CHARACTERIZATION AND HAZARD ZONATION OF THE MEADOW CREEK LANDSLIDE AFFECTING STATE ROUTE 9, PART OF THE COAL HILL LANDSLIDE COMPLEX, WESTERN KANE COUNTY, UTAH

by Francis X. Ashland, Greg N. McDonald, Lucas M. Shaw, and James A. Bay

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CHARACTERIZATION AND HAZARD ZONATION OF THE MEADOW CREEK LANDSLIDE AFFECTING STATE ROUTE 9, PART OF THE COAL HILL LANDSLIDE COMPLEX, WESTERN KANE COUNTY, UTAH

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ABSTRACT

The Coal Hill landslide complex in western Kane County, Utah, includes a large landslide (referred to as the Meadow Creek landslide) that is about 1.7 miles (2.7 km) wide and 1.3 miles (2.1 km) long and contains six smaller historical slides. State Route 9 (SR-9) crosses approximately a mile (1.6 km) of the southern part of the Meadow Creek landslide, including the largest of the six historical slides—the persistently moving landslide 1. The highway and its predecessor (State Route 15 [SR-15]) have been periodically displaced and damaged by landslide movement since the initial construction of SR-15 in 1928. We conclude from this study the following:

1. Most of the damage to SR-9 occurs where it crosses landslide 1 in the southwestern part of the Meadow Creek landslide. Pavement distress is generally localized near lateral shear zones that bound or are internal to landslide 1.
2. Monitoring using a survey-grade Global Positioning System (GPS) instrument detected movement of landslide 1 and the abutting southern part of the Meadow Creek landslide between early October 2005 and June 2007. Displacements in landslide 1 ranged from about 16 to 39 inches (41–99 cm) during the measurement period. Displacements in the abutting southern part of the Meadow Creek landslide ranged from approximately 2 to 7 inches (5–18 cm).
3. Spectral Analysis of Surface Waves (SASW) testing and geologic cross sections suggest a minimum depth of the southern part of the Meadow Creek landslide of about 40 feet (12 m). SASW testing suggests that landslide 1 may be between 84 and 100 feet (26–30 m) deep along abandoned State Route 15 (SR-15).
4. Hazard zonation using movement data and pavement distress observations yield slightly different results that reflect long-term versus short-term effects of landsliding, respectively. Movement-based zonation identifies the area of greatest likely future displacement of SR-9 consistent with the observed cumulative displacement of abandoned SR-15. Pavement-distress-based zonation identifies areas likely to be damaged periodically by persistent movement and requiring frequent repair.
5. Most of the landslide characteristics are adverse to and pose significant challenges to landslide stabilization. Continuing monitoring of landslide movement is intended to assess the feasibility of an alternate route upslope and around landslide 1.

INTRODUCTION

Recurrent landsliding in the Coal Hill area of western Kane County, Utah, has impacted the highway between Mount Carmel Junction and Zion National Park (current State Route 9 [SR-9] and former State Route 15 [SR-15]) since the initial construction of SR-15 in 1928. Landslide damage has necessitated perennial maintenance and repair, and local realignment and reconstruction of the highway (Gregory, 1950; Cashion, 1961; Doelling and Davis, 1989). The current alignment of SR-9, a rural east-west highway that crosses parts of Kane and Washington Counties and provides access to Zion National Park (figure 1), crosses part of the Coal Hill landslide complex (Doelling and Davis, 1989) about 5 miles (8 km) east of the park near milepost 50 (figure 2). Localized, recurrent damage to the highway requires frequent maintenance and repair, particularly during and immediately following wet years. This study began following the 2005 water year (October 2004–September 2005), the wettest on record at nearby Zion National Park and hereinafter referred to as the 2005 wet year.

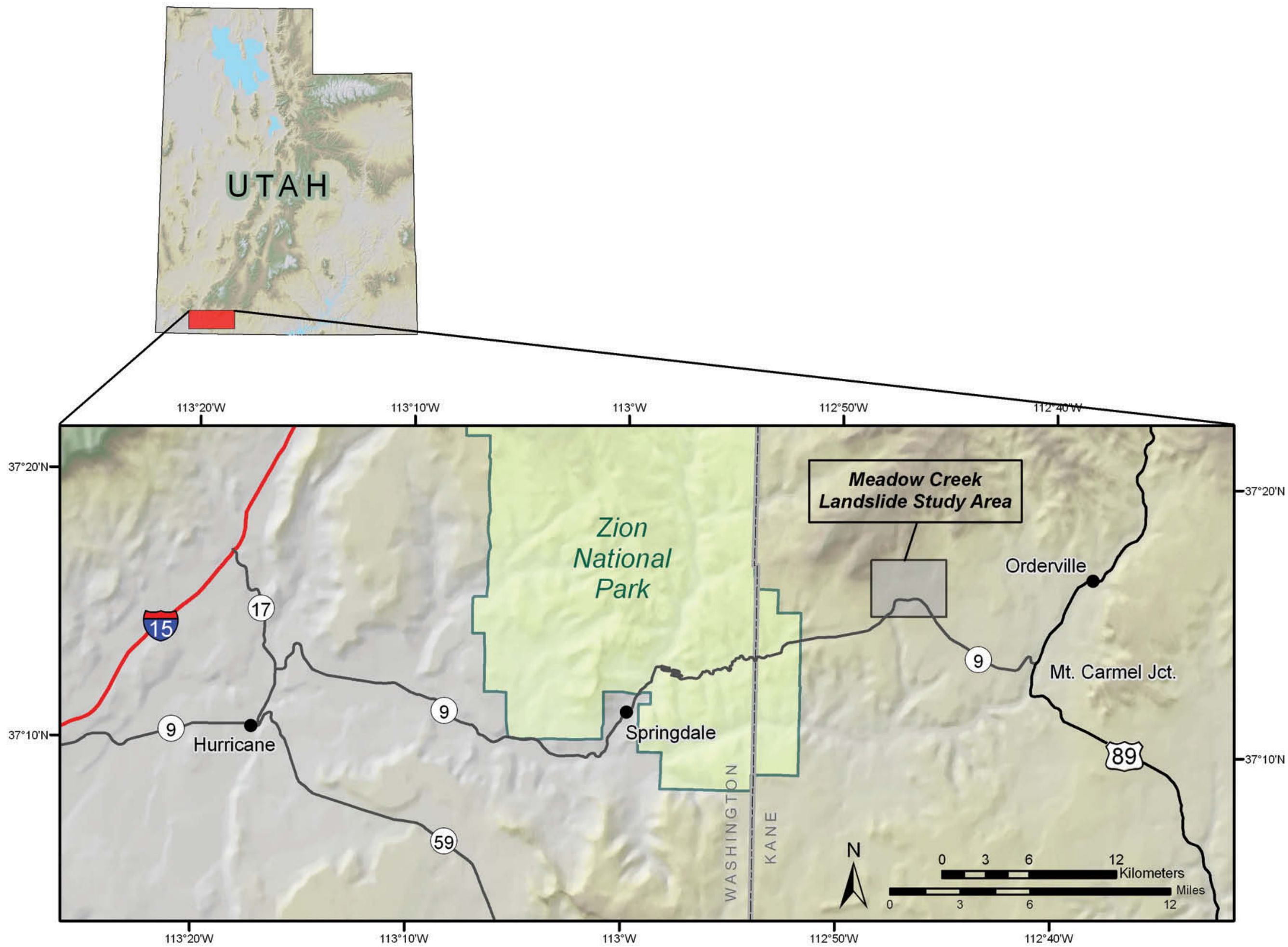

__Figure 1.__ Location of State Route 9 and Meadow Creek landslide study area (see figure 4) in Kane County, southwestern Utah. Study area location (see figure 4) shown.

This report summarizes the results of geologic and geophysical investigations conducted between October 2005 and June 2007 of a large landslide in the central part of the landslide complex—the Meadow Creek landslide, particularly the part crossed by SR-9 (figure 2). The purpose of the study was to map and characterize the Meadow Creek landslide to determine the relative landslide hazard (appendix A provides a summary of our field methods). Relative landslide hazard zonation provides a basis for assessing and prioritizing possible mitigation options, including a possible alternate highway alignment that may reduce road damage and repair costs, and predicting the location of future recurrent road damage. This study included the use of Spectral Analysis of Surface Waves (SASW) testing (Stokoe and others, 1994) to evaluate its utility in estimating the depth of landslide deposits and possibly identifying basal clay gouge in the surface-of-rupture zone.

PHYSIOGRAPHY AND GENERAL GEOLOGY

The Coal Hill landslide complex is in the western Colorado Plateau province near the confluence of Meadow Creek and Little Meadow Creek, the former a generally south-flowing tributary of the East Fork of the Virgin River. The area ranges in elevation from about 5800 (1770 m) to locally over 7000 feet (2130 m). Parts of the Coal Hill ridgeline are over 6400 feet (1950 m) in elevation near SR-9.

Subhorizontal Mesozoic sedimentary rocks underlie the landslide complex (Cashion, 1961; Doelling and Davis, 1989; Hylland, 2000; Sable and Hereford, 2004). The oldest rock unit in the vicinity of the landslide complex is the Jurassic Carmel Formation; its Crystal Creek Member, consisting mostly of reddish-brown sandstone and siltstone, crops out at the confluence of Meadow Creek and Little Meadow Creek. The overlying Paria River and Winsor Members of the Carmel Formation crop out along the two creeks and are locally overridden by landslide debris. The Paria River Member includes a prominent ledge- and cliff-forming alabaster gypsum bed, and the Winsor Member consists mostly of yellowish-gray sandstone. Sequentially overlying the Carmel Formation are three Cretaceous units—the Cedar Mountain and Dakota Formations and the Tropic Shale. Hylland (2000) mapped conglomerate and mudstone formerly included in the Dakota Formation (Doelling and Davis, 1989) as the Cedar Moun-

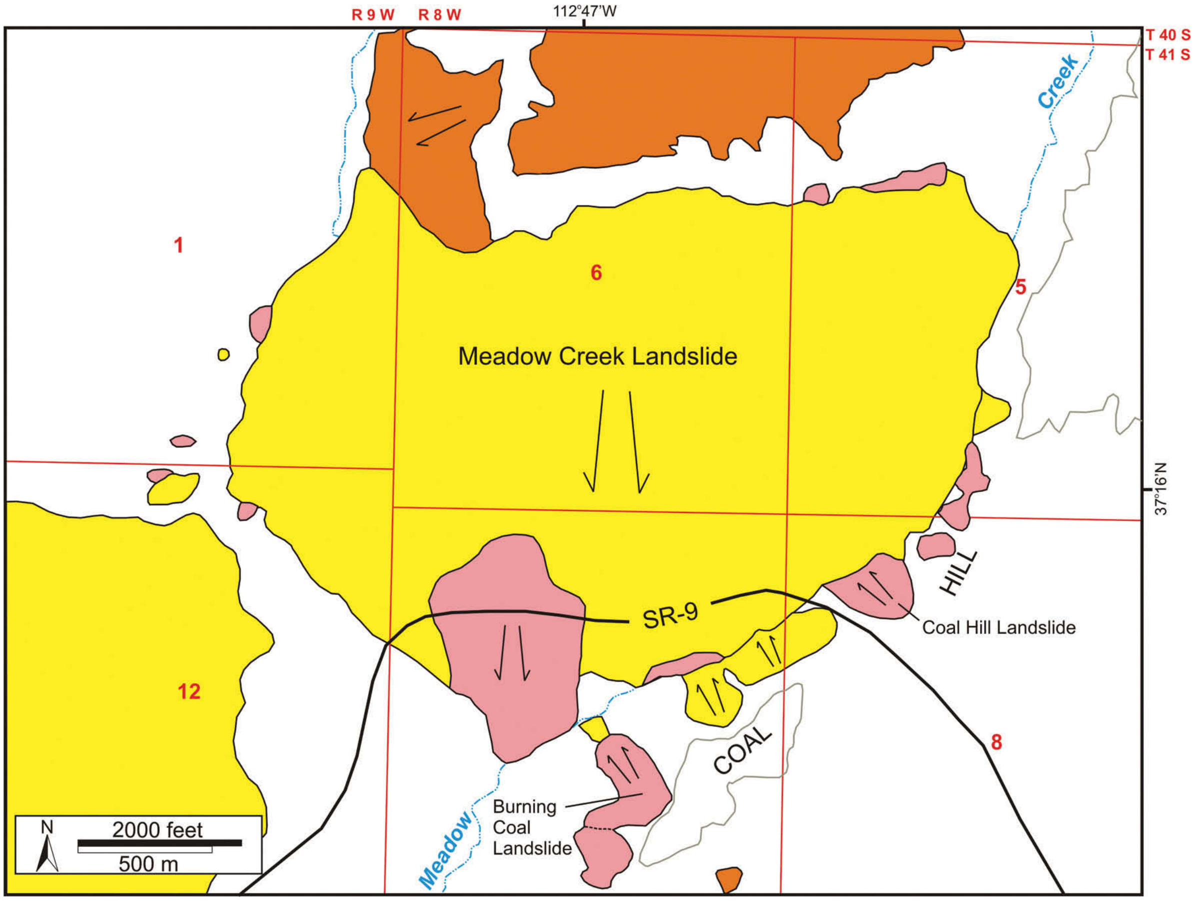

__Figure 2.__ Simplified geologic map of the Coal Hill landslide complex, western Kane County, Utah. Older (orange), younger (yellow), and historical (pink) landslides shown. Historical slides include Coal Hill and Burning Coal landslides (Stouffer, 1964). Arrows show approximate movement directions of selected landslides. State Route 9 (SR-9) crosses the Meadow Creek landslide (MCL). Unlabeled gray contour lines shown to define Coal Hill. Modified from Hylland (2000).

tain Formation (see Biek and others, 2003), which crops out around Coal Hill and locally along the slopes above the two creeks. The coal-bearing Dakota Formation, which consists mostly of mudstone and sandstone, underlies the upper part of Coal Hill, generally above elevation 6160 feet (1878 m), and crops out in slopes in the northern part of the landslide complex. Cashion (1961) had previously included the coal-bearing strata in the Tropic, but these strata were later redefined as Dakota (Lawrence, 1965; Elder and others, 1994). The Tropic Shale, consisting mostly of marine shale, crops out north and east of the landslide complex at elevations generally above 6600 feet (2012 m).

BACKGROUND

The original highway across the Coal Hill area, State Route 15 (SR-15), was constructed in 1928 (Stouffer, 1964) (figure 3), and was locally referred to as the Zion–Mount Carmel Highway (circa 1930–32). A newspaper article (Richfield Reaper, 1930) indicates landsliding threatened SR-15 by early 1930, forcing stabilization efforts on the downslope side of the highway at Big Meadow Wash (probably Meadow Creek). By 1932, a landslide had destroyed the bridge across Big Meadow Wash (Kane County Standard, 1932; Richfield Reaper, 1932). Gregory (1950) reported that landsliding at Coal Hill forced the realignment of the highway four times since 1930 (figure 3). Stouffer's (1964) interviews with highway maintenance personnel revealed that landsliding was most frequent in the 1930s and associated with a period of wet winters. A deep snowpack in early 1936 was followed by the most significant damaging movement in the subsequent spring. However, between 1939 and 1960, no significant landslide movement occurred. Cashion (1961) indicated that landslide movement north of Meadow Creek (referred to as the "creep zone" by Stouffer [1964]) also caused maintenance problems on SR-15.

In 1955, the State Road Commission (SRC), predecessor of the Utah Department of Transportation, proposed a new alignment of SR-15 and subsurface investigations for the proposed alignment began in 1956. The SRC revised the alignment slightly and conducted additional subsurface investigations in 1962. Stouffer (1964) indicated that construction of the new alignment was in progress by September 1963. Doelling and Davis (1989) indicated the original SR-15 alignment was

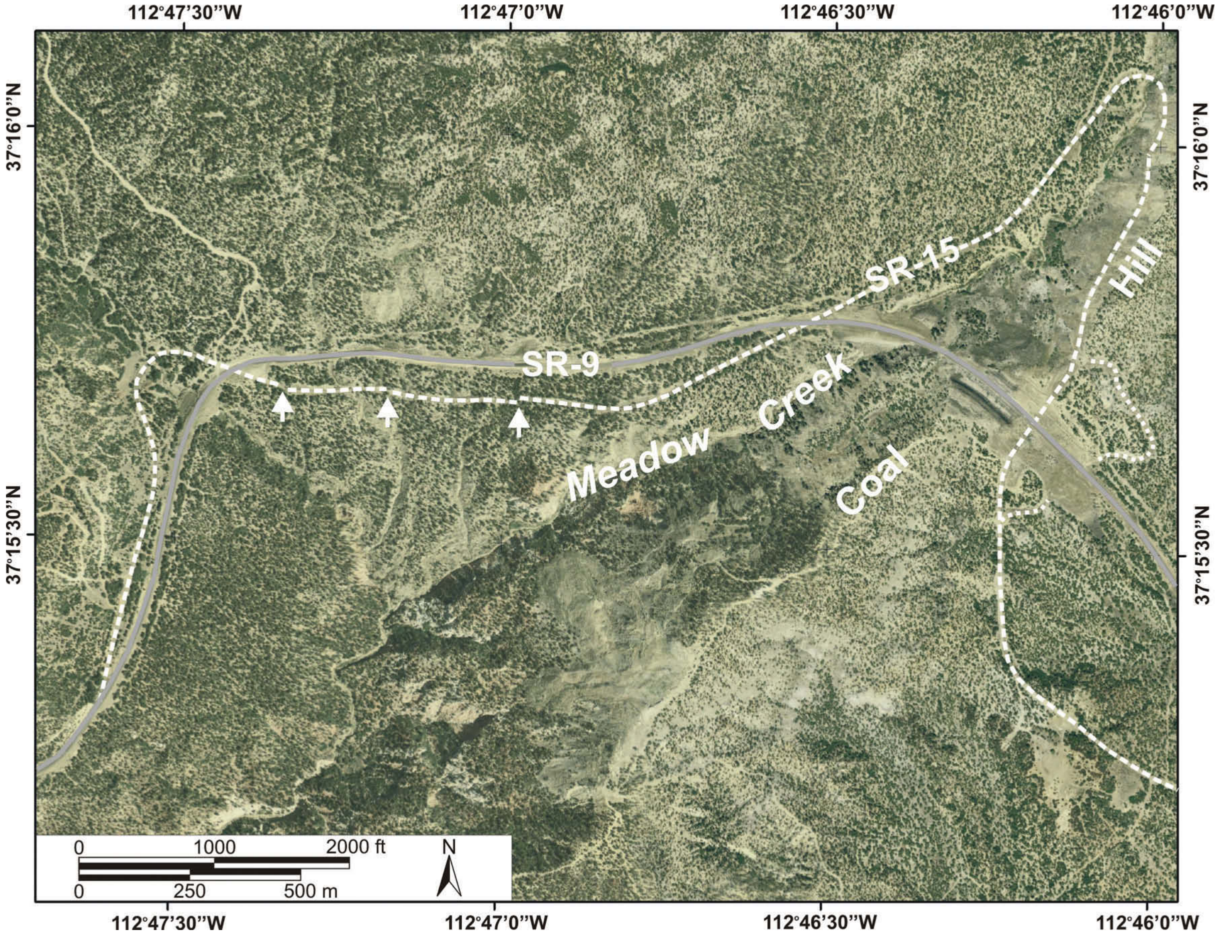

Figure 3. Aerial photograph showing current State Route 9 (SR-9) and abandoned State Route 15 (SR-15) in the Coal Hill area, western Kane County, Utah. SR-15 alignment was abandoned in 1964. The new highway was subsequently renumbered as SR-9 in 1978. Arrows show where abandoned SR-15 is offset or severed by landslide movement. Detached dotted lines on southeast side of Coal Hill show temporary alignment of SR-15 used during construction of present highway across Coal Hill (circa 1963–64).

abandoned in 1964. SR-15 was renumbered in 1978, becoming State Route 9 (SR-9), so that the former route number could be used for Interstate 15 (I-15 on figure 1). Photographs taken in 1986 (Doelling and Davis, 1989) show offset of the abandoned highway (former SR-15).

Doelling and Davis (1989) documented landslide movement north of Meadow Creek between 1983 and 1986 that damaged SR-9. In early 1985, the most severely damaged part of SR-9 was regraded and resurfaced, but the highway was damaged again by 1986. This study documents pavement distress in late 2005 caused by movement during and immediately following the 2005 wet year.

COAL HILL LANDSLIDE COMPLEX DESCRIPTION

The Coal Hill landslide complex includes a large landslide between Meadow Creek on the east and south, Little Meadow Creek on the west, and a large south-facing escarpment on the north, referred to as the Meadow Creek landslide (figures 2, 4, and 5). In addition, the Coal Hill landslide complex includes a series of slides on the northwest-facing slope of Coal Hill southeast of Meadow Creek that includes the Coal Hill landslide and Burning Coal landslide (Stouffer, 1964) (figures 2 and 5). The Meadow Creek landslide also contains six historically active landslides. This study focuses on the Meadow Creek landslide and the six historical slides within it (figures 4 and 5).

Meadow Creek Landslide

Hylland (2000) mapped the Meadow Creek landslide (figures 2, 4, and 6) as a Holocene to latest Pleistocene slide containing possible local (unmapped) areas of historical movement, and mapped four historical landslides within the main slide. Measurements taken as part of this study show no evidence for movement of the entire Meadow Creek landslide, but indicate movement in the southern part of the slide delineated by Stouffer (1964) as the "creep zone."

The Meadow Creek landslide is about 1.7 miles (2.7 km) wide and 1.3 miles (2.1 km) long, and consists of two parts: an upper extensional area characterized by narrow ridges and

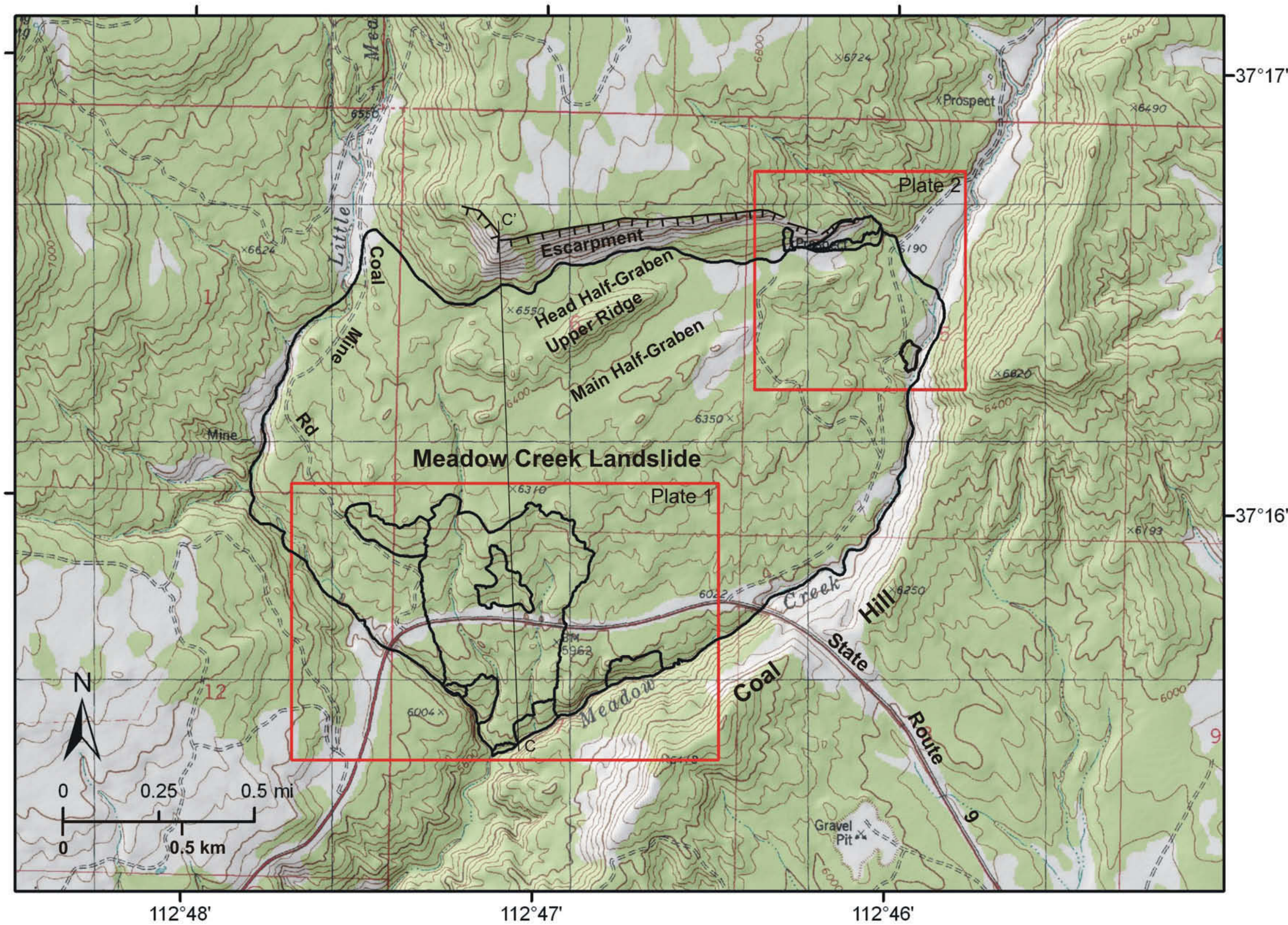

Figure 4. *Location of the Meadow Creek landslide in western Kane County, Utah. Inset boxes show areas of detailed mapping in plates 1 and 2. Landslide perimeter modified from Hylland (2000). Boundaries of mapped landslides within Meadow Creek slide shown (see plates for additional details). Cross section C-C′ shown on figure 15. Base from U.S. Geological Survey Clear Creek Mountain 7.5′ quadrangle. Shaded relief from 10-meter Digital Elevation Model (DEM).*

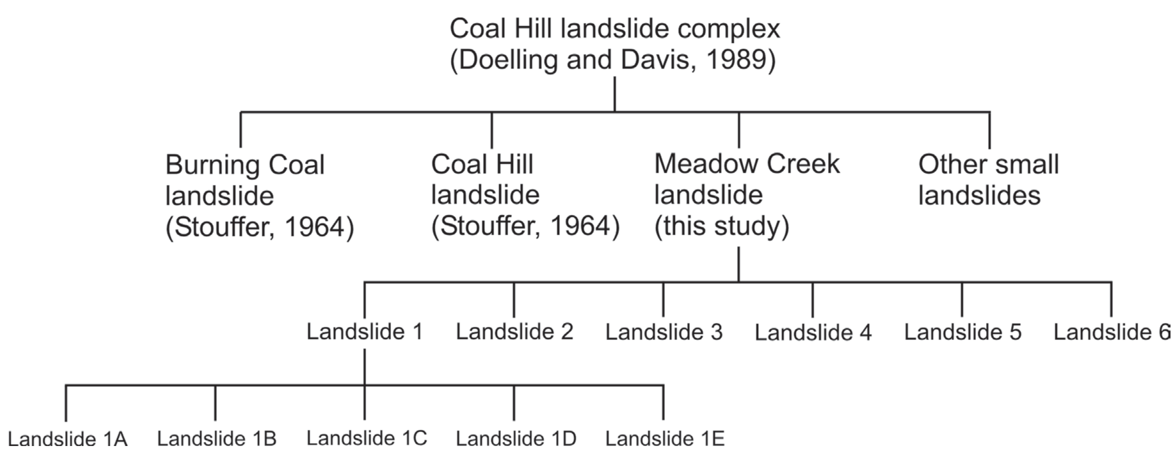

Figure 5. *Flow chart showing hierarchy of landslides in the Coal Hill landslide complex. See figure 2 for locations of Coal Hill, Meadow Creek, and Burning Coal landslides.*

Figure 6. Panoramic view to the north of the Meadow Creek landslide from Coal Hill. Large escarpment in background is the main scarp.

broad flat areas (possible half-grabens), and a lower, gently to locally moderately sloping area that includes four of the mapped historical landslides in the complex, the exceptions being two slides in the escarpment slope. The upper member of the Dakota Formation and lower part of the Tropic Shale are exposed in the main-scarp escarpment that defines the northern boundary of the slide. The narrow northeast- to locally east-trending ridges consist mostly of the upper member of the Dakota Formation. White sandstone that caps the crest of the upper ridge (figure 4) is likely the "sugarledge sandstone" of the upper member of the Dakota (Cashion, 1961; Hylland, 2000). Local dark gray soils suggest underlying coal, also indicative of the Dakota. One area of septarian nodules in the upper part of the landslide suggests that the landslide may locally contain the lower part of the overlying Tropic Shale or debris derived from it; the lower part of the Tropic Shale is exposed in the upper part of the main-scarp escarpment. The upper extensional area extends downslope to about elevation 6200 feet (1890 m) where it transitions into an area that is generally sloping and incised. Locally, the lower area is characterized by back-tilted surfaces with sag ponds indicating deep-seated rotational sliding. Local flat areas, particularly in the southeastern part of the landslide, may be the result of prehistoric stream terracing, deep-seated rotational sliding, or the near-horizontal attitude of underlying strata beneath the landslide debris near the crest of the Meadow Creek canyon slope.

Field observations suggest a transition in material type from north to south. In the northern upper area of the slide, surficial materials consist of large rotated blocks of displaced rock, which form the ridges. Unconsolidated deposits consisting of mostly sand and silt fill the half-grabens that separate the ridges. In the lower part of the landslide, particularly south of SR-9, surficial materials consist of heterogeneous unconsolidated debris. Stouffer (1964) recognized a similar transition in material type at both the Coal Hill and Burning Coal landslides.

Historical Landslides

The Meadow Creek landslide contains six historical landslides, two in the escarpment slope and four in the lower part of the main slide. Hylland (2000) mapped four of these landslides and Stouffer (1964) mapped another. The sixth landslide was identified during this study. These six landslides are numbered 1 through 6 on plates 1 and 2. Reactivation of four of these (landslides 1, 2, 3, and 5) occurred in 2005, and some evidence, such as ground cracks and locally oversteepened slopes, suggests minor movement of the other two slides (landslides 4 and 6). Table 1 summarizes measured dimensions and average slopes of the historical landslides.

Landslide 1

Landslide 1 (plate 1) is the largest historical slide in the Meadow Creek landslide (table 1) and contains five smaller landslides (landslides 1A through 1E) within its boundaries that were active in 2005. Movement of three of these caused considerable local ground deformation. Doelling and Davis (1989) initially mapped the east- and west-flank shear zones that bound the landslide, but did not map its entire perimeter. We map the east-flank shear zone to the west of where it was delineated by Doelling and Davis (1989). Hylland (2000) mapped landslide 1 as a large historical slide in the southwestern part of the Meadow Creek slide. Our mapping indicates that landslide 1 extends farther upslope than as mapped by Hylland (2000). Our road-damage inventories along SR-9 and former SR-15 (see sections below) indicate that most of the damage occurs within the boundaries of landslide 1.

Landslide 1 is characterized by two well-defined shear zones on its flanks, numerous internal shear zones, and a variety of ground-deformation features. The head of the landslide consists of a series of en echelon or stepping scarps that extend upslope into the upper extensional part of the Meadow Creek landslide. The uppermost scarps in landslide 1 consist of reactivated, downslope-side, ridge-bounding scarps. Sinkholes commonly form along these scarps, suggesting local soil piping at locations where snowmelt and rainwater collects and infiltrates along them. Seasonal seeps are commonly present at the base of steep, downslope-facing, internal scarps, and local back-tilted surfaces are present in the head of landslide 1.

The east- and west-flank shear zones (figures 7A and 7B) are

Table 1. *Summary of approximate dimensions and average slopes of active slides in the Meadow Creek landslide. Landslide locations shown on plates 1 and 2. See appendix for discussion of field methods and probable measurement errors.*

Landslide	Length (ft)	Width (ft)			Local Relief (ft)	Ave. Slope (percent)
		Toe	Upper	Other		
1	3200–3500	1630	---	1880*	500–510	15
1A	875	750	210	---	180	21
1B	650	---	310	---	170	26
1C	130	---	300	---	40	22
1D	110	---	350	---	40	36
1E	270–330	710	---	---	85	30
2	260	---	1070	---	60–100	23**
3	250	---	630	---	140	56
4	300	140	120	---	160	53
5	240	---	---	910***	140	56
6	230	---	420	---	65–80	28–34

Notes: *Width along SR-9
**Western part
***Middle slide

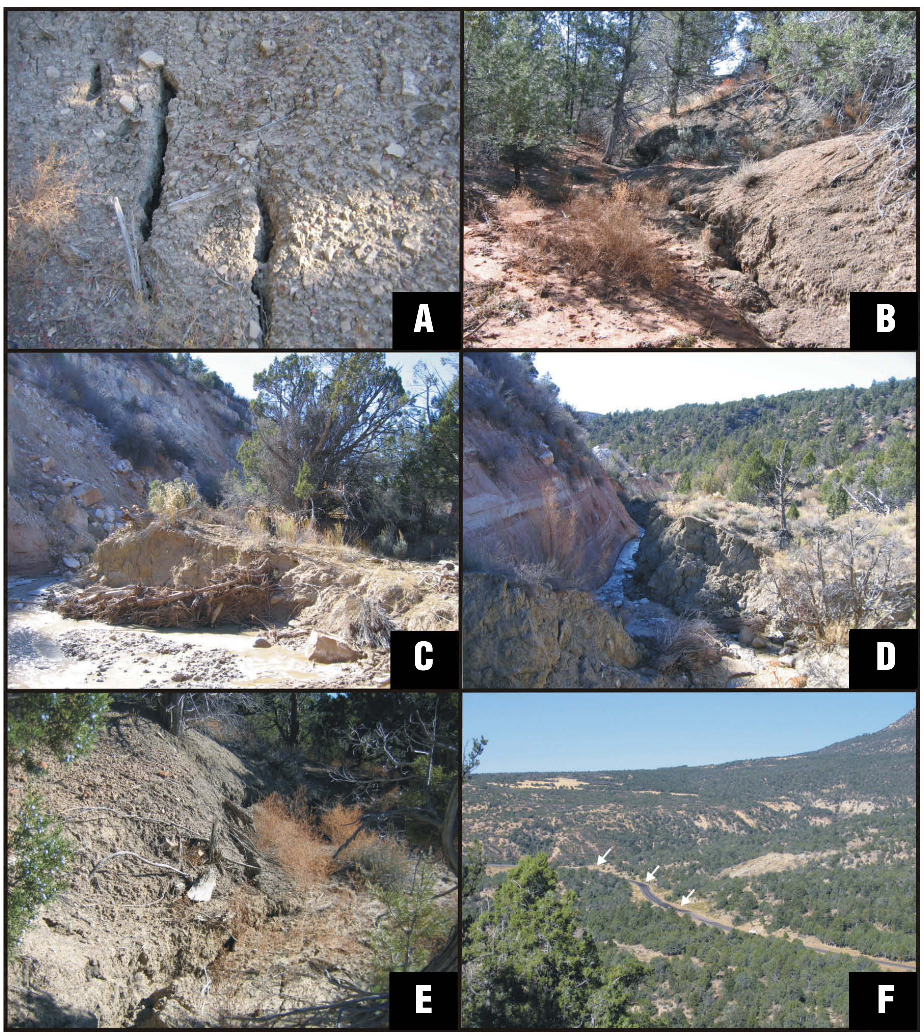

Figure 7. *Ground deformation and road damage in landslide 1. (A) Left-stepping ground cracks that form part of the west-flank shear zone. (B) View to the south-southwest of part of the east-flank shear zone. Zone crosses photograph diagonally from lower right to center, then steps to right. In this area, low hummocks are folded debris above a thrust system. (C) Southeastern corner of landslide toe where it intersects east-flank shear zone. Meadow Creek is deflected about 43 feet (13 m) by landslide. (D) View to the west-southwest of toe where some landslide debris remains on south side of Meadow Creek (lower left corner). (E) View of typical offset on pre-existing scarp in head of landslide. (F) View to the west of damaged part of SR-9 (arrows point to darker asphalt patches) caused by movement of landslide 1. Photographs taken in October (F) and November (A-E) 2005.*

Figure 8. Exposure of carbonaceous shear zone in toe of landslide 1, suggesting that the landslide debris is partly derived from the Cretaceous Dakota Formation.

characterized by en echelon, right- and left-stepping ground cracks, respectively. Movement in 2005 resulted in nearly continuous ground-crack zones along both flanks from the head to the toe of landslide 1. The east-flank shear zone intersects Meadow Creek where the toe of landslide 1E deflects the creek about 43 feet (13 m) (figure 7C). The west-flank shear zone intersects Little Meadow Creek a short distance upstream from a sinkhole that captures the entire creek flow. From that point the creek flows through a tunnel in landslide debris for about 210 feet (64 m) (plate 1). Doelling and Davis (1989) described this tunnel, suggesting that it has existed for at least 20 years (their field observations date from the mid-1980s).

The lower part of landslide 1 is locally intensely deformed, characterized by numerous ground cracks and fissures, minor scarps, pressure ridges (folds), and ground tilting. Along Meadow Creek, slickensided, carbonaceous (coal-bearing) gouge is exposed in the toe thrust system (figure 8), suggesting that the surface of rupture of landslide 1, and likely also the main landslide, is at least in part in the Dakota Formation. Geologic mapping (Hylland, 2000) and subsurface data (Stouffer, 1964) indicate that the surface of rupture of many of the complex's landslides may have formed in bentonitic mudstone included in the Cedar Mountain Formation (Biek and others, 2003).

We mapped five slides (landslides 1A through 1E) within landslide 1, but other small, shallow, unmapped slides exist, particularly on local steep slopes along incised drainages. Landslide 1A (figure 9) is the largest of these landslides and its toe is about 165 feet (50 m) upslope of SR-9 (plate 1). Landslide 1A is approximately 875 feet (267 m) long and varies in width from about 210 feet (64 m) at its head to approximately 750 feet (229 m) at its toe (table 1). The landslide is characterized by a prominent main scarp zone (figures 9A and 9B) that follows an irregular trace and locally exceeds 20 feet (6 m) in height; a back-tilted area with a sag pond at its head (figure 9E); and an irregular, discontinuous toe thrust system (figure 9D). Movement of the landslide has displaced power poles on the lower part of the slide about 21 feet (6 m). Locally, the ground surface is intensely deformed and disrupted (figure 9C).

The other four slides (figure 10) in landslide 1 are downslope of SR-9 and former SR-15, and abut either Little Meadow Creek (landslides 1B and 1C) or Meadow Creek (landslides 1D and IE). Landslide 1B is directly west of an incised drainage that crosses the western part of landslide 1 and flows into Little Meadow Creek. The landslide is characterized by a main scarp that locally exceeds 10 feet (3 m) in height. Landslide 1C is upslope of the lower part of the tunnel along Little Meadow Creek. Movement in 2005 resulted in offset and ground cracking along the main scarp of the slide (figure 10B). Landslide 1D is at the confluence of Little Meadow Creek and Meadow Creek and is characterized by intense ground deformation (figures 10C and 10D). Landslide 1E (figures 10E and 10F) is in the southeastern toe of landslide 1 and is characterized by locally intense ground deformation and a zone of scarps in its upper part. The 43-foot (13-m) deflection of Meadow Creek occurs at landslide 1E, and some, if not most, of the deflection is likely the result of local movement of this smaller slide rather than global movement of landslide 1. Stouffer (1964) documented deflection of Meadow Creek by landslide 1E, but did not quantify it.

A comparison of previous landslide mapping (Cashion, 1961; Stouffer, 1964; Doelling and Davis, 1989; Hylland, 2000), aerial photographs, topographic maps of the complex, and road-damage accounts suggests most of the historical movement of landslide 1 likely occurred during the past four decades. Stouffer (1964) mapped small slides near our landslides 1B and 1C along Little Meadow Creek and landslide 1E along Meadow Creek, but did not show a large slide equivalent to landslide 1 in the "creep zone." In addition, accounts of road damage in Stouffer (1964) indicated several inches of downslope movement per year in the "creep zone," and more significant movement in wet years. Stouffer (1964) did not describe the movement and road damage as being localized in the vicinity of our landslide 1, but our review of aerial photographs, dated 1960 and hence predating his study, identified damage to SR-15 localized to the shear zones on the

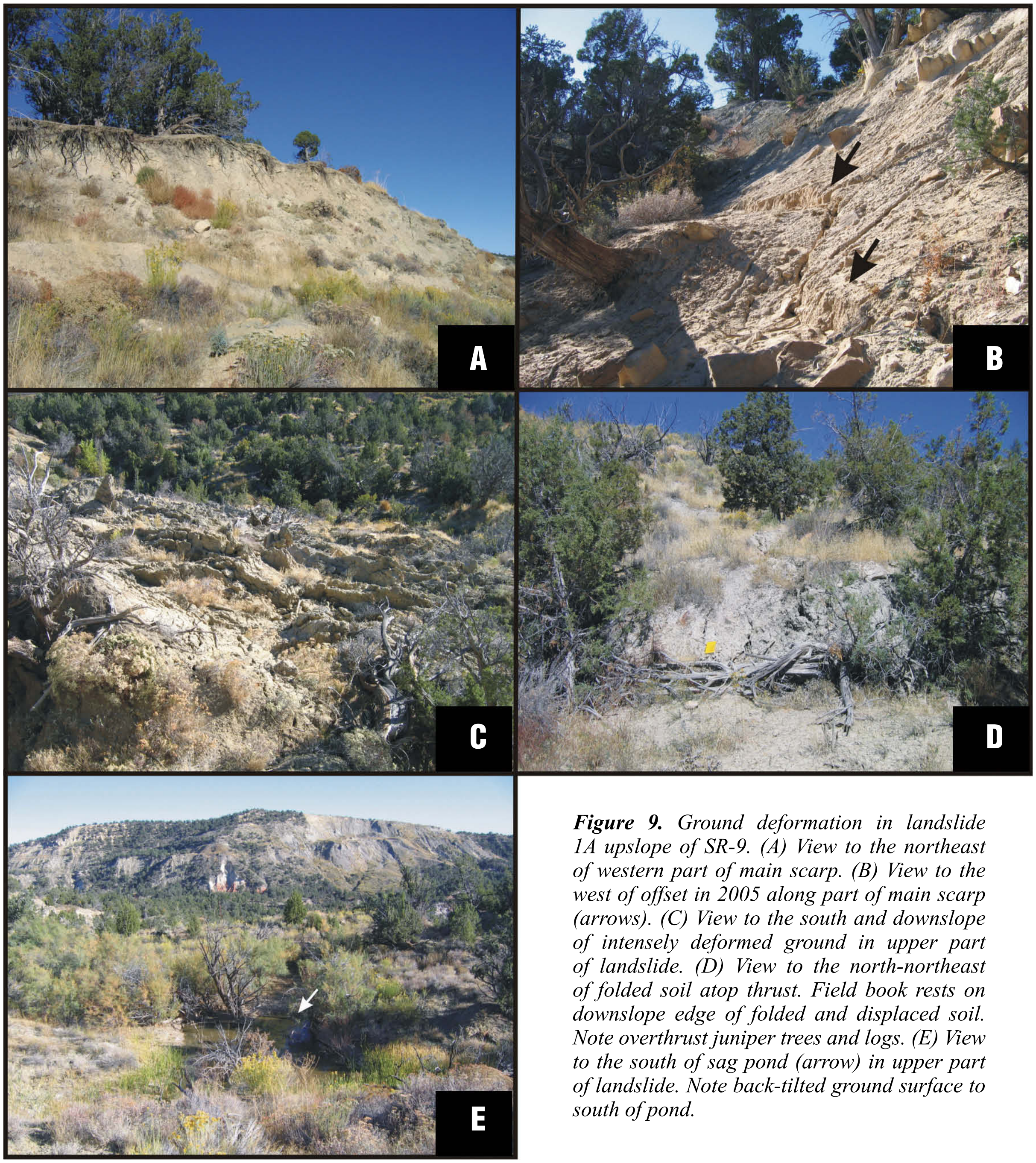

Figure 9. Ground deformation in landslide 1A upslope of SR-9. (A) View to the northeast of western part of main scarp. (B) View to the west of offset in 2005 along part of main scarp (arrows). (C) View to the south and downslope of intensely deformed ground in upper part of landslide. (D) View to the north-northeast of folded soil atop thrust. Field book rests on downslope edge of folded and displaced soil. Note overthrust juniper trees and logs. (E) View to the south of sag pond (arrow) in upper part of landslide. Note back-tilted ground surface to south of pond.

east and west flanks and a major internal shear zone of landslide 1. However, the 1960 aerial photographs do not show any significant offset in the SR-15 alignment, consistent with Stouffer's (1964) road movement description. Doelling and Davis (1989) mapped the flanks of landslide 1, but showed the east-flank shear zone farther to the east than that later mapped by Hylland (2000) and this study. Doelling and Davis (1989) also documented offset of abandoned SR-15 by 1985. Aerial photographs dated 1994 clearly show offset in the SR-15 alignment at the boundaries and internal shear zones in landslide 1. Thus, we conclude that movement of landslide 1 has been more significant subsequent to Stouffer's (1964) investigation than in the period prior to his study (1928–1964).

Landslide 2

Landslide 2 abuts landslide 1 on the west above Coal Mine Road on the west side of the Meadow Creek landslide (plate 1). Landslide 2 is characterized by a well-defined main scarp zone that was active in 2005, but a poorly defined toe. In the eastern part of the head of the landslide is a back-tilted surface (figure 11A) with a sag pond on its northern edge, suggesting deep-seated rotational sliding. Numerous east-trending ground fissures with local sinkholes are also present in the eastern head of the slide. To the west, ground-deformation patterns suggest shallower landsliding than in the east. We infer that an oversteepened slope north of Coal Mine Road is

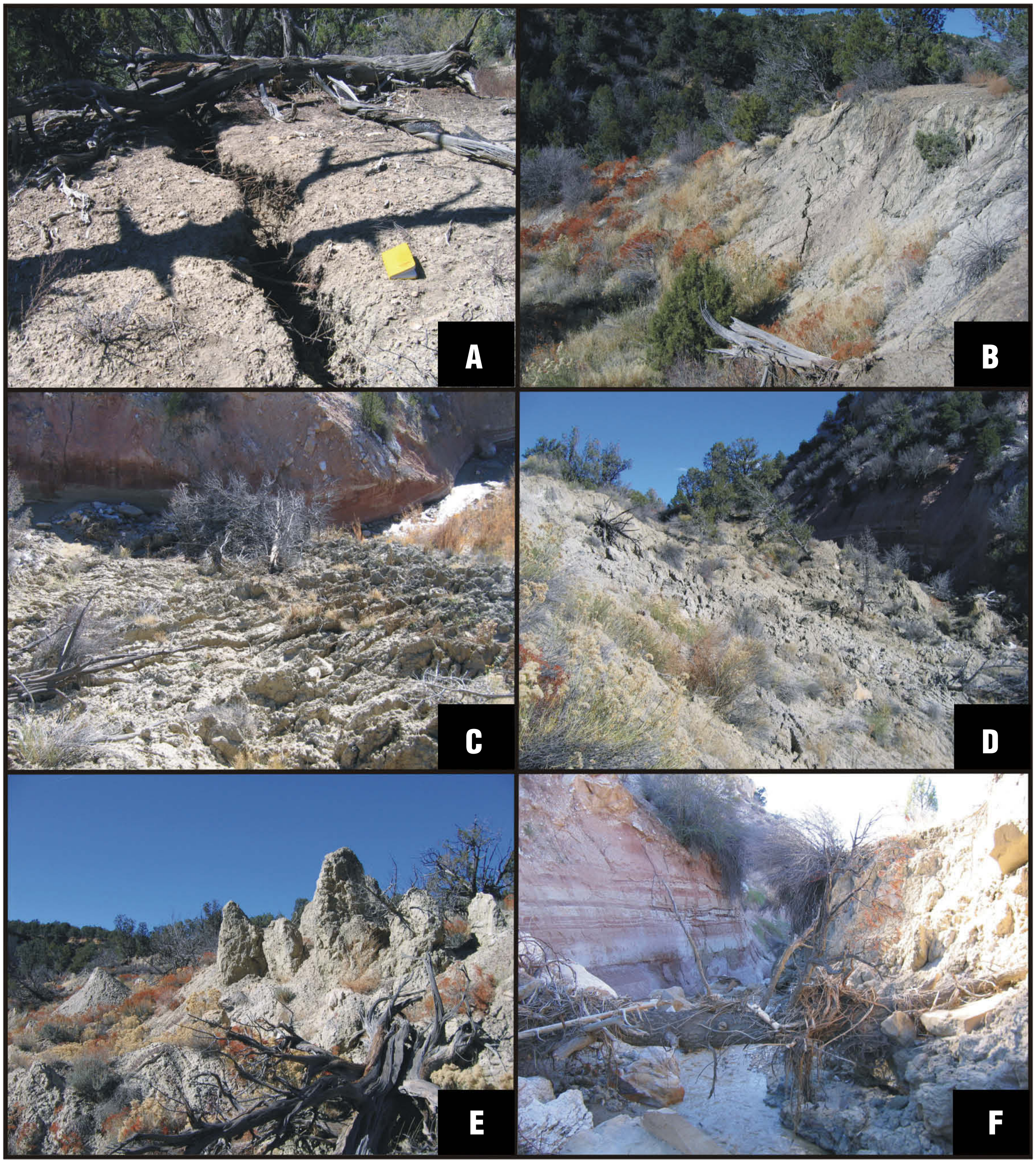

Figure 10. *Other smaller active slides in landslide 1. (A) Crown fissure above main scarp of landslide 1B. (B) View to the northwest of main scarp of landslide 1C and offset in 2005. (C) View to the south-southwest of intensely deformed part of landslide 1D. (D) View to the east of landslide 1D. (E) View to the west of broken soil blocks in lower part of landslide 1E. (F) View to the west-southwest and downstream of landslide debris (right) exposed in toe of landslide 1E along Meadow Creek.*

the probable toe of the landslide (figure 11B). Whereas offset on the main scarp occurred in 2005, translation of landslide debris at the toe appears to have been minimal. Instead, movement of the upslope part of the landslide may have resulted in ground tilting and folding at the toe with little, if any, translation. A reconnaissance downslope of the jeep road revealed no evidence of ground deformation indicative of deep-seated landsliding in 2005. However, damage to the SR-15 culvert (figure 12) across Little Meadow Creek suggests historical movement in this area, either of the southwestern part of the Meadow Creek landslide (the western part of the "creep zone") or an as-yet unmapped slide that includes landslide 2. If the latter, this suggests that landslide 2 is a partial reactivation of a larger pre-existing slide (not shown on plate 1) that extends downslope to Little Meadow Creek.

Landslide 3

Landslide 3 (plate 1) is north of Meadow Creek in the southern part of the Meadow Creek landslide. Stouffer (1964) mapped a landslide in what is now the western part of landslide 3 and

Hylland (2000) mapped landslide 3 as a historical landslide. Most of landslide 3 reactivated in 2005, locally causing considerable disruption of the ground surface (figures 11C and 11D). Our mapping of the 2005 landslide boundary suggests that the landslide likely enlarged to the north and west since it was mapped by Hylland (2000) using 1994 aerial photographs. Some or all of this enlargement probably occurred in 2005. The eastern part of the landslide did not reactivate in 2005, but at least two small, shallow landslides occurred in 2005 to the east of the active part of the slide and within the eastern limits of the landside as mapped by Hylland (2000).

Landslide 4

A small slide (landslide 4) exists directly west of an abandoned coal mine adit (Meeks-Carrol mine of Cashion, 1961) in the

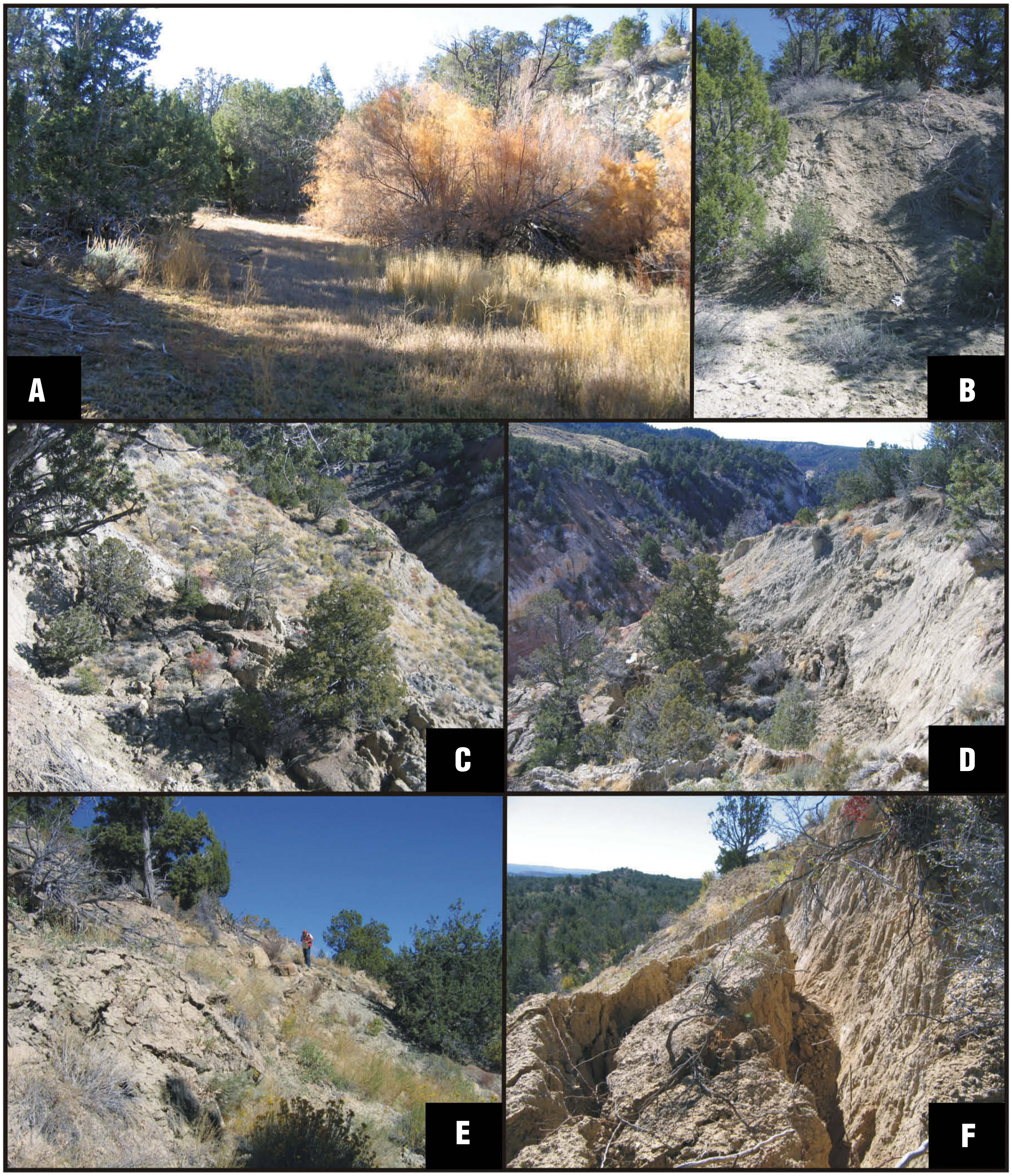

Figure 11. *Other historical slides in the Meadow Creek landslide. (A) View to the west of back-tilted ground surface in eastern head of landslide 2. Sag pond exists along north edge of area to right of tamarisk (orange leaves). (B) Toe of landslide 2 northeast of Coal Mine Road. (C, D) Views of ground deformation in upper part of landslide 3. Ground surface was locally disrupted by movement in 2005. (E) View to the northeast of toe of active part of landslide 5. Lower active toe thrust in 2005 was in about the middle of historical landslide mapped by Hylland (2000). (F) View to the west of the main scarp of landslide 5. Most of the offset visible in photograph likely occurred in 2005.*

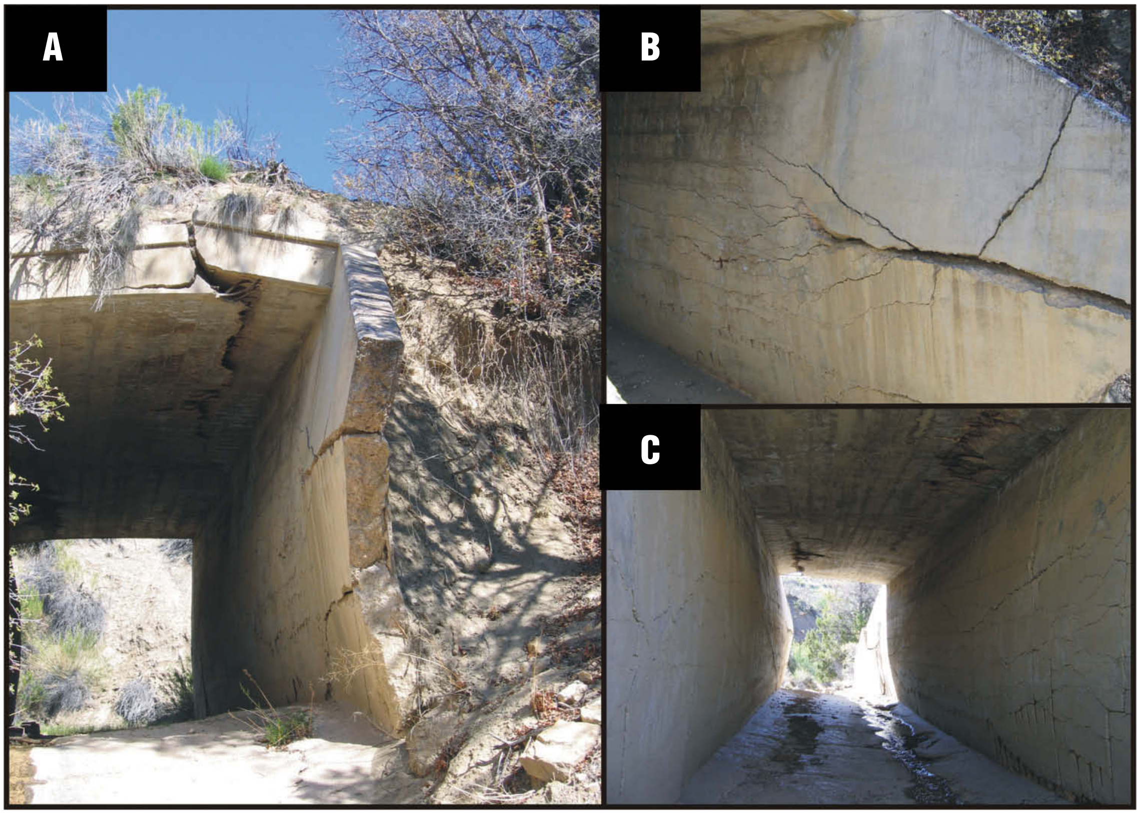

Figure 12. *Damage to box culvert at abandoned SR-15 crossing of Little Meadow Creek. (A) View upstream showing damage to northeast wall of box culvert and upper deck. (B) Damage to northeast wall of box culvert. (C) View downstream of interior of culvert showing hourglass distortion of originally rectangular box culvert.*

eastern part of the large escarpment that bounds the Meadow Creek landslide on the north and is the main scarp (plate 2). The landslide abuts the ruins of the abandoned coal mine and overthrusts a jeep road to the mine adit, indicating historical movement. Observations including the fresh appearance of the landslide perimeter, wet soils in the upper slide, and a 15-foot-wide (5 m) shallow landslide in the main scarp slope suggest some minor movement of the slide in 2005. Seeps and abundant phreatophytes exist in the upper part of the landslide.

Landslide 5

Landslide 5 is the larger and easternmost of two historical landslides mapped by Hylland (2000) in the eastern part of the large escarpment (plate 2). In 2005, landslide 5 partially reactivated and enlarged in an upslope direction. The toe (figure 11E) of the active part of the landslide is in the middle of the deposit mapped by Hylland (2000). A series of scarps and ground fissures occur in the upper part of the active slide. Along the eastern part of the main scarp zone (figure 11F), a narrow horst separates landslide 5 from an active, shallow debris slide (not mapped on plate 2) to the north. Ground deformation features suggest landslide 5 becomes shallower to the west, similar to landslide 2. In the early part of 2005, local shallow debris flows originated from the toe area of the active part of the slide (not mapped). One flow traveled downslope of the historical toe mapped by Hylland (2000). During our fieldwork in November 2005, audible rock falls originated from the upper part of the landslide, suggesting the slide remained active in the latter part of 2005.

Landslide 6

Stouffer (1964) mapped a small rotational slide (plate 2) abutting Meadow Creek along the east edge of the Meadow Creek landslide. Our mapping indicates a northward enlargement of the landslide since the early 1960s. The toe of the landslide deflects Meadow Creek to the east near the central part of the slide. Local cracks along the base of the main-scarp colluvium and near the crest of the main scarp suggest minor movement of the landslide in 2005. White precipitate deposits (efflorescence) in the lower part of the landslide indicate local seasonal seeps that likely flow in the early part of the year.

LANDSLIDE DEPTH AND GEOMETRY

Significant uncertainty exists regarding the depth of the Meadow Creek landslide and the smaller slides within it. The dimensions of the Meadow Creek landslide, the escarpment (main scarp) height, and the main-scarp heights of the smaller slides within it suggest a depth of 100 feet (30 m) or greater upslope of SR-9, likely increasing toward the escarpment where the relief locally exceeds 400 feet (120 m) (figure 4). South of SR-9 and along the perimeter of the Meadow Creek landslide, the depth of the landslide is likely less than 100 feet (30 m). Data from a geotechnical borehole and seismic refraction line suggest that the Meadow Creek landslide may be about 40 feet (12 m) deep along its southeastern edge near where SR-9 crosses onto the slide (Stouffer, 1964). We used two approaches to estimate the depth of the landslide: (1) Spectral Analysis of Surface Waves (SASW) testing and (2) geologic cross sections.

Spectral Analysis of Surface Waves (SASW) Testing

On June 20 and 21, 2006, we conducted Spectral Analysis of Surface Waves (SASW) testing (Stokoe and others, 1994) in conjunction with seismic refraction testing at three locations on the Meadow Creek landslide near SR-9 (figure 13). Site 1 is near the southeast edge (toe) of the slide on a gravel road north of SR-9. The other two locations are on the flanks of landslide 1 along abandoned SR-15.

The primary purpose of the testing was to evaluate the feasibility of using the SASW method, which can detect low-velocity layers at depth, to determine the depth of the landslide. Clay gouge in the basal surface-of-rupture zone will likely be remolded and fully softened, and should cause a velocity inversion. One of the limitations of the SASW method is its inability to detect thin, deep layers. Generally, a layer should have a velocity contrast of at least 20 percent and a thickness greater than 20 percent of its depth to be detected using the SASW method.

The three measured shear-wave-velocity profiles are compared on figure 14. A significant inversion exists at site 1, near the toe of the Meadow Creek landslide, at a depth of between 28 and 48 feet (9–14 m). This velocity inversion is not as large as the more shallow ones at sites 2 and 3, but is consistent with a surface-of-rupture zone. Data from a nearby geotechnical borehole and seismic refraction line (Stouffer, 1964), located about 300 to 400 feet (90–120 m) to the east-southeast of site 1, support this interpretation, and indicate landslide depths of 38 and 42 feet (12 and 13 m), respectively. These depths are bracketed by the upper and lower boundaries defining the velocity inversion at site 1.

The near-surface soils in the top 15 feet (5 m) are stiffer at site 1 than at sites 2 and 3. Both sites 2 and 3 have a significant velocity inversion in the upper 15 feet with a very low-velocity layer at the base of the inversion. However, both sites 2 and 3 are along abandoned SR-15, and a highway embankment exists on the downslope side of the test areas. The shallow velocity inversion may be related to fill density or condition in the embankment fill and reflect a decreasing level of compaction of the fill with depth. No other velocity inversions were detected at either site; however, a shear-wave-velocity contrast at depths of 100 and 84 feet (30 and 26 m) at sites 2 and 3, respectively, may be the base of landslide 1.

The results, particularly those at site 1, suggest that basal surface of rupture zones can be detected using SASW testing, particularly where they occur at moderate depth (less than 50 feet [15 m]). However, further subsurface investigations are needed to confirm the results.

Geologic Cross Sections

Cross section C-C' (figure 15) shows a conceptual model of the Meadow Creek landslide. The cross section assumes that the basal surface of rupture in the upper part of the landslide is relatively flat sloping, roughly parallel to bedding, and in the Cedar Mountain Formation. The dip (about 25 degrees) of back-tilted blocks of Dakota Formation that form the prominent ridges in the upper part of the landslide are based on field measurements. The subsurface geometries of landslides 1 and 1A are constrained by field mapping of the toe and main-scarp locations and, for landslide 1, the depth determined by SASW testing along SR-15. The basal surface of rupture of landslide 1 is likely in the Carmel Formation although landslide debris at the surface appears to be mostly derived from overlying formations.

In-place Carmel Formation is mapped (Doelling and Davis, 1989; Hylland, 2000) along Meadow Creek adjacent to the toe of the landslide. Two north-south cross sections between SR-9 and Meadow Creek show the possible geometry of the Meadow Creek landslide where it overrides the Carmel Formation and in the area of the lower east side of landslide 1 (figure 16, plate 1). The landslide deposits are about 40 feet (12 m) thick where they override the Camel Formation (section A-A'). The thickness of the landslide deposits likely increases upslope, and a minimum depth of about 60 feet (18 m) is inferred at SR-9 assuming a horizontal basal contact, but a greater depth is possible if a north-dipping basal contact exists.

Cross section B-B' through the lower east side of landslide 1 shows an estimated geometry using a possible depth from the SASW testing along abandoned SR-15. Cross section B-B' suggests a deeper basal surface-of-rupture zone in landslide 1 than in the adjacent part of the Meadow Creek landslide directly to the east. Thus, a subhorizontal erosional surface in the Carmel Formation must be at least 60 feet (18 m) lower than at cross section A-A', if it exists at all beneath landslide 1.

ROAD DAMAGE INVENTORY

Recurrent, but localized, road damage has occurred along SR-9 and abandoned SR-15 where the roads cross the southern part of the Meadow Creek landslide since construction of SR-15 in 1928. Stouffer (1964) documented that SR-15 (figure

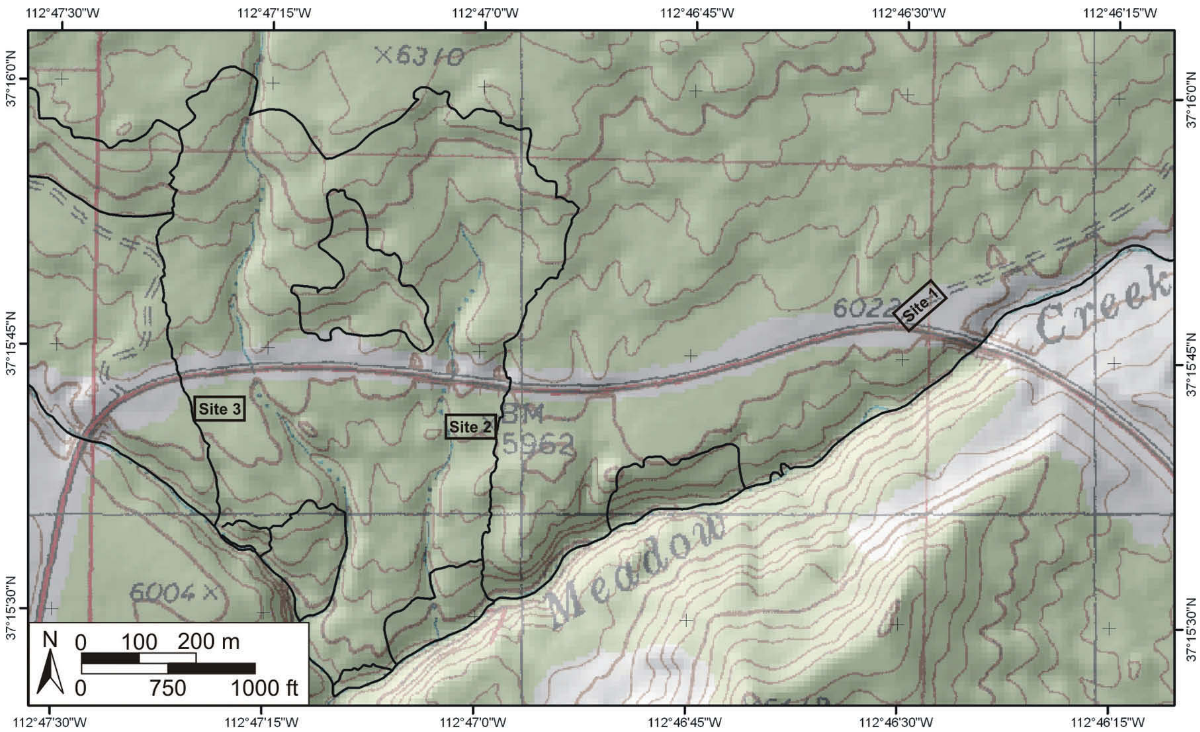

Figure 13. Locations of SASW testing on the Meadow Creek landslide (labeled site 1-3). Boundaries of landslide 1 and other slides shown for reference (see plate 1 for further details). Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.

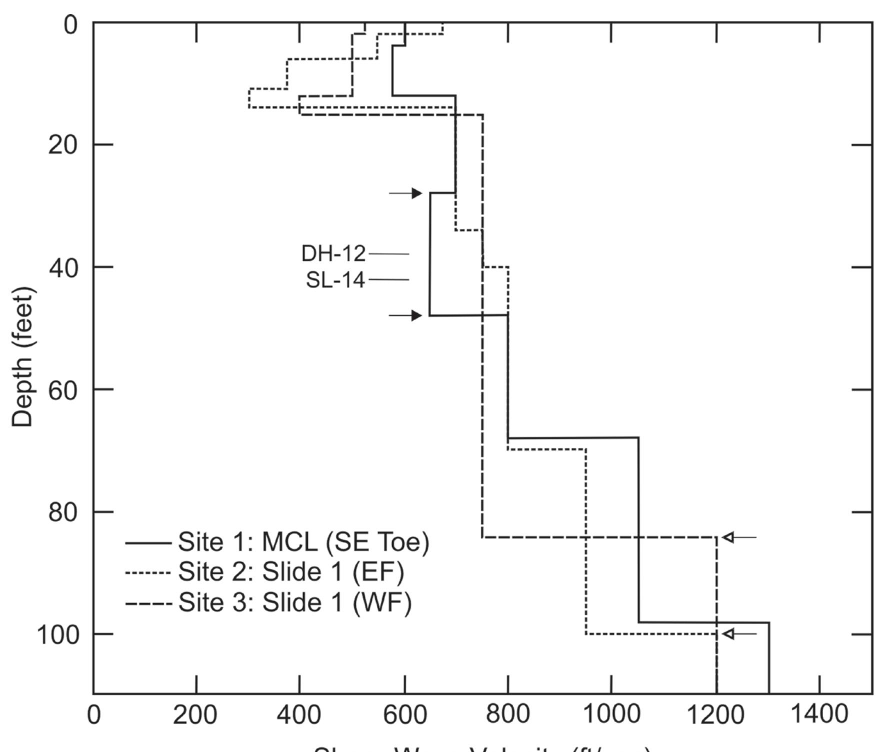

Figure 14. Comparison of shear-wave-velocity profiles determined from SASW testing. Site 1 is on the southeastern toe of the Meadow Creek landslide (MCL) near a previous geotechnical borehole (DH-12) and seismic refraction line (SL-14) (see Stouffer, 1964). A shear-wave-velocity inversion between the depths of 28 and 48 feet (8.5–15 m) (solid arrows) brackets the depth of the landslide deposit determined from the borehole and seismic line (38 and 42 feet [12–13 m], respectively). Sites 2 and 3 are on the east (EF) and west (WF) flanks of landslide 1 along abandoned SR-15. Sharp velocity contrasts at depths of 84 and 100 feet (26–30 m) (open arrows) may indicate the depth of the landslide. See figure 13 for site locations.

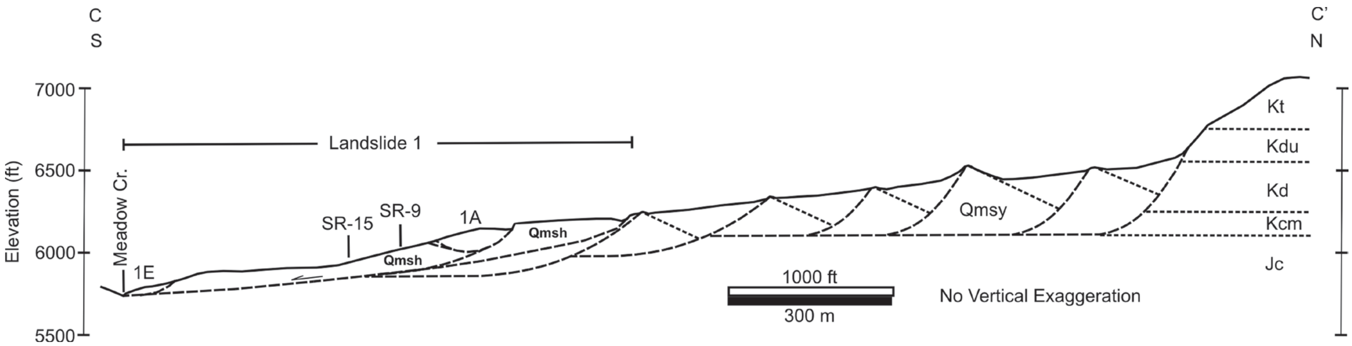

Figure 15. *Conceptual geologic cross section of the Meadow Creek landslide. See figure 4 for section line location. Geologic units: Qmsh – historical landslide 1 (including landslides 1A and 1E), Qmsy –Meadow Creek landslide, Kt – Tropic Shale, Kdu – upper member of Dakota Formation, Kd – main body of the Dakota Formation, Kcm – Cedar Mountain Formation, Jc – Carmel Formation. Bedrock unit thicknesses estimated from Hylland (2000).*

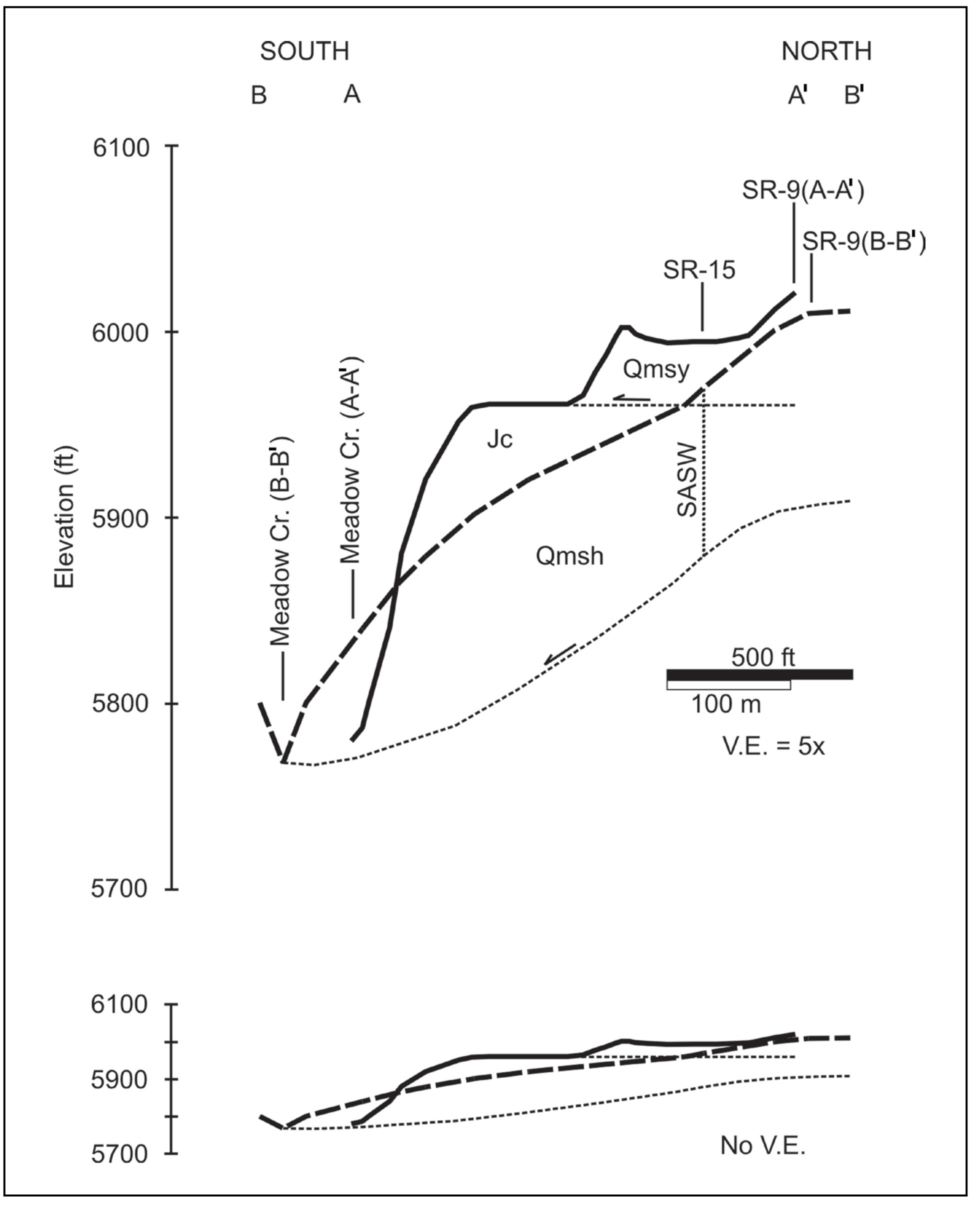

Figure 16. *Geologic cross sections showing possible geometries and minimum depths of southernmost Meadow Creek landslide (A-A') and southern part of landslide 1 (B-B'). Solid black and long dashed lines are topographic profiles for cross sections A-A' and B-B', respectively. Short dashed lines are estimated surfaces of rupture. Vertical line shows estimated depth of landslide deposits from SASW testing. Lower cross sections are same as upper without vertical exaggeration (V.E.). See plate 1 for cross-section line locations. Geologic units: Qmsh – landslide 1, Qmsy – Meadow Creek landslide, Jc – Carmel Formation.*

3) moved several inches per year toward Meadow Creek and noted that most of the movement occurred during the spring following snowmelt. Doelling and Davis (1989) measured 16-foot and 20-foot (5-m and 6-m) total offsets of abandoned SR-15 along the shear faults bounding landslide 1 on July 23, 1985. These measurements indicate an average annual rate of movement of between 9.1 and 11.4 inches per year (23–29 cm/yr). However, Doelling and Davis (1989) also indicated that movement amounts and road damage were greater during wet years such as 1983, when landslide 1 moved several feet. Doelling and Davis (1989) also documented that SR-9 was regraded and resurfaced in the spring of 1985, at a cost of about $150,000, but by September 10, 1985, the road was offset 1 inch and 1/2 inch (2 and 1 cm) on the west and east boundaries of landslide 1, respectively. By the summer of 1986, offset of the highway exceeded 1 foot (30 cm).

2005 SR-9 Damage Inventory

Most of the damage to SR-9 where it crosses the Meadow Creek landslide occurs in the 1880-foot-wide (570 m) stretch across landslide 1. Mapping indicates that the damage is related mostly to ground deformation near lateral shear zones (figures 17, 18, and 19), particularly the flanking shear zones, and local embankment failures.

In 2005, significant pavement damage and lateral offset of the highway occurred at both the west- and east-flank shear zones of landslide 1. The combined length of damaged highway across these two zones, about 505 feet (154 m), is equivalent to about a quarter (27 percent) of the length spanned by SR-9 across landslide 1.

At the west-flank shear zone (figures 17 and 18), the length of damaged highway was about 160 feet (49 m). Right-lateral offset of the white stripe along the north side of the highway at the west-flank shear zone was 1.37 feet (0.4 m). Discrete lateral offsets of the white stripe, both right-lateral and left-lateral, ranged from 0.2 to 0.8 inch (0.5–2 cm) across six other shears in the abutting damage zone.

At the east-flank shear zone (figure 19), the length of damaged highway was about 345 feet (105 m). The amount of left-lateral offset across the east-flank shear could not be directly measured because of a lack of striping in the recently repaired pavement. Vertical displacement also occurred across the east-flank shear in 2005 with a net down-to-the-west offset. Antithetic structures with a down-to-the-east sense of displacement to the west of the east-flank shear zone formed a broad graben with local, narrow internal grabens within its limits. A pair of northwest-trending deformation features consisting of a monoclinal flexure and a road crack defined the boundaries of a broad graben that is about 240 feet (73 m) wide. Another antithetic structure closer to the east-flank shear transitioned from a small scarp in the north to a monoclinal flexure in the south and defined the western boundary of a graben along the east-flank shear that ranged between about 25 and 35 feet (8–11 m) wide.

Most of the remaining damage along SR-9 occurred directly downslope of landslide 1A that is approximately 165 feet (50 m) upslope of the northern edge of pavement. A small cluster of road cracks and lateral shears in SR-9 are along trend of a major right-lateral shear zone that completely offsets abandoned SR-15. An internal right-lateral shear, across which the highest amount of displacement was measured (about an inch), is part of this cluster of road damage that occurred directly upslope of the major internal shear zone (plate 1) that offsets SR-15 by 28 feet (8.5 m) (see Abandoned SR-15 Damage and Displacement section below). The northeast trend of the lateral shear in the road suggests it is a secondary shear to the major internal shear zone which trends northwesterly directly downslope of SR-9. The major internal right-lateral shear zone may branch upslope into a fan of lateral shears. Such a fan would cause considerable ground disruption and possibly explain both the clustering of road cracks in SR-9 and the presence of landslide 1A directly upslope.

2007 SR-9 Damage Along the Flanks of Landslide 1

By mid-June 2006, SR-9 had been repaved where it crosses the two flanks of landslide 1 (figure 20A and 20C). Continued movement of landslide 1 between June 2006 and 2007 resulted in additional damage to the repaired sections of the highway (figures 20B and 20D) where it crosses the west- and east-flank shear zones. By early May 2007, a new shear crack had formed across the highway along the west-flank shear zone (figure 20B) that offset the centerline yellow striping about 3 inches (8 cm). On the north edge of the highway the shear crack splayed into several diagonal cracks to form a horsetail (figure 20B) with minor offset to the white stripe. Along the east-flank shear zone (figure 20D) a set of west-side-down scarps had formed by early May 2007. Measured horizontal offset across the westernmost scarp was 1.7 inches (4.2 cm). The damaging movement occurred despite below-normal precipitation in 2006 and early 2007.

Abandoned SR-15 Damage and Displacement

Mapping indicates that the abandoned SR-15 highway is cut and offset by 10 lateral shear zones where it crosses landslide 1 (figure 21, plate 1). Measured offsets of the yellow centerline stripes on abandoned SR-15, based on accurate mapping using a survey-grade GPS instrument, indicated between approximately 42.7 and 61 feet (13–18.6 m) of displacement of the roadway since it was abandoned in 1964. The average annual displacement rate based on these measurements is between about 12.5 and 17.9 inches per year (32–45 cm/yr); however, the rate of movement of the landslide has likely varied depending on ground-water levels (Stouffer, 1964; Doelling and Davis, 1989).

Table 2 summarizes the measured offsets across shear zones

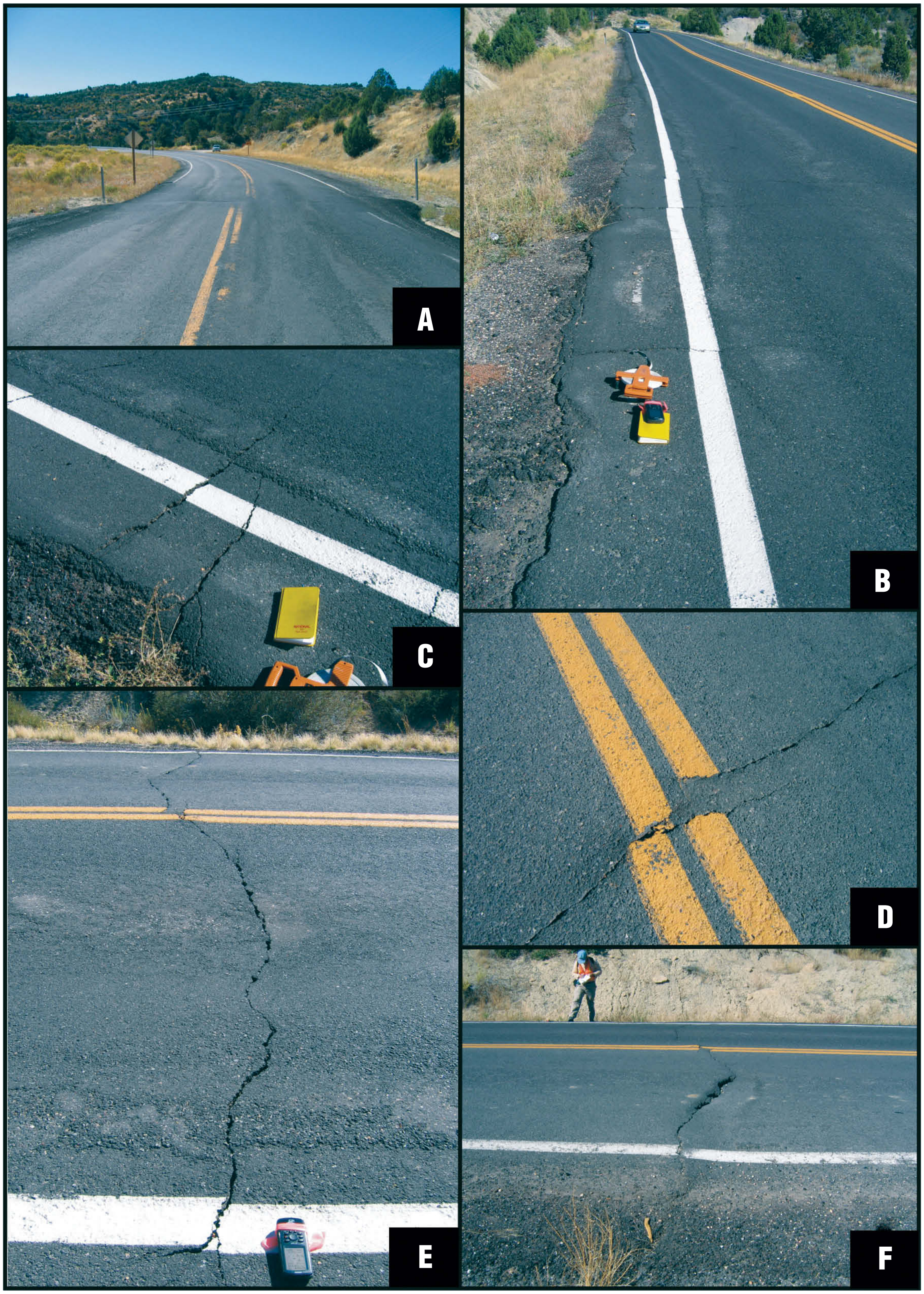

Figure 17. *Damage to SR-9 near the west-flank shear zone of landslide 1 in October 2005. (A) View to the west of right-lateral offset (see center stripe) by west-flank shear zone. Offset of northern (right) white stripe on October 4, 2005, was 1.37 feet (0.42 m). (B) View to the east of small offset of northern white stripe by cluster of lateral shears. Three of four shears are right-lateral. (C) View of cluster of lateral shears in B. Note that lateral shear to left of field book does not cut new layer of asphalt. Maximum offset of white stripe is 0.8 inch (2 cm). (D) Offset of centerline stripes by right-lateral shear that bounds eastern edge of damage zone abutting west-flank shear zone. Offset of southern white stripe along edge of road (see F) is 1.9 inches (4.8 cm). (E) View to the south of the same right-lateral shear. Note horsetail splay at lower (northern) white stripe. (F) View to the north of same lateral shear as shown in D and E. Note damage to eastbound lane.*

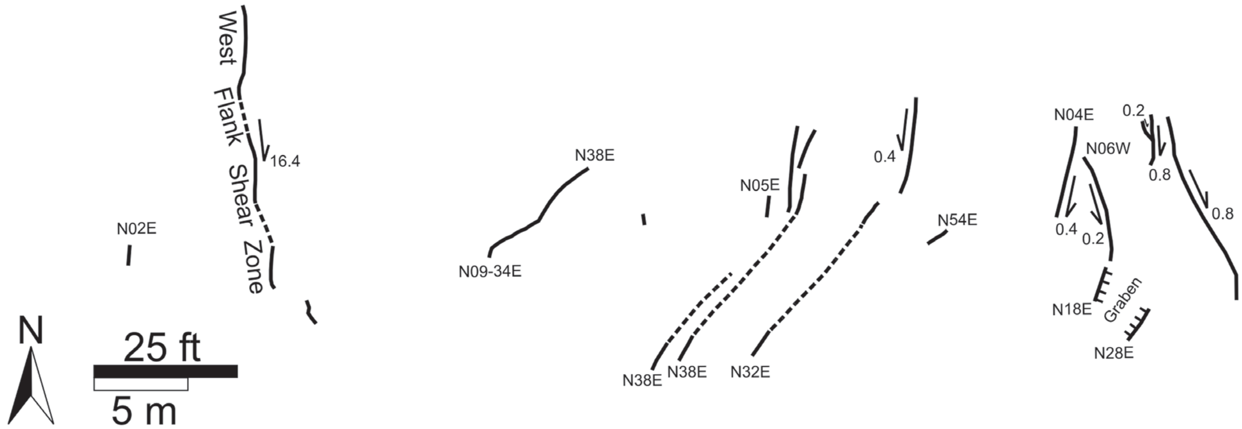

Figure 18. *Sketch map of the damage zone near the west-flank shear zone of landslide 1 in October 2005. Arrows indicate lateral shears or shear zones. Numbers indicate amount of offset (in inches) of northern white stripe along edge of SR-9. Trends of road cracks indicated (e.g., N32E). Dashes show approximate continuity of some cracks mapped separately along the north and south edges of road. Hachures indicate small scarp with vertical offset. Small graben exists in eastern part of damage zone. Northern and southern limits of cracks approximately define the edge of highway pavement. See discussion in Field Methods section for limitations of mapping.*

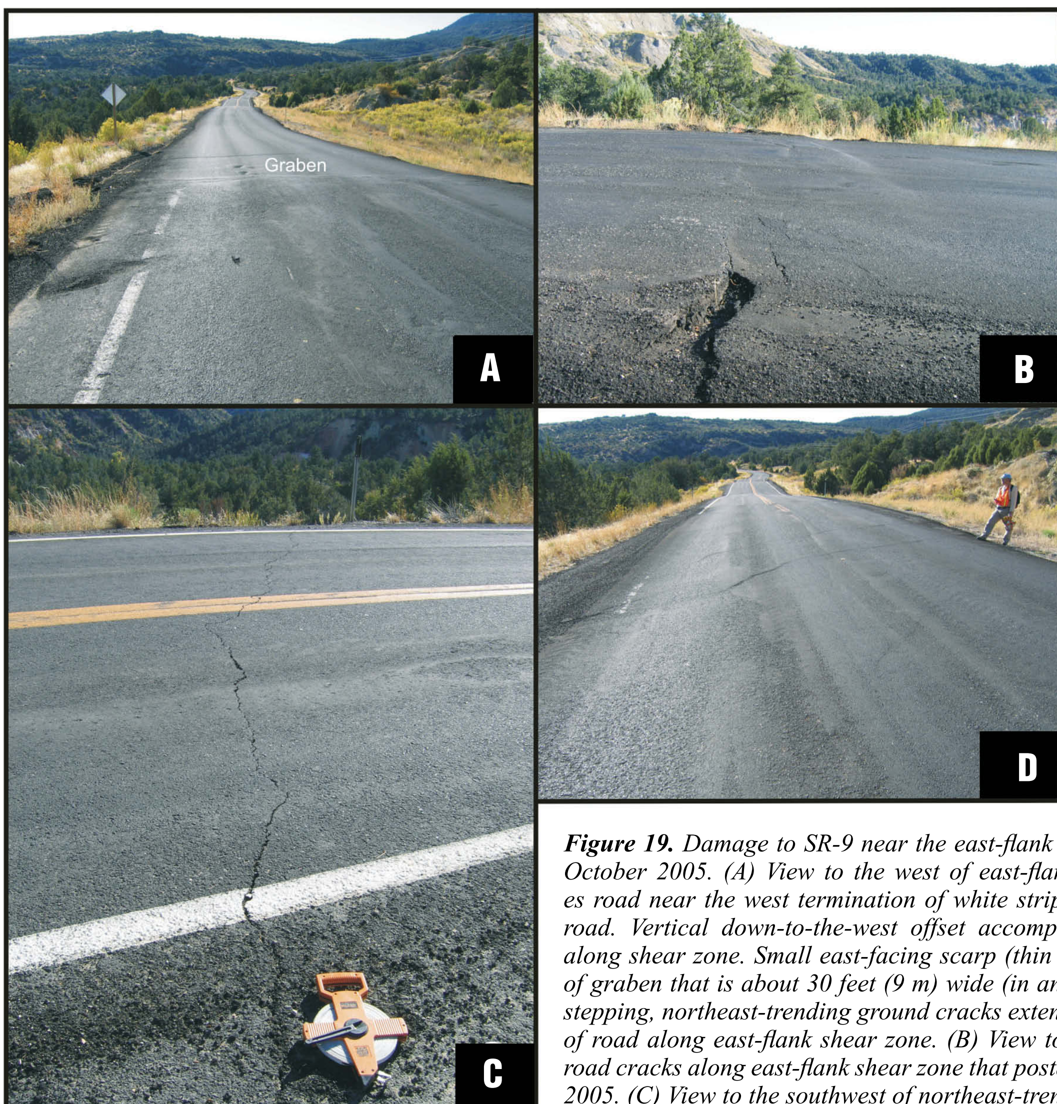

Figure 19. *Damage to SR-9 near the east-flank shear zone of landslide 1 in October 2005. (A) View to the west of east-flank shear zone, which crosses road near the west termination of white stripe along south (left) edge of road. Vertical down-to-the-west offset accompanies left-lateral movement along shear zone. Small east-facing scarp (thin dark line) defines west edge of graben that is about 30 feet (9 m) wide (in an east-west direction). Right-stepping, northeast-trending ground cracks extend north and south from edge of road along east-flank shear zone. (B) View to the south of right-stepping road cracks along east-flank shear zone that postdate repair of SR-9 earlier in 2005. (C) View to the southwest of northeast-trending right-lateral shear that bounds damage zone on the west. (D) View to the west of northwest-trending, parallel road crack and monocline in western part of damage zone. Monocline defines a broad graben that extends about 240 feet (73 m) along SR-9 and is bounded on the east by the east-flank shear zone.*

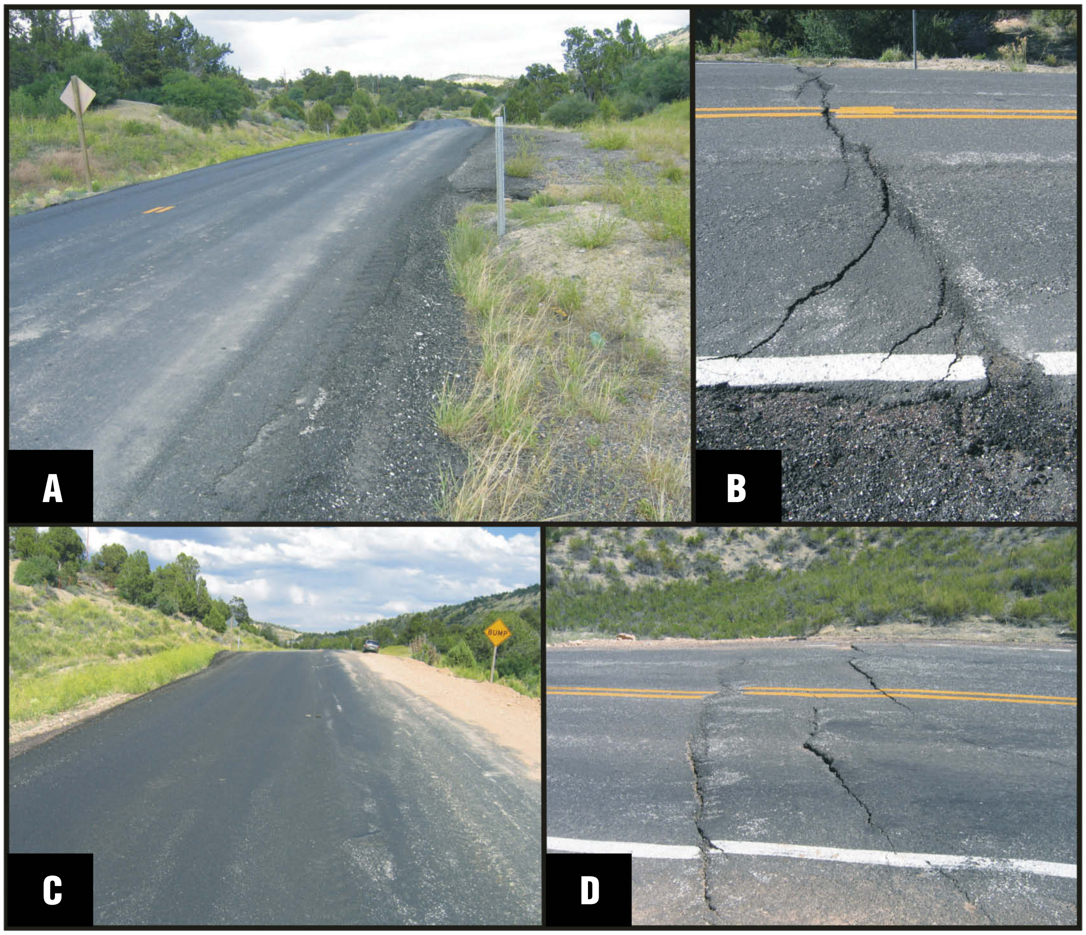

Figure 20. *Additional road damage to SR-9 by May 2007. (A) View to the east where SR-9 crosses the west-flank shear zone. Note highway surface was recently repaved. Photograph taken on June 13, 2006. (B) View to the south of damage along west-flank shear zone on May 8, 2007. Measured horizontal offset of yellow striping was about 3 inches (8 cm). (C) View to the east where SR-9 crosses the east-flank shear zone. Note highway surface was recently repaved. Photograph taken on June 13, 2006. (D) View to the north of damage along east-flank shear zone on May 8, 2007. Measured horizontal offset of white stripe (lower left) was about 1.7 inches (4.2 cm).*

and the total displacement of SR-15. Table 3 compares measured offset across the east- and west-flank shear zones of landslide 1 to previous measurements reported in Doelling and Davis (1989). Table 3 shows that most of the offset across the bounding shear zones occurred between 1964 and 1985.

LANDSLIDE MOVEMENT

Documented Historical Movement

Previous researchers have documented episodic movement of several of the landslides in the Coal Hill landslide complex, and provided descriptions suggesting possible continuous movement of parts of two slides. Stouffer (1964) inferred intermittent (or episodic) movement of the Coal Hill landslide and upper Burning Coal landslide based on historical accounts, review of aerial photographs, limited fieldwork, and a short period of monitoring of the toe of the Coal Hill slide that showed no movement between September 1962 and April 1963. Stouffer's (1964) use of the term "creep" to describe movement of the lower parts of the Burning Coal and Meadow Creek landslides suggests very slow, continuous movement. This inference is supported by reports by SRC staff (Stouffer, 1964) of a few inches of creeping movement per year in the Meadow Creek landslide where crossed by former SR-15. One shortcoming in Stouffer's (1964) assessment of the nature of movement of the Coal Hill landslide is his reliance on reports of "no significant movement," which do not preclude very slow, continuous movement. A review of aerial photographs dated 1960 and 1967, a time period spanning Stouffer's fieldwork in 1962–63, shows movement of landslide 1 and the Coal Hill and Burning Coal landslides, sometime during those seven years. Doelling and Davis (1989) also documented movement of landslide 1 between 1983 and 1986, but did not specifically describe the nature of the movement. A photograph in Heppler (2004) shows recent road repair near the east-flank shear zone of landslide 1 in 2004, suggesting at least minor recent movement during the dry period prior to the 2005 wet year. Thus, seasonal movement (coincident with or

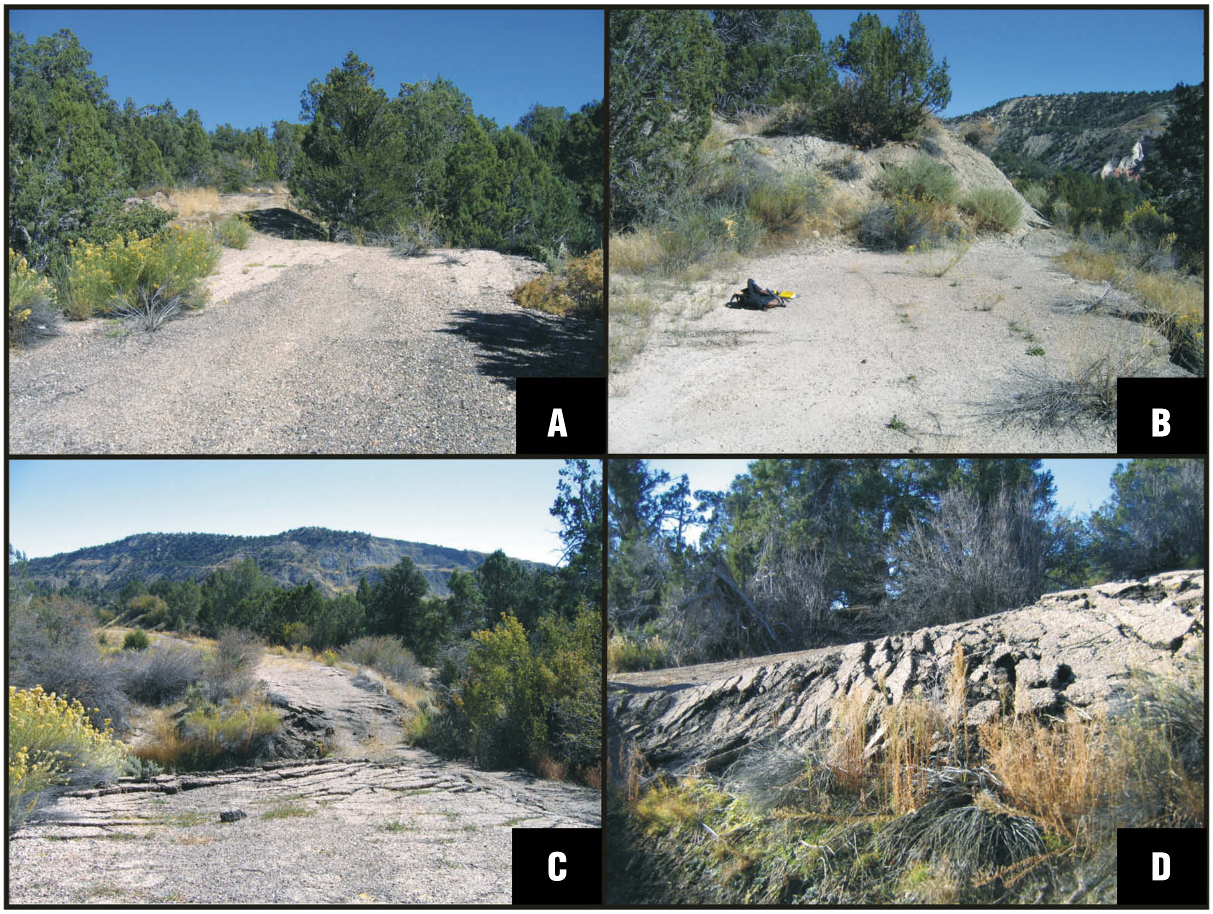

Figure 21. *Offset and road damage to abandoned SR-15. (A) View to the east of left-lateral offset along the east-flank shear zone. (B) View to the east of right-lateral offset along a major internal lateral shear. (C) View to the east-southeast of road damage and right-lateral offset along the west-flank shear zone. (D) Detail of pavement damage at west-flank shear zone.*

Table 2. *Summary of cumulative offsets along shear zones and cumulative SR-15 displacement.*

Station[1]	Offset[2] (feet)	Description
1 to 5	**61[3]**	**Right-lateral shear zones**
1	18	West-flank shear zone
2	2.5	Internal shear zone
3	1	Internal shear zone
4	28	Major internal shear zone that completely offsets abandoned highway
5	12	Internal shear zone
8	2	Internal shear zone
6 to 10	**42.5 to 44.5[3]**	**Left-lateral shear zones**
6	2.5	Internal shear zone
7	4.0	Internal shear zone
9	9.5	Internal shear zone
10	28.5	East-flank shear zone

[1]Station numbers are sequential from west to east across landslide 1. Right-lateral shear zone at station 8 is within area of left-lateral shear zones. See plate 1 for shear-zone locations.

[2]Measured using survey-grade GPS instrument.

[3]Cumulative displacement of SR-15 across zone.

Table 3. *Comparison of cumulative offset of SR-15 in 1985 and 2005.*

Feature[1]	1985 Offset[2] (feet)	2005 Offset[3] (feet)	Difference (feet)	Percent of offset post-1985	Annual Rate of Movement (1964–1985) (in/yr)	Annual Rate of Movement (1985–2005) (in/yr)
EFSZ	20	28.5	8.5	30	11.4	5.1
WFSZ	16	18	2	11	9.1	1.2

[1]EFSZ, east-flank shear zone; WFSZ, west-flank shear zone.
[2]Our measurements and photographic evidence suggest that the reported 1985 offset measurements in Doelling and Davis (1989) for the EFSZ and WFSZ, 16 and 20 feet, respectively, were reversed.
[3]Measured using survey-grade GPS instrument.

immediately following each year's snowmelt) may have been occurring even in the dry years of the early 2000s.

Landslide Movement Monitoring

We performed landslide movement monitoring between October 2005 and June 2007 using a survey-grade Global Positioning System (GPS) instrument (figure 22). The initial surveying was conducted in October 2005, with subsequent measurements taken in November 2005, June 2006, and June 2007. Additional survey points were installed in the upper part of the Meadow Creek landslide in November 2005. At those points, only three measurements (an initial and two subsequent measurements) were made. Appendix A provides additional information on our landslide movement monitoring method.

The primary objective of the landslide movement monitoring was to assess the state of activity of landslides crossed by SR-9 (the southern Meadow Creek landslide and landslide 1). Therefore, many of the survey points were installed along the SR-9 corridor. A second objective was to assess the state of activity of the entire Meadow Creek landslide, in part to evaluate the feasibility of an alternate highway route around landslide 1. In addition, we monitored movement of two other mapped historical slides (landslides 2 and 6) in the Meadow Creek landslide; these landslides were selected primarily based on easy access along graded roads. Movement of landslides 3, 4, and 5 was not monitored due to access difficulty and safety concerns for the survey crew related to slope steepness and intense ground deformation.

Summary of Landslide Movement Monitoring Results

The monitoring results indicate movement of the southern part of the Meadow Creek landslide crossed by SR-9 (figure 23). During the measurement period, the largest movement occurred within the boundaries of landslide 1, where we measured a maximum horizontal displacement of about 39 inches (99 cm). Outside of the mapped boundaries of landslide 1, movement along the SR-9 corridor ranged from 2 to 7 inches (5-18 cm). Stouffer (1964) mapped this active part of the slide, including part of landslide 1, as the "creep zone" and reported minor displacement, typically a few inches per year, of former SR-15. We detected no movement along the eastern and western edges of the Meadow Creek landslide, upslope of the intersection of SR-9 and Meadow Creek and along Coal Mine Road north of landslide 2, respectively. However, we measured minor movement, about 4 inches (9 cm), directly upslope of the mapped boundaries of landslide 1 in the upper part of the Meadow Creek slide, suggesting the possibility of incipient upslope enlargement of landslide 1. The western boundary of the upslope active area appears to be the unnamed, ephemeral, south-flowing drainage that transects the western part of the Meadow Creek landslide and landslide 1. No movement was detected elsewhere in the upper part of the Meadow Creek landslide, including in the main half-graben (figure 4). We measured minor movement of landslide 2 (about 2 inches [5 cm]), but landslide 6 was inactive during the measurement period.

State of Activity of the Entire Meadow Creek Landslide

Our movement monitoring results for the area upslope of SR-9 (figure 23) through June 2007 (a measurement period spanning less than 20 months) do not suggest movement of the entire Meadow Creek landslide; however, such movement cannot be completely ruled out. Movement in the apparently inactive part of the landslide may be occurring at rates too slow to detect over the relatively short measurement interval. If the average movement rate in the upper part of the Meadow Creek landslide was less than 0.6 inch per year (<1.6 cm/yr) then the total maximum movement during the 20-month measurement period would have been about 1 inch (2.5 cm) and near the detection threshold of the movement monitoring technique.

Assuming the possibility of undetected movement of the entire landslide, the variation in the rate of movement in the slide may be due to differences in the slope of both the ground surface and the underlying surface of rupture (sliding). Most of the survey points where movement was not detected are

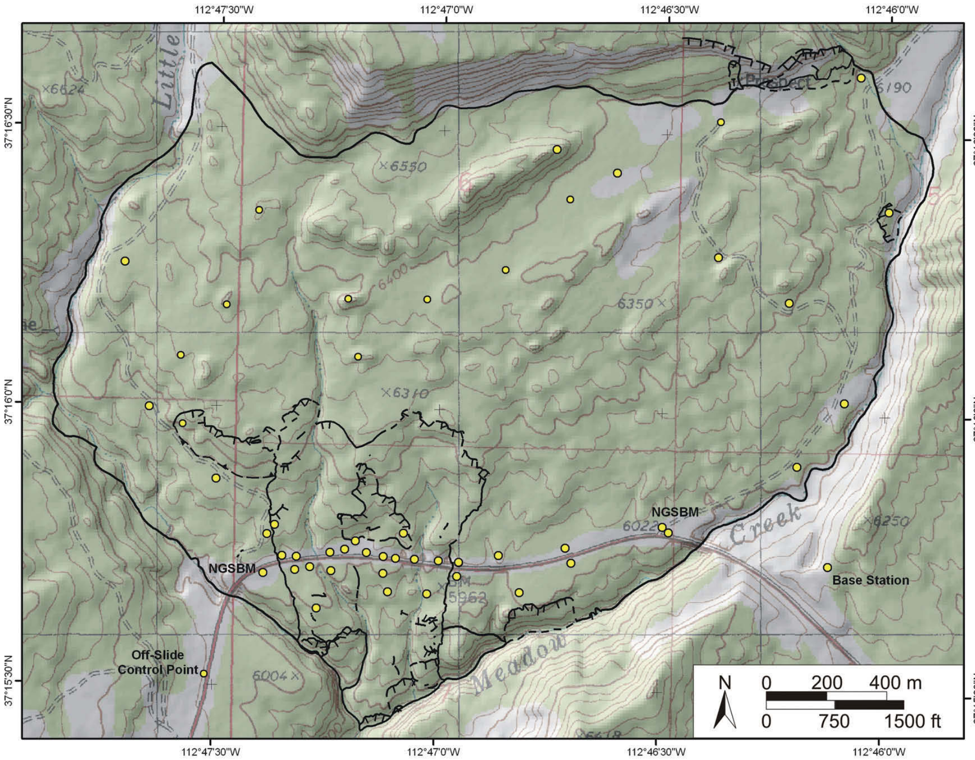

Figure 22. *Location of GPS survey points used for landslide-movement monitoring. Boundaries of landslide 1 and other slides shown for reference (see plate 1 for further details). Locations of base station, off-slide control point, and two National Geodetic Survey benchmarks (NGSBM) shown. Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.*

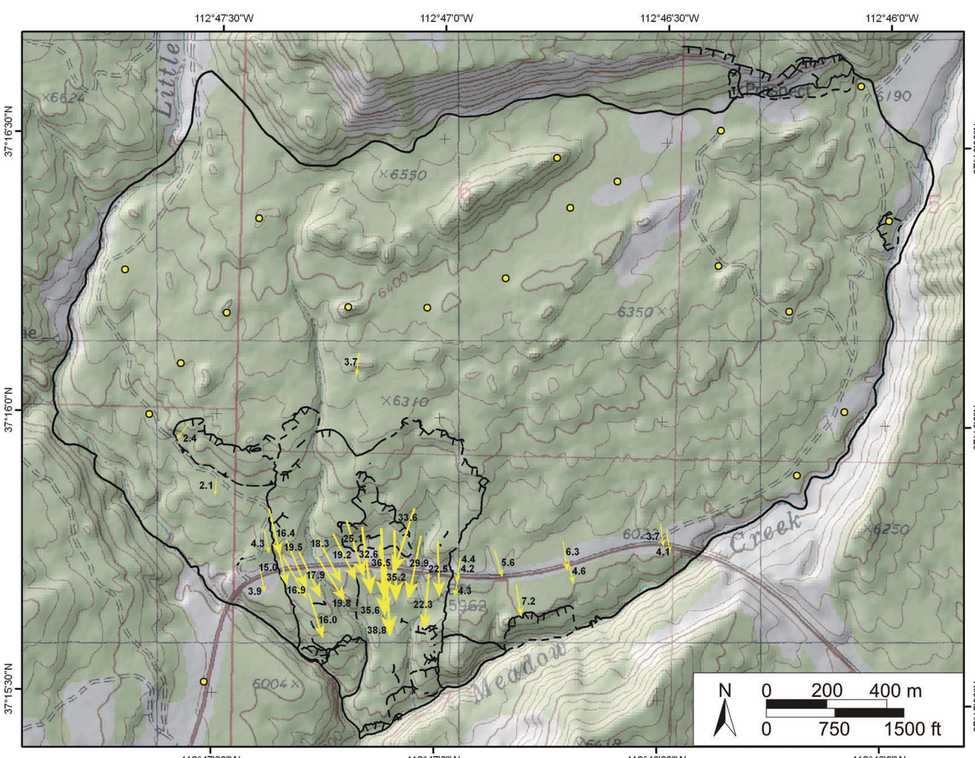

Figure 23. *GPS-measured movement in southern and west-central parts of the Meadow Creek landslide between fall 2005 and June 2007. Movement amounts (inches) and directions shown by yellow arrows. Yellow dots indicate survey points where no movement was detected. Boundaries of landslide 1 and other slides shown for reference (see plate 1 for further details). Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.*

in the northern part of the landslide where the average slope ranges between 9 and 13 percent, flatter than the average slope of landslide 1 and the abutting southern part of the Meadow Creek slide. Where movement was detected in the southern part of the landslide, but outside the limits of landslide 1, the average slope exceeds 11 percent, and generally ranges between 13 and 16 percent. This active area also includes the moderate to steep bluff along Meadow Creek that generally exceeds 25 percent slope.

If movement is occurring only in the southern part of the Meadow Creek landslide, then a small, recently active scarp at an approximate elevation of 6240 feet to the east of landslide 1 may define the upper limit of the active part of the slide. West of landslide 1, the main scarp of landslide 2 is at about the same elevation (6260 feet). Thus, the main scarp of landslide 2 may define the upslope boundaries of both the historical slide and the active part of the westernmost Meadow Creek landslide. Our upper limit of active landsliding in the Meadow Creek slide closely coincides with the queried upper contact of the "creep zone" defined by Stouffer (1964).

Movement of Landslide 1

During the measurement period, the largest and most damaging movement occurred in landslide 1. The maximum total movement of landslide 1 was approximately five times greater than the maximum total movement in the southern part of the Meadow Creek landslide. However, the relative changes in the rate of movement over the measurement period were generally similar in both landslides.

Total Movement Between October 2005 and June 2007

The total movement of landslide 1 between October 2005 and June

2007 ranged from 16 to about 39 inches (41–99 cm), varying incrementally across the width of the slide (figure 24) with the largest movement in the east-central part. The total movement decreases toward the flanks of the landslide resulting in a generally bow-shaped pattern of movement across the width of the slide (figure 25). Figures 24 and 25 also show that the largest movement was in the area directly downslope of landslide 1A between the major internal right-lateral shear zone and the east-flank shear zone. The movement vectors of points in the western part of landslide 1 converge slightly with those in the central and eastern part. The major internal right-lateral shear zone (plate 1) appears to be the boundary between these two movement areas. West of the internal right-lateral shear the movement amounts are more uniform, decreasing slightly toward the west-flank shear zone. Movement amounts appear to be relatively uniform upslope and downslope of SR-9 within the slide, but the maximum distance between survey points bracketing the highway corridor that includes SR-9 and abandoned SR-15 is only about 1000 feet (300 m). Thus, the apparent relatively uniform movement along the length of the landslide may be due to the short distances between survey points that span, at a maximum, less than a third of the total length of the slide.

Implications of Fall 2005 Movement

Movement of landslide 1 was detected in the fall of 2005, between early October (October 5 through 7) and mid-November (November 17 and 18) 2005 (figure 26). Movement was also detected during this period in the southern part of the Meadow Creek landslide to a lesser degree of certainty where most movement amounts were below our inferred resolution. The data suggest that the southern part of the Meadow Creek landslide complex, including landslide 1, had remained

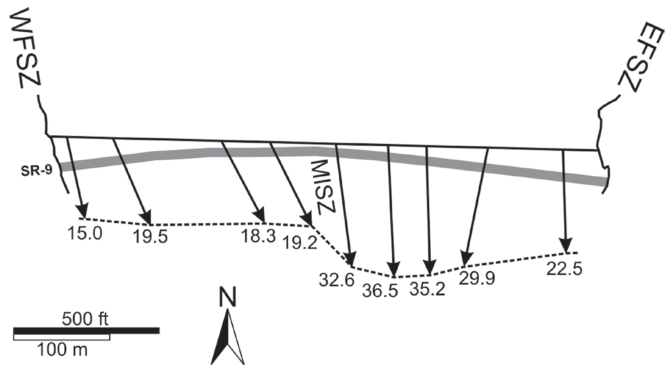

Figure 25. *Variation in displacement across landslide 1. Figure shows the horizontal displacement (inches) of a hypothetical straight line across the slide during the measurement period (October 2005 to June 2007). Displacement has a generally bow-shaped pattern (in plan view) increasing toward the right center of the slide from both flanks. A significant step in displacement occurs across the main internal shear zone (MISZ). Parts of east- and west-flank shear zones (EFSZ, WFSZ) and SR-9 shown.*

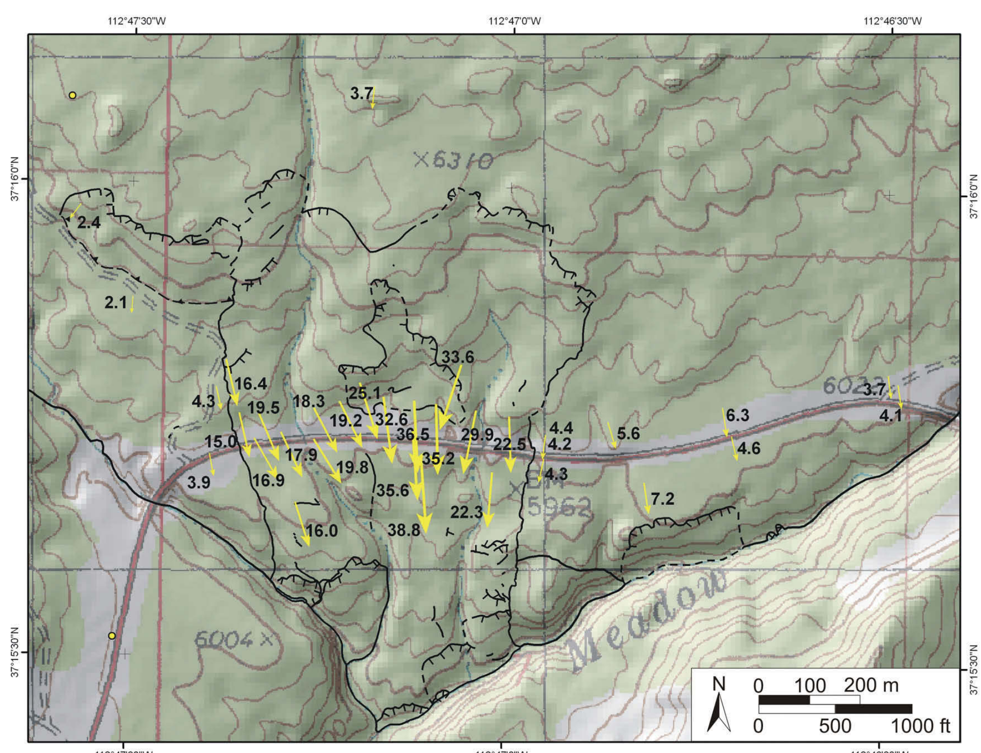

Figure 24. *Movement in and near landslide 1 between fall 2005 and June 2007. Movement amounts (inches) and directions shown by yellow arrows. Boundaries of landslide 1 and other slides shown for reference (see plate 1 for further details). Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.*

active throughout most of 2005. Movement amounts for this six-week period ranged from about 1.6 inches (4 cm) near the west flank to 4.5 inches (11 cm) in the central part of landslide 1, the maximum amount corresponding to an average rate of movement of about 38 inches per year (97 cm/yr). Movement amounts near the east-flank shear zone ranged between about 2.2 and 2.5 inches (5.6–6.4 cm). The data shown on figure 27 suggest that movement likely continued through the early part of 2006.

The movement of landslide 1 at a very slow rate in the fall of 2005 occurred during a period in which seasonally low ground-water levels typically exist and movement has generally suspended in most monitored northern Utah landslides (Ashland, 2003, 2007). Ongoing movement in late 2005 suggests ground-water levels in the landslide were high enough to sustain movement. Field observations suggest most, if not all, of the mapped landslides in the Coal Hill landslide complex reactivated in 2005, including the original Coal Hill and Burning Coal landslides of Stouffer (1964), indicating regionally high ground-water levels earlier in the year.

Changes in Average Movement Rates

The average movement rates of the Meadow Creek landslide and landslide 1 gradually decreased during the measurement period (figure 28), likely as a result of declining ground-water levels with a return of dry conditions following the 2005 wet year. Table 4 summarizes the average rate of movement for the two slides between October 2005 and June 2007. Consideration of the variation in the number of days in each measurement period and likely seasonal fluctuations in movement rate is recommended before direct comparison of the average movement rates in table 4. Significant variation in movement rate likely occurs in late winter/early spring, coincident with and shortly following the snowmelt and rising ground-water levels in the landslides. As ground-water levels rise during late winter/early spring the movement rate likely rapidly accelerates, and later decreases or movement suspends in the dry summer months as ground-water levels decline.

Persistent Movement of Landslides in the Complex

Our movement monitoring results and field observations, in addition to historical accounts of landslide movement (Stouffer, 1964; Doelling and Davis, 1989), indicate that most of the landslides in the Coal Hill landslide complex have at least a decades-long history of persistent movement. Stouffer (1964) described minor displacement of SR-15 in the "creep zone" portion of the Meadow Creek landslide, where our monitoring detected movement at a very slow rate between October 2005 and June 2007. Thus, movement of the southern part of the landslide has persisted, at least episodically, over the past four decades. The activity of smaller landslides along Meadow Creek, including landslide 1B, 1E, and 3, which Stouffer (1964) identified as active in the early 1960s, has also spanned over four decades. Our review of aerial photographs dating from the 1960s showed damage to SR-15 along the

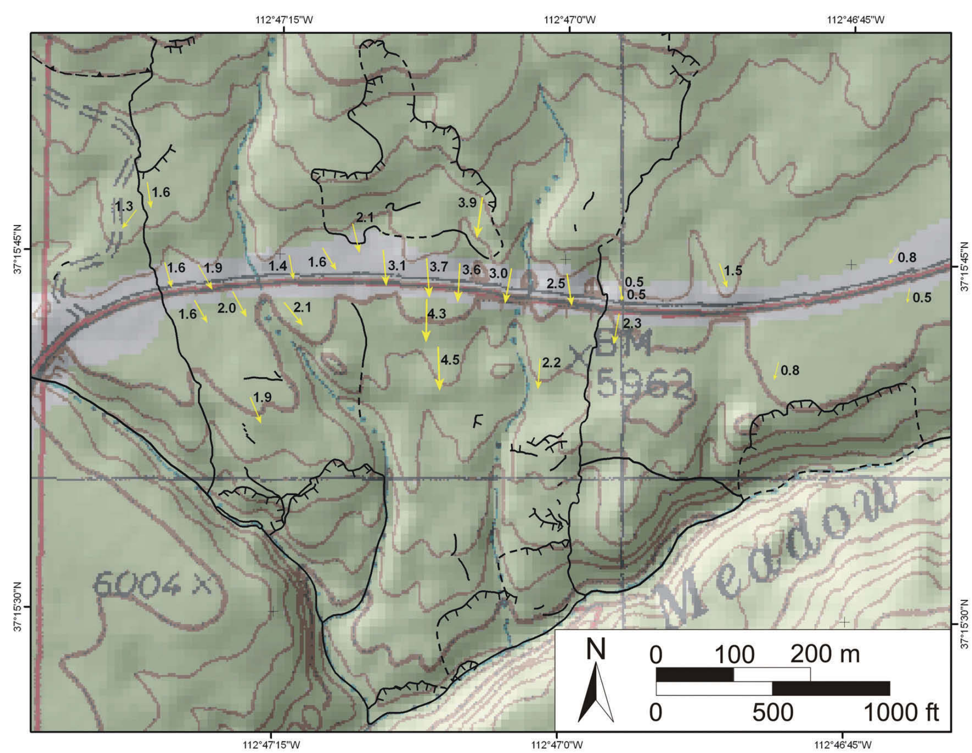

Figure 26. Movement in and near landslide 1 between early October and mid-November 2005. Movement amounts (inches) and directions shown by yellow arrows. Boundaries of landslide 1 and other slides shown for reference (see plate 1 for further details). Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.

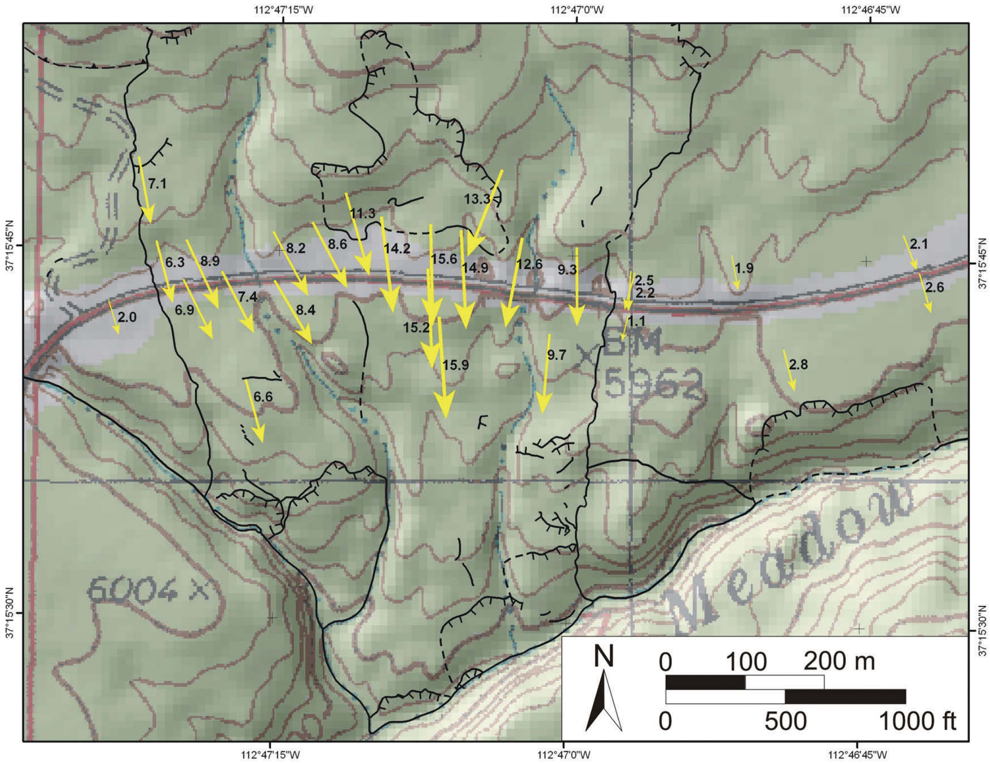

Figure 27. *Movement in and near landslide 1 between mid-November 2005 and mid-June 2006. Movement amounts (inches) and directions shown by yellow arrows. Boundaries of landslide 1 and other slides shown for reference (see plate 1 for further details). Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.*

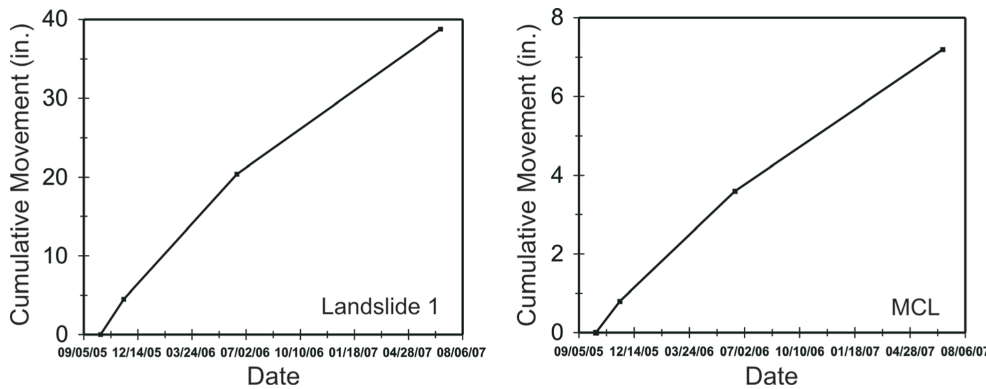

Figure 28. *Cumulative movement history of landslide 1 and southern Meadow Creek landslide (MCL) between October 2005 and June 2007. Plots are for GPS stations with maximum movement during measurement period (see figure 23). Plots show that whereas the total movement of landslide 1 was five times greater than that of the lower part of the Meadow Creek landslide (note change in vertical scale), the change in movement rates were similar. The movement rates at both slides decreased in the dry years (2006 and 2007) following the 2005 wet year.*

Table 4. *Summary of landslide movement rate and change in rate between October 2005 and June 2007.*

Measurement Period	**Landslide 1**		**Meadow Creek landslide**	
	Ave. Rate (in/yr)	Rate Change[1] (%)	Ave. Rate (in/yr)	Rate Change[1] (%)
Oct–Nov 05	38	---	6.7	---
Nov 05–Jun 06	28	74	4.8	72
Jun 06–Jun 07	18	64	3.4	71
Oct 05–Jun 06	30	---	5.1	---
Jun 06–Jun 07	18	60	3.4	67

[1]Ratio of average rate and previous average rate.

flanks of landslide 1. This, in addition to the similar damage in the early 1980s (Doelling and Davis, 1989) and the movement and resulting damage between 2005 and 2007 documented in this study, identifies landslide 1 as being persistently active for over four decades. Reconnaissance in May 2007 of the Burning Coal landslide, a landslide that may have originated in the past 70 years (post-1938; Stouffer, 1964), also showed evidence for recent activity. In contrast, landslides 4 and 6 showed no evidence of movement during the period of this study, and are thus examples of currently dormant slides.

ZONATION OF RELATIVE LANDSLIDE HAZARD

We delineated zones of relative landside hazard along the SR-9 corridor and for the entire Meadow Creek landslide using both movement data and pavement distress observations. Movement data and distress observations yield different zonation results, and the implications of the differences are discussed below. Movement-based zonation is limited by the distribution and number of survey points, so the hazard boundaries using this approach are well defined only where survey points are relatively closely spaced. The boundary between the low and moderate hazard areas is based on interpolation between widely spaced survey points.

Movement-Based Zonation

Figures 29 and 30 show the landslide-hazard zonation for the SR-9 corridor and entire Meadow Creek landslide, respectively, based on measured movement between fall 2005 and June 2006. Table 5 summarizes the movement-based approach used for landslide-hazard zonation. Although based on movement amounts during a finite, arbitrary measurement period, the results using this approach are consistent with the geologic mapping and indicate landslide 1 as the highest hazard. On the basis of measured movement, we subdivided landslide 1 into two hazard areas—very high and high—the former being where the largest future displacement of SR-9 is likely. The very high zone contains the point of maximum displacement and most of the mapped lateral shears in abandoned SR-15 (table 2, plate 1). The very high zone also contains at least the southeastern part of landslide 1A, landslide 1D, and the western part of landslide 1E, all of which are areas of intense ground deformation. On figure 30, landslides 3 and 5 are also designated as high hazard, based on inferred movement amounts suggested by the similar extent and intensity of ground deformation to that in landslide 1.

Distress-Based Zonation

Landslide-hazard zonation of the SR-9 corridor based on pavement distress (figure 31) illustrates that highway damage is localized near the major lateral shear zones bounding and within landslide 1. Areas in the very high zone include the three widest areas of pavement distress adjacent to the east-flank, major internal, and west-flank shear zones, and two smaller clusters of distress in landslide 1. A high hazard characterizes the remaining area along SR-9 in landslide 1, based on the potential for lateral enlargement of the clusters of pavement distress rather than on the relative pavement distress compared to other sections of SR-9 outside of landslide 1. A moderate hazard characterizes the remainder of SR-9 where it crosses the active, but very slow-moving southern part of the Meadow Creek landslide. Pavement distress in this area consists mainly of road cracks.

Comparison of Zonation Methods

Differences in the results of the two zonation approaches reflect, in part, the long- versus short-term effects of landsliding. The results of the movement-based approach are consistent with the observed displacement of abandoned SR-15. The very high hazard category contains the most displaced part of abandoned SR-15, including several severely damaged zones (plate 1), thus the approach appears to best characterize the potential long-term effects of landsliding on SR-9. The section of SR-9 in the very high hazard zone will likely be displaced the farthest downslope in the future. The pavement-distress approach identifies areas of recent damage clustered adjacent to shear zones that generally separate areas having different movement rates. Thus, it appears to best characterize the short-term effects of landsliding on SR-9. The sections of SR-9 in the very high zone will likely continue to experience pavement distress during episodes of movement and will require repair. The easternmost area abutting the east-flank shear zone will pose the greatest challenge because vertical offset (of the highway and ground surface) accompanies deformation.

DISCUSSION

The landslide-hazard zonation maps provide guidance on predicting the short- and long-term effects of landsliding on SR-9. However, complete assessment of the feasibility of possible mitigation or management options requires additional information and ultimately cost-benefit analyses. The dimensions and probable depth of landslide 1 and the width of the adjacent active parts of the Meadow Creek landslide suggest landslide stabilization would be costly and technically challenging. Uncertainty regarding the state of activity of the entire Meadow Creek landslide must also be resolved. Figure 30 provides a preliminary basis for assessing an alternate highway route around and upslope of landslide 1 that may reduce the frequency and magnitude of future repairs. However, the potential for further upslope expansion of landslide 1 needs to be assessed, as do conditions in the western part of the Meadow Creek landslide where an alternate route would need to traverse to reconnect to the existing highway alignment west of Little Meadow Creek. The state of activity of the parts of the Meadow Creek landslide where a possible alternate high-

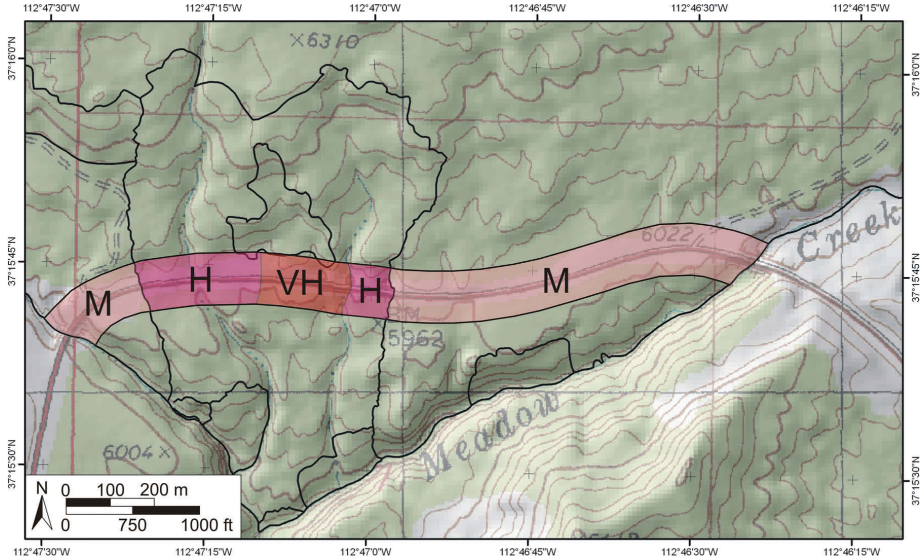

Figure 29. *Movement-based zonation map of the SR-9 corridor. VH – very high, H – high, and M – moderate. See table 5 for additional explanation of hazard categories. Boundaries of landslide 1 and other slides shown for reference (see plate 1 for further details). Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.*

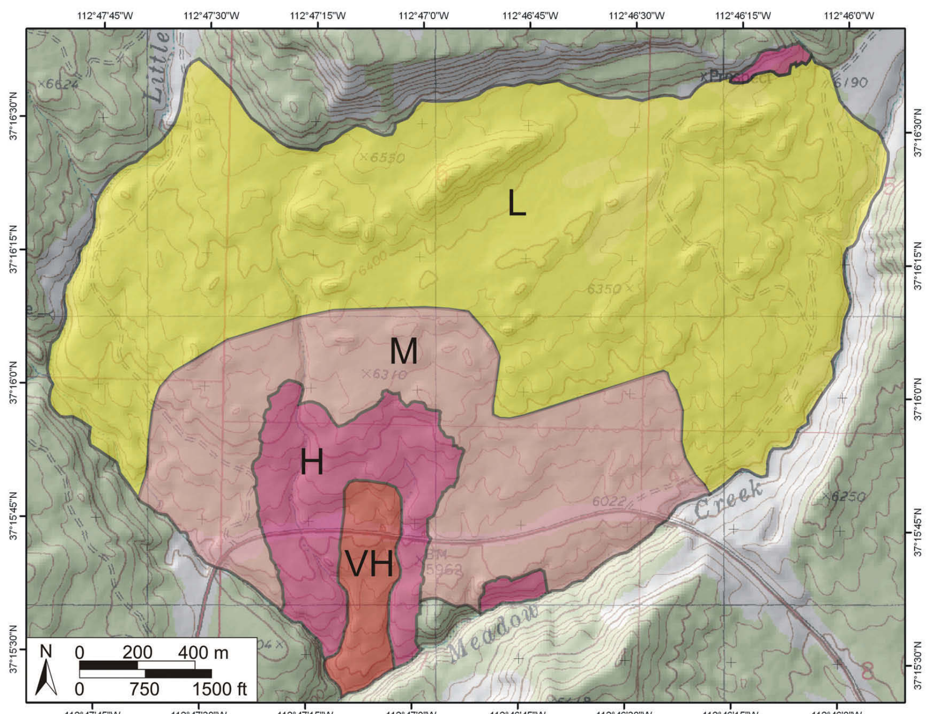

Figure 30. *Movement-based zonation map of the Meadow Creek landslide. VH – very high, H – high, M – moderate, and L – low. See table 5 for additional explanation of hazard categories. Hazard-category boundaries based on movement measurements, mapped landslide boundaries, location of internal deformation features, and other field observations. Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.*

Table 5. *Summary of movement-based landslide-hazard-zonation approach.*

Hazard Category[1]	Measured Movement[2] (Inches)	Possible Implications
Very High (VH)	>16	Maximum displacement of highway
High (H)	8–16	Locally concentrated road distress
Moderate (M)	<8	Some road cracking
Low (L)	Not detected	Inactive or very slow – no distress

[1]Hazard zones shown on figures 29 and 30.

[2]Measured movement for period between fall 2005 and June 2006 used as basis for defining hazard categories.

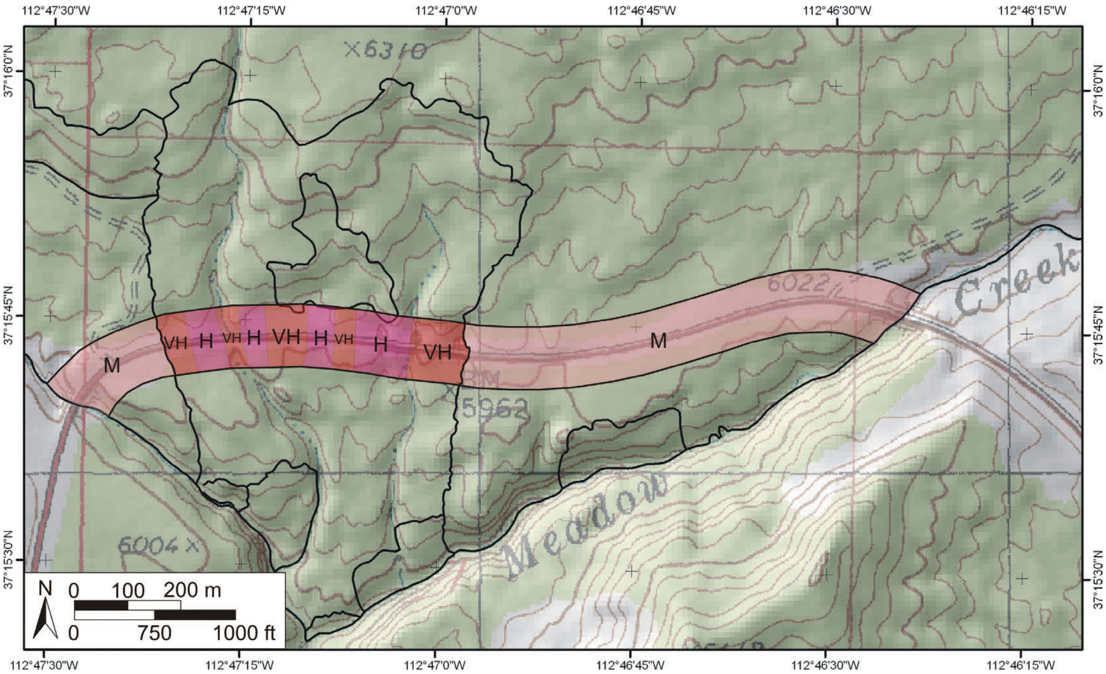

Figure 31. Distress-based zonation map of the SR-9 corridor. VH – very high, H – high, and M – moderate. See text for discussion of hazard categories. Boundaries of landslide 1 and other slides shown for reference (see plate 1 for further details). Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter DEM.

way route may bypass landslide 1 is being further investigated by continued movement monitoring.

Whereas a cost-benefit analysis of any mitigation option, including an expensive alternate route around landslide 1, may reveal continued highway maintenance as the most cost-effective management approach, future movement behavior may necessitate landslide mitigation. To date, the most movement in a single year has only been "several feet" (Doelling and Davis, 1989); however, future, large-displacement movement of landslide 1 cannot be ruled out. Such large-displacement movement of large, clay-rich landslides has occurred elsewhere in central and northern Utah (Fleming and others, 1978; Duncan and others, 1986; Ashland, 2003). In southern Utah, earthquake-induced historical landsliding has resulted in moderate movement (tens of feet), which initiated in a matter of minutes, and that caused intense ground deformation (Jibson and Harp, 1996). The encroachment of landslide 1A onto the highway may result from future large-displacement movement. Whereas the absence of large-displacement movement during the nearly 80-year record of the two highways (SR-9 and SR-15) may suggest a low probability for such movement, other case histories indicate otherwise. In 1997, the reactivation of the Shurtz Lake landslide resulted in tens of feet of displacement of power-line transmission poles that had not moved, at least significantly, in the previous 70 years (Ashland, 2003).

CONCLUSIONS

The results of field investigations and movement monitoring using a survey-grade GPS instrument reveal active landsliding where SR-9 crosses the southern part of the Meadow Creek landslide. Between October 2005 and June 2007, the maximum total movement was about 39 inches in landslide 1 and about 7 inches in the adjacent southern part of the Meadow Creek landslide. Movement of landslide 1 in the fall of 2005 suggests high ground-water levels during and following the 2005 wet year. Movement continued in 2006 and 2007 despite a return to dry conditions, but average movement rates decreased.

The most severe damage to SR-9 occurred in the 1880-foot-long (570 m) section of SR-9 that crosses landslide 1. Damage to the SR-9 pavement in 2005 was concentrated along lateral shear zones that both bound and are internal to landslide 1. In 2005, a combined 505 linear feet (154 m) of highway was damaged adjacent to the east- and west-flank shear zones that bound landslide 1. Most of the other landslide-related damage generally occurred upslope of a cluster of internal lateral shears that offset abandoned SR-15 in the area of greatest displacement of landslide 1.

Distress- and movement-based relative landslide hazard zonation maps for the SR-9 highway corridor and the Meadow Creek landslide provide important information for prioritizing and assessing the feasibility of mitigation options and predicting future damage. Differences in the results of the two zonation approaches reflect, in part, the short- versus long-term effects of landsliding.

The dimensions, probable depth, and geologic and hydrologic characteristics of landslide 1 suggest stabilization may be both costly and technically challenging. An alternate highway route around landslide 1 may reduce maintenance costs and is technically feasible, but expensive. The potential for upslope expansion of landslide 1 or future movement of the entire Meadow Creek landslide affecting such an alternate route requires further investigation and are the primary objectives of our continued movement monitoring.

Our study demonstrated the feasibility of using SASW testing to identify low-velocity, basal clay gouge at moderate depth (less than 50 feet [15 m]) in the surface-of-rupture zone of a landslide. SASW testing detected a velocity inversion between depths of 28 and 48 feet (9–14 m) that bracketed the depth of the basal surface-of-rupture zone of the Meadow Creek landslide identified in a nearby borehole and on a seismic refraction line at depths of 38 and 42 feet (12 and 13 m), respectively. In landslide 1, where the basal surface-of-rupture zone appears to be at greater depth, a velocity inversion that corresponded with the basal surface of rupture zone was not detected by the SASW method. The preliminary results suggest SASW testing may provide a relatively low-cost means of estimating the depth of landslides that are shallower than 50 feet (15 m).

ACKNOWLEDGMENTS

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APPENDIX

FIELD METHODS

Geologic fieldwork was conducted in the fall of 2005, from October 4 to 7 and November 16 to 18. We mapped landslide boundaries and ground deformation features using a recreation-grade Global Positioning System (GPS) instrument with an approximate horizontal accuracy range of between 10 and 30 feet (3–9 m) at the time of the fieldwork. Maps of the 2005 landslides and dimensions listed in this report were derived using this method. Duplicate measurements from the same instrument indicated that short-term variation in horizontal position was typically less than 2 to 3 feet (0.6–0.9 m). Duplicate measurements on separate dates yielded differences in horizontal position of about 8 feet (2.4 m). Based on the minimum measurement in table 1 (110 feet [34 m]), the estimated maximum error of dimensions described in this report is about 7 percent.

We measured landslide movement using a survey-grade GPS instrument with an approximate accuracy of about 0.75 in (2 cm). We initially installed most of the survey points along SR-9 in October 2005 and added additional points, including some in the upper part of the Meadow Creek landslide, in November. Survey points were installed using varying lengths of rebar and a plastic survey cap. At two locations, we installed two lengths of rebar (2-feet and 3-feet [0.6 and 0.9 m]) to monitor possible depth-related influence on movement amounts and noted no significant difference in the measured movement amount. Survey points were installed in locally flat areas to reduce the potential for shallow local movement of the survey points. We also reoccupied two permanent, deeply founded National Geodetic Survey (vertical control point) benchmarks on the landslide for comparison purposes with nearby movement monitoring results. In addition, we established a separate control point off and to the west of the landslide. In November 2005, the survey points installed in October were remeasured and additional survey points installed (all points shown on figure 22). Additional GPS survey measurements were taken in June 2006 and 2007.

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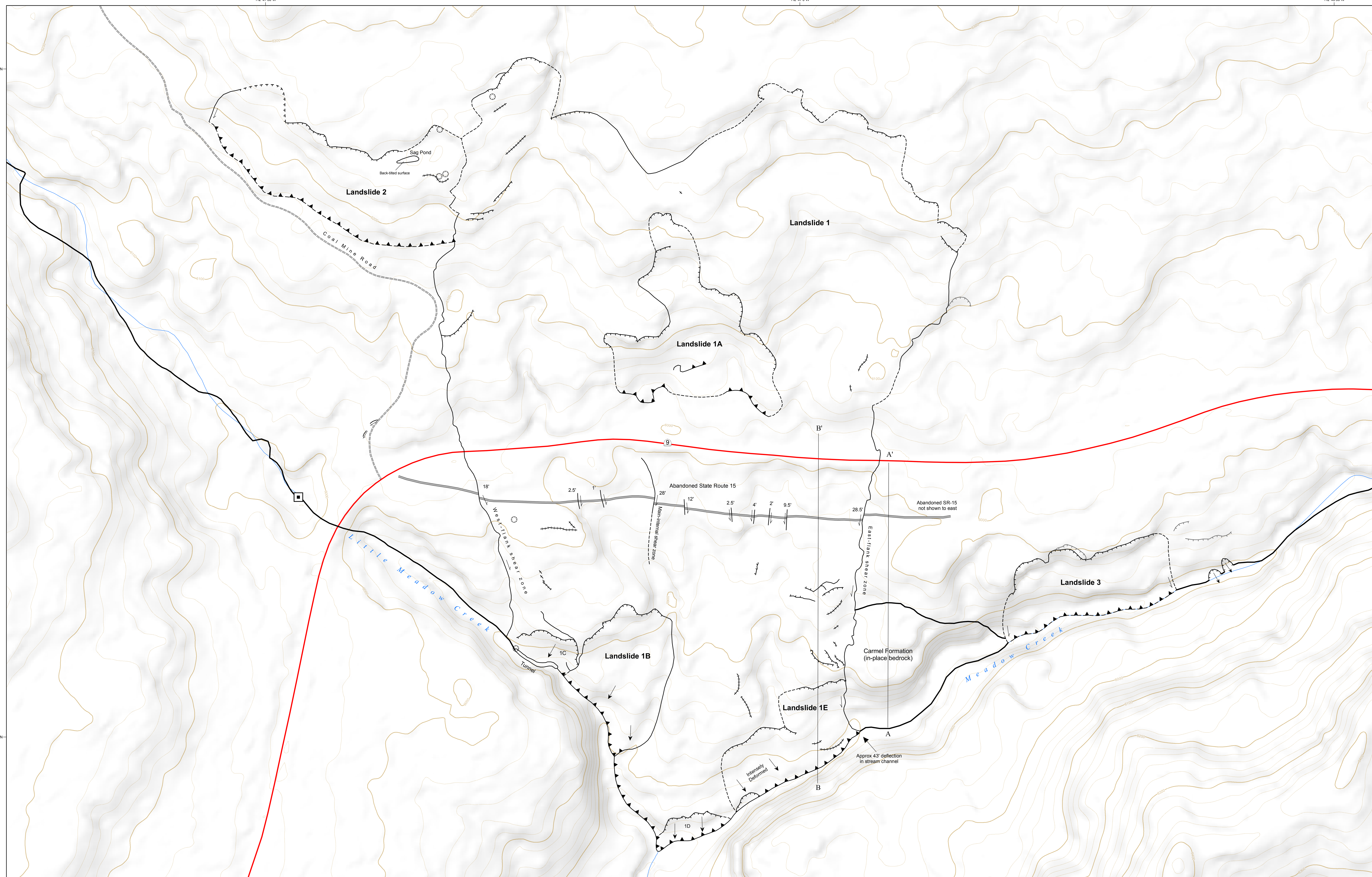

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- Toe thrust; dashed where approximate
- Scarp, dashed where approximate; hachures on downdropped side
- Inactive scarp
- 12' Lateral shear and amount of offset in feet
- Damaged SR-15 culvert
- 1A Numbered landslides active in 2005; see text for more information
- Other boundary; dashed where approximate
- Approximate landslide movement direction
- Perimeter of Meadow Creek landslide (Hylland, 2000; this study)
- A — A' Line of cross section; see figure 16
- Ground crack
- Sinkhole

SCALE 1:2,400
500 250 0 500 Feet
100 50 0 100 Meters
CONTOUR INTERVAL 20 FEET

DETAILED MAP OF THE SOUTHWESTERN PART OF THE MEADOW CREEK LANDSLIDE, COAL HILL LANDSLIDE COMPLEX

by

Francis X. Ashland, Greg N. McDonald, Lucas M. Shaw, and James A. Bay

2009

UTAH
MAP LOCATION

12°01'
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2009

Hillshade and contours from 5m auto-correlated data
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1886

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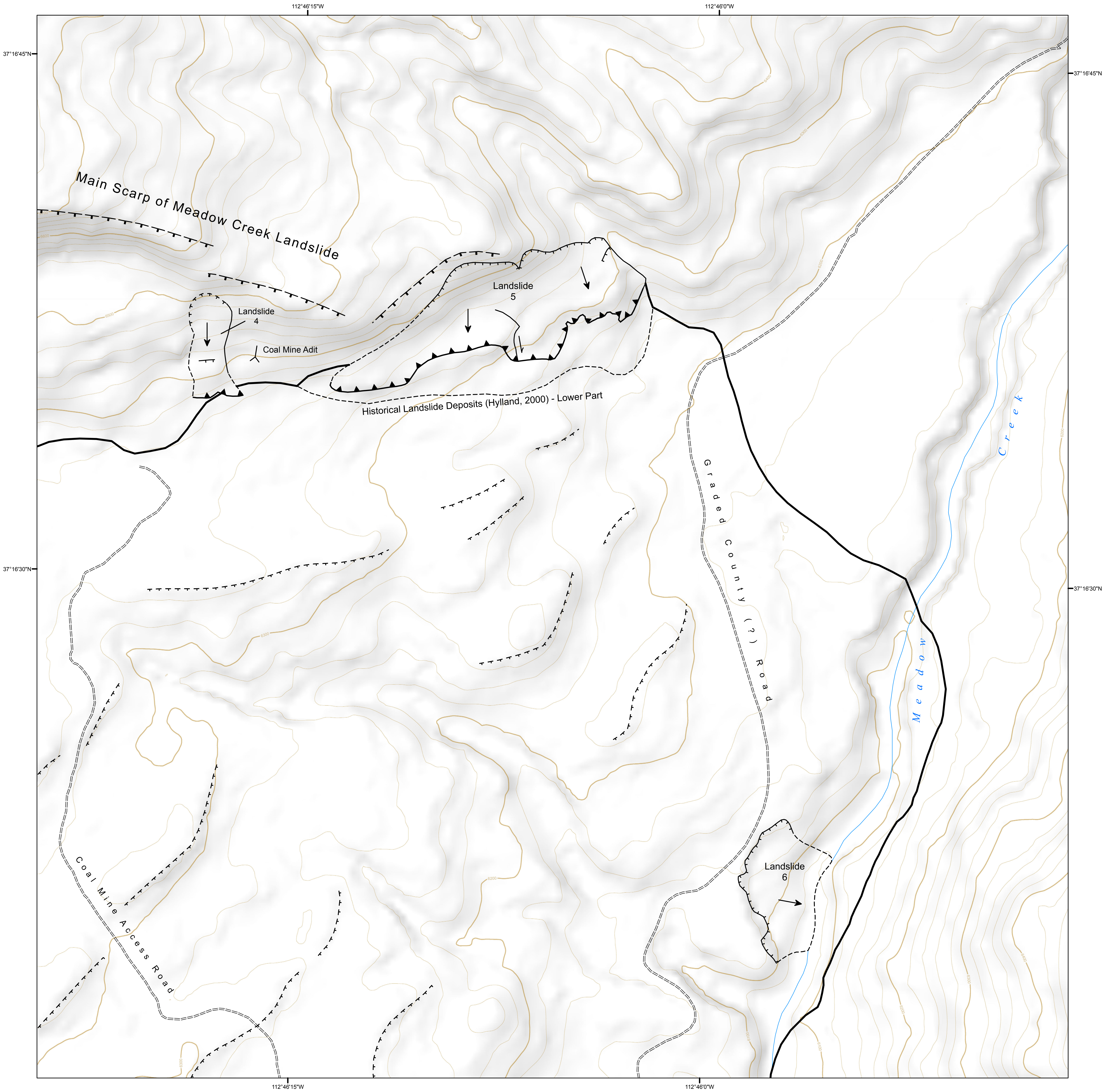
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

Plate 2
Utah Geological Survey Special Study 131
Characterization and Hazard Zonation of the Meadow Creek Landslide Affecting State Route 9, Kane County, Utah



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UTAH
MAP LOCATION

SCALE 1:2,400
500 250 0 500 Feet
100 0 100 Meters
CONTOUR INTERVAL 20 FEET

12°02'
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2009

Hillshade and contours from 5m auto-correlated data
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1866

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DETAILED MAP OF THE NORTHEASTERN PART OF MEADOW CREEK LANDSLIDE, COAL HILL LANDSLIDE COMPLEX

by

by Francis X. Ashland, Greg N. McDonald, Lucas M. Shaw, and James A. Bay

2009

Other boundary; dashed where approximate
Perimeter of Meadow Creek landslide (Hylland, 2000)
Toe thrust
Approximate main scarp of landslide
Scarp, dashed where approximate, hachures on downdropped side
Approximate minor scarp bounding ridges (typically near base of slope)
Approximate landslide movement direction
Lateral shear