch of the Washington Fault, subparallel to the primary fault trend, had been

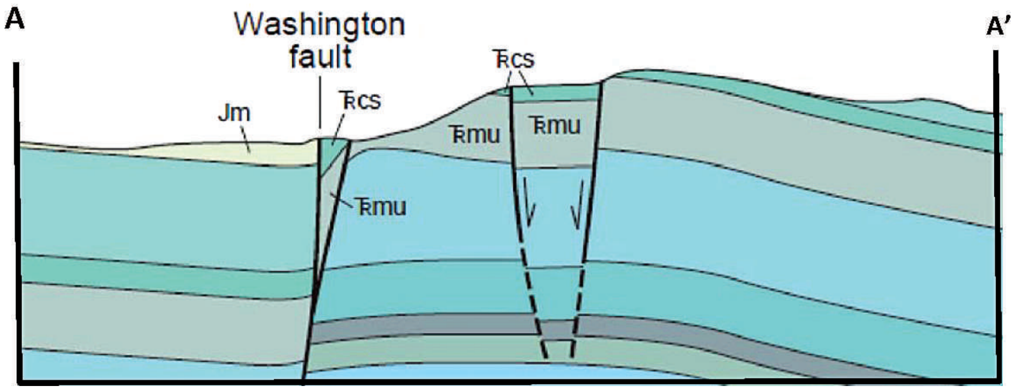

Figure 15. Section A-A′. Trcs = Shinarump Conglomerate; Trmu = upper red member of the Moenkopi Formation; Jm = Moenave Formation. Figure is from Hayden (2005); reprinted with permission.

mapped east of the main fault trace (Figures 14 and 15), and we considered that the 80-ft-high (24 m) headscarp may have formed along that fault. We initially discounted the possibility that the scarp was created by tectonic faulting because the relatively young-looking scarp at the head of the postulated landslide did not extend into the soft sediments at the foot of the bluff. We now attribute this anomaly to differential erosion of the highly resistant Shinarump Conglomerate that forms the Warner Ridge cap rock and underlying soft mudstones and shales of the Moenkopi Formation.

The Warner Ridge study demonstrates the uncertainties inherent in geomorphic interpretation of potential landslides. Field reconnaissance and mapping proved decisive in this evaluation. Fortunately, there are excellent bedrock exposures throughout the study area. Absent such exposures, a more definitive origin of the feature would have remained elusive. Although we remain undecided about the origin of the anomalous thrust fault near the toe of the slope, our present hypothesis is that it is not a landslide feature but rather represents an unusual manifestation of the local tectonic environment.

SUMMARY AND CONCLUSIONS

Based on our collective experience, and as shown in our several case studies, we find that many otherwise competent geologists have difficulty recognizing old or erosionally subdued landslides. Experience and training in landslide recognition, both at the university level and in practice, are often lacking. Further, many geologists do not recognize that landslides are a major factor in shaping Earth's surface.

It is important to be able to differentiate between landslide and fault scarps, and just to be able to recognize landslides, for several reasons. First, landslides may produce structures such as shear zones, grabens, and folds that are otherwise anomalous to the region's geologic environment and history. Structures observed in an unrecognized landslide will result in a false interpretation of the geologic history of an area and failure to properly evaluate the geologic hazard represented by these features. Second, misinterpretation of landslide scarps or shear zones will result in an erroneous interpretation of the seismic hazard of a region. For example, West et al. (1996) concluded as a result of their study of Smyrna Bench that the seismic hazard for the Hanford Nuclear Reservation several miles to the south needed to be reevaluated. Third, professional judgments based solely on reconnaissance or aerial-photographic interpretation may totally misidentify the true origin of landslide and fault-like geologic structures. The implications of such judgments are many, ranging from effects on public health, safety, and welfare to costly litigation.

In summary, this report highlights the importance of four critical elements in scientific methodology and geoengineering practice that need to be heeded in order to avoid the types of mistakes and controversy in geologic interpretation cited herein.

1. The importance of geological context (e.g.., does a mapped fault have a length, orientation, and age consistent with the local tectonic setting? Is the area/formation known to be subject to landslide processes?).
2. The importance of developing reasonable multiple working hypotheses and conducting field investigations to test alternative hypotheses (not just to try to confirm or deny one preferred alternative).
3. The recognition that large-scale landslides, in particular, manifest geomorphological and geological characteristics that can mimic tectonic features.
4. The importance of maintaining perspective on the ultimate use or significance of the geological interpretation.

The goal of many of the case studies cited here is to safeguard life and property. In several of the cases, we find that the potential landslide hazard may be a greater risk to the constructed environment than the potential tectonic hazard. Failure to maintain a perspective on all the geologic hazards present at a given site represents a failure of both the scientific method and the societal responsibilities of the professional engineering geologist.

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