LANDSLIDE INVENTORY AND SUSCEPTIBILITY FOR DOUGLAS COUNTY, COLORADO

Kassandra Lindsey
Colorado Geological Survey – Colorado School of Mines
Golden, CO
2018

Highlands Ranch area, CO

COLORADOGEOLOGICALSURVEY
COLORADO SCHOOL OF MINES

OF 18-07

ACKNOWLEDGEMENTS

A special thanks is due to the following individuals for their contributions to the mapping efforts: Ralph Shroba (USGS Emeritus) for reviewing the map and text, Matt Morgan and Karen Berry with Colorado Geological Survey (CGS) for internally reviewing the materials associated with the publication, Larry Scott with CGS for assembling the map plate, and Kevin McCoy and F. Scot Fitzgerald with CGS, and Erinn Johnson, formerly with CGS, for their help conducting field work and development of landslide data.

INTRODUCTION

The CGS aims to provide geologic hazard susceptibility maps to state and local governments for use in their planning processes and hazard mitigation plans. The Landslide Susceptibility Map of Douglas County is part of a statewide effort to develop landslide inventory and susceptibility maps for landslide-prone areas in Colorado. Douglas County is the seventh most populous county in Colorado with the town of Castle Rock being the main population area that is quickly becoming an extension of the Denver Metro Area. This study seeks to evaluate and map known and previously unmapped landslide deposits with the aid of new high-resolution light detection and ranging (lidar) data and identify landslide susceptible zones based on slope derived from a 10-m DEM and geology from geologic maps at various scales.

A landslide is the failure and downslope movement of soil or rock due to the force of gravity exceeding the internal strength of the material. A distinct failure or rupture surface commonly forms below the failed mass on the surface where the weaker material moves downslope relative to the stronger, underlying material. Landslides can occur suddenly and move rapidly or can be slow moving. All landslides have the potential to inflict a significant amount of damage to structures. The type of material (for example rock, soil, or a mix) and failure movement mechanism (for example slide, flow, and fall) that provides nomenclature for the type of landslide (Varnes, 1978; Cruden and Varnes, 1996). In this study, rockfalls, debris flows, and very slow-moving slumps and soil creep were not mapped.

Topography, geology, and hydrology greatly influence the potential for a failure to occur. In areas of very steep slopes and/or steeply dipping bedrock, the driving force caused by the steepness can exceed the internal strength of the material. Water content of the material can also greatly influence the likelihood of a slope failure. It is very common for initiations to occur during or shortly after precipitation events that exceed normal precipitation. An increase in pore pressure may weaken material, promote instability, and cause it to move downslope. In general, mitigation can be applied to slow landslide movement; however, landslide-prone areas should be examined and evaluated by a professional engineer before construction.

The landslide deposits identified in this study are chiefly rotational or translational slides. Landslide deposits consist of varying materials. These deposits may have very distinct morphology, depending on the age and materials that comprise the deposit. They are commonly recognized by a headscarp at the top, indicating where the landslide mass failed and moved away from the material farther upslope. The toe or base of landslide deposits are usually compressed and mounded where material has moved downslope and over the ground surface. The main body of the deposit is typically hummocky and may have contained enough water to cause it to flow. On older, eroded landslide deposits, these features become more subdued and can be difficult to identify without examining exposures of the landslide deposits. Older landslide deposits are easier to identify with the aid of lidar imagery.

GEOLOGIC SETTING

Slopes on the flanks of buttes and mesas comprise the prominent topographic relief east of the Front Range in Douglas County. These landforms are capped by steam-channel deposits that have undergone topographic inversion leaving the former riverbeds now high in the landscape. Many of the buttes and mesas are underlain by sandstones and mudstones of the Dawson Formation overlain by the gravel-rich beds of Castle Rock Conglomerate and Larkspur Conglomerate. Some are underlain by the volcanic rock composed of Wall Mountain Tuff. Typically, the Dawson Formation is weakly cemented, highly erodible, and prone to the development of debris flows on the perimeters of the buttes and mesas. However, very few landslides have been previously mapped in these areas.

Bedrock hogbacks are present from the northwestern part of the county, near Chatfield State Park, and in the south-central part of the county, near Perry Park. The popular Roxborough State Park is located within this area. Weak shale like the Niobrara Formation and Pierre Shale are prevalent along the east sides of the hogbacks. These rock units typically fail parallel to the dip direction.

There are some landslide deposits mapped in areas of crystalline bedrock. These landslides are not well known or documented, as seeing them on aerial photography can be difficult and they are not easily accessed.

There are landslide deposits in Douglas County that are not associated with topographic or geologic features mentioned above. The majority of these deposits are failures that formed in the alluvium along stream channels.

The major bedrock units in Douglas County are a briefly described in Table 1. They are arranged from youngest at the top to oldest at the bottom. Quaternary surficial deposits are commonly composed of sand, gravel, and windblown (eolian) sediment.

Table 1. Major rock units found in Douglas County and used as a part of this study. Unit Descriptions were obtained from various CGS-produced 1:24,000-scale geologic maps.

Age and Rock Unit	**Description**
late Eocene Castle Rock Conglomerate	Pebble, cobble, and boulder arkosic conglomerate composed of subround to round fragments of pink and gray granite and quartz with subordinate gnessic metamorphic rocks, quartzite, red sandstone, and chert in a coarse to very coarse quartz and feldspar sand matrix.
late Eocene Wall Mountain Tuff	Moderately to densely welded tuff of rhyolitic composition.
late (?) Eocene Larkspur Conglomerate	Arkosic conglomerate composed of pebbles and cobbles of pink granite or pink feldspar in a coarse to small-pebble quartz and feldspar matrix.
Paleocene-Eocene Dawson Formation	Made of six units ranging from sandstones to claystones.
Late Cretaceous-Paleocene Denver Formation	Claystone, siltstone, sandstone, and conglomerate.
Cretaceous Laramie Formation	Coal-bearing or sandy shale and sandstone.
Cretaceous Fox Hills Sandstone	Micaceous sandstone.
Cretaceous Pierre Shale	Gray to dark gray shale.
Cretaceous Niobrara Formation	Thin-bedded, laminated, limey shale, chalk, and limestone.
Cretaceous Benton Shale	Siltstone, calcareous shale, and limestone.
Cretaceous Carlile Shale (CCS), Greenhorn Limestone (GLS), Graneros Shale (GS), undivided	CCS: Thin bedded shale. GLS: Thinly interbedded shale and fossiliferous limestone. GS: Shale beds containing bentonite layers and silt lenses.
Cretaceous Dakota Group	Quartz sandstone and shale beds.
Cretaceous Purgatoire Formation	Shale and siltstone beds with thin sandstone and siltstone beds.
Jurassic Morrison and Ralston Creek formations	Soft, variegated claystone and mudstone beds containing thin beds of marl, limestone, sandstone, and minor conglomerate.
Triassic to Permian Lykins Formation	Thin-bedded sandy siltstone and shale in a clay matrix.
Permian Lyons Sandstone	Red, tan, and gray cross-bedded fine grained quartz arenites with isolated conglomerates.
Pennsylvanian Fountain Formation	Pink, red, and white arkosic sandstones with interbedded pebble and cobble conglomerate, sandy and micaceous shales and siltstones.
Mississippian Leadville Limestone (LLS) and Williams Canyon Member (WCM)	LLS: Fine-grained, massive limestone. WCM: Calcitic sandstone, lime mudstone, and dolomitic mudstone.
Ordovician Manitou Limestone	Resistant, fine-grained limestone and dolomitic limestone.
Cambrian Sawatch Sandstone	Quartz-rich sandstone; locally conglomeratic.

METHODOLOGY

The landslide deposit inventory was developed using a slope map created from a 1-m resolution lidar DEM underlain by the 1-m DEM. Elevation contours at various intervals derived from the lidar data were also used to aid in identifying and mapping landslide deposits. The datasets were examined at 1:24,000-, 1:10,000-, and 1:5,000-scales to identify deposits of various sizes and various degrees of post-depositional erosion and surface modification. Geomorphic features like headscarps and hummocky topography were used to delineate the landslide deposits; however, headscarps and other landslide features were not mapped. Aerial photography, and high-resolution stereo-imagery were also examined using ArcGIS software.

Each landslide deposit was assessed on the basis of their morphologic features and assigned a confidence level using a system developed by Burns and Madin (2009). Well expressed landslide deposits (easily identified head scarp, hummocky topography, etc.) were assigned a high confidence whereas poorly expressed deposits were assigned a low confidence. As many mapped landslide deposits as possible were field verified.

Landslide susceptibility maps were developed using criteria modified from Wills and others (2011), Ponti and others (2008), and Wilson and Keefer (1985) (Table 2). Slope maps derived from 10-m DEMs and published 1:24,000- and 1:100,000-scale geologic maps were used to develop the landslide susceptibility maps. The 1:100,000-scale maps were used where there was no larger scale geologic map coverage. A coverage map of geologic maps used for Douglas County landslide susceptibility is shown in Figure 1.

Table 2. Susceptibility developed for Douglas County for this study.

Slope Class	Group A	Group B	Group C
1 (0-5°)	0	0	0
2 (5-10°)	0	V	VII
3 (10-15°)	0	VII	VIII
4 (15-20°)	0	VIII	IX
5 (20-30°)	VI	IX	X
6 (30-40°)	VII	IX	X
7 (>40°)	VIII	IX	X

Figure 1. Geologic maps and scales used to develop landslide susceptibility for Douglas County.

The slope map was divided into seven slope classes and each mapped geologic rock unit assigned to one of three relative rock strength groups (Table 3). Competent sandstones and other similar rocks were assigned to Group A as the highest rock strength group, friable sandstones or sandstone units that have many interbedded siltstones, claystones, and/or shales were assigned to Group B as the moderate rock strength group, and rocks that are predominantly or entirely siltstones, claystones, and/or shales were assigned to Group C as the lowest rocks strength group. Surficial deposits in gently sloping terrain were assigned to Group A. All other surficial deposits were assigned to the groups that were assigned to the bedrock units directly adjacent to them. When surficial units were in contact with multiple bedrock units of different groups, they were assigned to the strength group of the lowest strength bedrock unit. This was done by selecting surficial deposits by their proximity to bedrock deposits in ArcGIS.

Table 3: Relative rock strength groups and the units assigned to each group. Surficial units were treated differently depending upon their topographic location and proximity to bedrock units.

Group A (High Strength)	**Group B (Moderate Strength)**	**Group C (Low Strength)**
Castle Rock Conglomerate Wall Mountain Tuff Larkspur Conglomerate Dawson Formation Denver Formation Lyons Sandstone Leadville Limestone and Williams Canyon Member Fountain Formation Manitou Formation Sawatch Formation	Dakota Group Fox Hills Sandstone	Laramie Formation Lykins Formation Morrison and Ralston Creek formations Niobrara Formation Pierre Shale Purgatoire Formation Carlile Shale, Greenhorn Limestone, and Graneros Shale Benton Shale

Modifications were made to the model of Wills and others (2011) including adjusting the slope classes and which susceptibility designations (V, VI, VII, VIII, IX, X) were associated with which geologic groups and slope classes. This was done because the original model by Wills and others (2011) over-estimated the susceptibility of landslides in Group A and underestimated the susceptibility of landslides in Group B and Group C. The Pierre Shale, in particular, can fail at very low slope and dip angles, sometimes as low at 10°.

Areas such as slopes of lawns, artificial fill along roads, and modified urban drainages were overestimated in the susceptibility raster (Figure 2a). In order to remove this overestimation in the raster, it was converted to a point file and the points corresponding to the overestimated cells were removed manually and converted back to a raster (Figure 2b). Following this manual clean-up, the raster was processed using the focal statistics tool in ArcGIS with the neighborhood setting set to a 3x3 cell, the statistic type set to median, and the ignore no data in calculations box checked. The resulting raster was then processed by the majority filter tool with the number of neighbors to use set to 8 and replacement threshold set to half. The raster was then processed through the majority filter again using the same settings (Figure 2c). This final raster was then converted to smoothed polygons using tool developed by the CGS (Figure 2d). Due to the ignore no data setting in the focal statistics tool, the susceptibility estimations moved out into major areas without susceptibility and therefore needed to be clipped back so as to not over represent susceptibility where there is none.

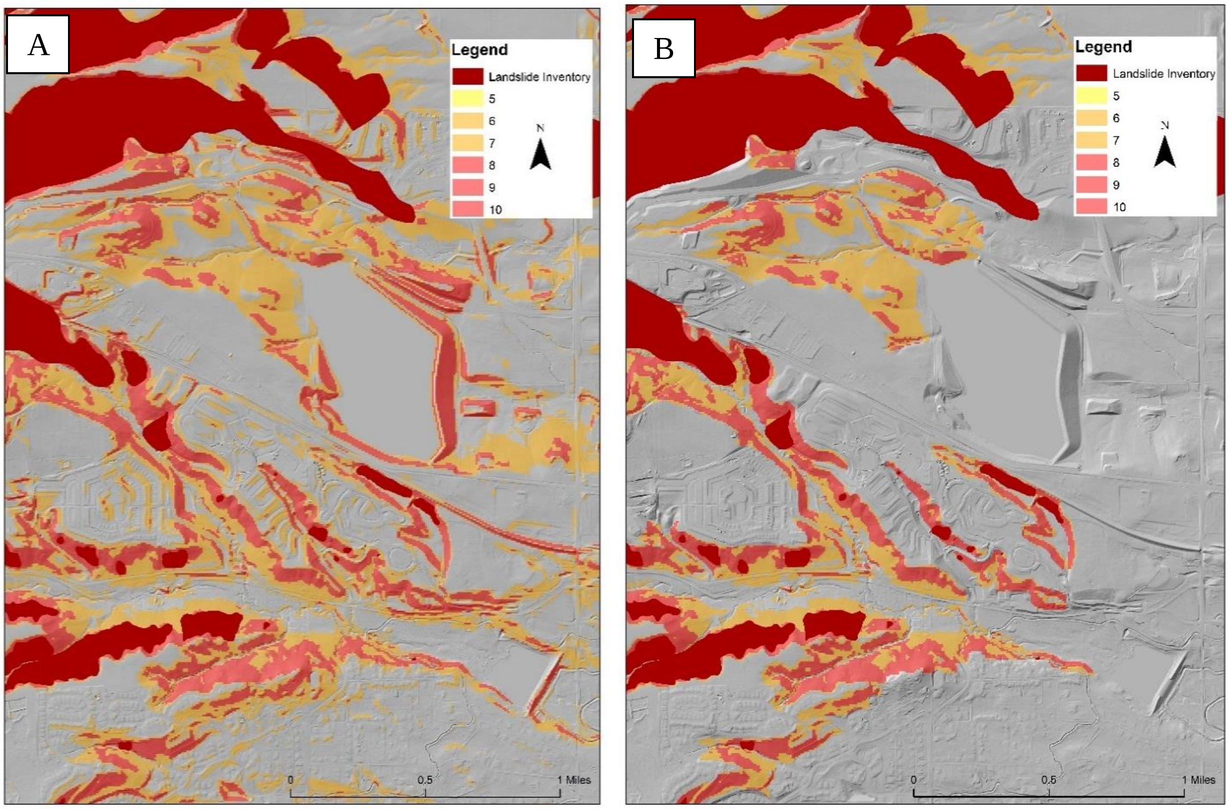

Figure 2. a) Susceptibility raster before any overestimation is removed. b) Susceptibility raster after overestimated cells were manually removed by converting the raster to a point file, deleting necessary points, and converting the point file back to a raster.

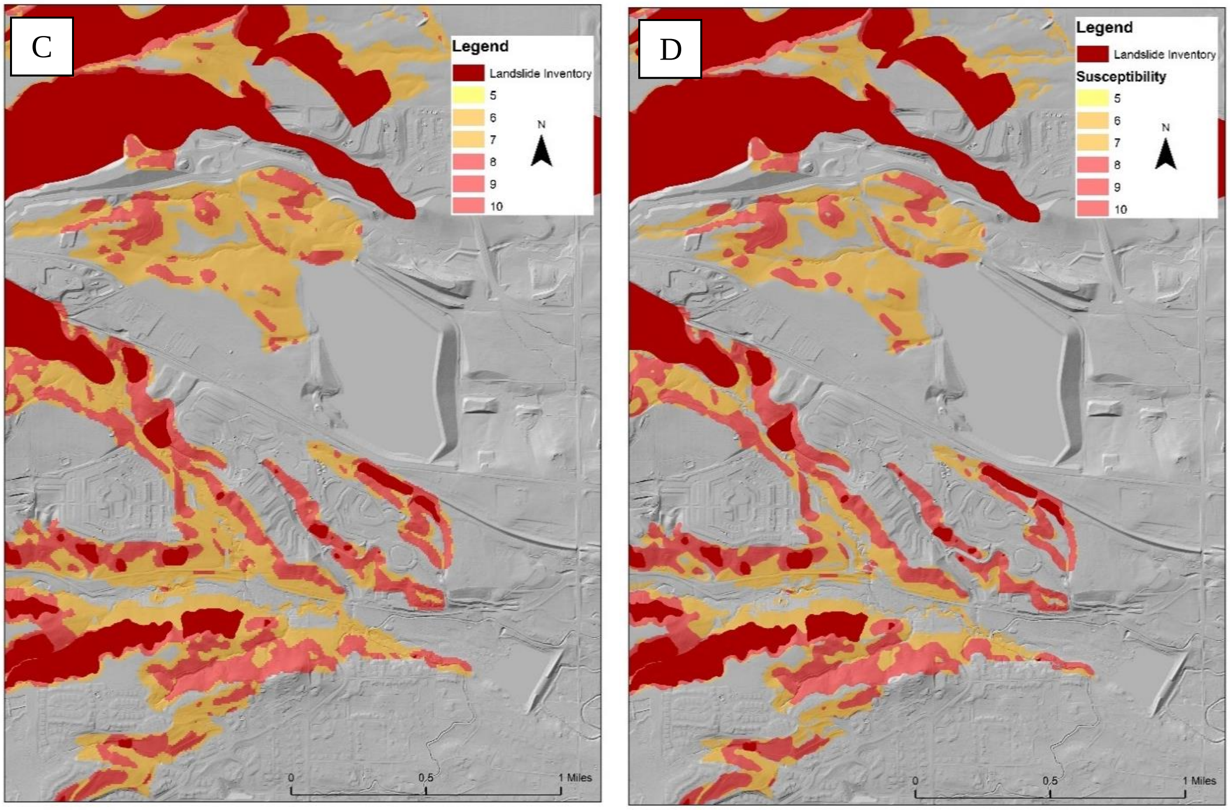

Figure 2. c) Susceptibility raster after being processed through the focal statistics tool and the majority filter tool twice. d) Susceptibility shapefiles with smoothed susceptibility polygons and the landslide inventory overlain.

Landslide susceptibility for Precambrian crystalline bedrock in the foothills region was not evaluated in this study. Rockfall is the dominant process in that region of Douglas County, as the rocks are predominantly very competent granites, gneisses, schists, and related rocks. The susceptibility represents the areas that are likely to generate rockfall instead of a rotational or translational slide; however, mapped landslide deposits in that region are kept in this study. Methods for identifying susceptibility will continually be developed and evaluated. If a more suitable method for identifying landslide susceptibility in this area is developed, an update will be made.

MAP USE AND LIMITATIONS

This map is intended to be used at 1:24,000 scale. The coverage shows areas that have mapped landslide deposits and areas that are susceptible to the development of landslides. Due to the nature of the geologic maps used and the limitations of the model, areas that are more susceptible to rockfall or debris flow may be included in the coverage of the susceptibility map. The map is not intended to give site-specific information as to the precise area and level of risk. No levels of risk are assigned. It should be used as a tool to evaluate where slope stability issues may occur. Susceptibility does not imply that landslides will occur in susceptible areas. It indicates that landslides have occurred in similar areas and that combination of the geology and slope of the area may be favorable for landslides to form in the future.

Proper evaluation by a qualified geotechnical engineer or engineering geologist should be made on a site-specific basis prior to future development or alteration to the ground surface that many impact slope stability. Disclosure of potential landslides should be made to any prospective land buyers.

REFERENCES CITED

Burns, W. J., and Madin, I. P., 2009, Protocol for inventory mapping of landslide deposits from Light Detection and Ranging (lidar) imagery: Oregon Department of Geology and Mineral Industries, SP-42 (https://www.oregongeology.org/pubs/dds/slido/sp-42_onscreen.pdf).

Cruden, D. M., and Varnes, D. J., 1996, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., eds., Lanslide investigation and mitigation: Washington, D.C., National Academy Press, Transportation Research Board Special Report 247 p.

Maberry, J. O., and Lindvall, R. M., 1972, Geologic map of the Parker quadrangle, Arapahoe and Douglas Counties, Colorado: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I-770-A, scale 1:24,000 (https://pubs.er.usgs.gov/publication/i770A).

Maberry, J. O., and Lindvall, R. M., 1977, Geologic map of the Highlands Ranch quadrangle, Arapahoe and Douglas Counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1413, scale 1:24,000 (https://pubs.er.usgs.gov/publication/gq1413).

Morgan, M. L., 2015, Geologic Map of the Piney Creek Quadrangle, Arapahoe, Douglas, and Elbert Counties, Colorado: Colorado Geological Survey, Open-File Report OF-15-12, scale 1:24,000.

Morgan, M. L., McHarge, J. L., and Barkmann, P.E., 2005, Geologic Map of the Sedalia Quadrangle, Douglas County, Colorado: Colorado Geological Survey, Open-File Report OF-05-06, scale 1:24,000.

Morgan, M. L., Temple, Jay, Grizzell, M. T., and Barkmann, P. E., 2005, Geologic Map of the Dawson Butte Quadrangle, Douglas County, Colorado: Colorado Geological Survey, Open-File Report OF-04-07, scale 1:24,000.

Ponti, D. J., Tinsley, J. C., III, Treiman, J. A., and Seligson, H., 2008, Ground deformation, section 3c *in* Jones, L. M., Bernknopf, R., Cox, D., Goltz, J., Hudnut, K., Mileti, D., Perry, S., Ponti, D., Porter, K., Reichle, M., Seligson, H., Shoaf, K., Treiman, J., and Wein, A., 2008, The ShakeOut Scenario: U.S. Geological Survey, Open-File Report 2008-1150 and California Geological Survey Preliminary Report 25 (http://pubs.usgs.gov/of/2008/1150/).

Ruleman, C. A., Bohannon, R. G., Bryant, Bruce, Shroba, R. R., and Premo, W. R., 2011, Geologic Map of the Bailey 30’ x 60’ quadrangle, north-central Colorado: U.S. Geological Survey, Scientific Investigations Map SIM-3156, scale 1:100,000 (https://pubs.er.usgs.gov/publication/sim3156).

Scott, G. R., 1962, Geology of the Littleton quadrangle, Jefferson, Douglas, and Arapahoe Counties, Colorado: U.S. Geological Survey, Bulletin 1121-L, scale 1:24,000 (https://pubs.er.usgs.gov/publication/b1121L).

Temple, Jay, Busacca, Alan, Mendel, David, and Sicard, Karri, 2008, Geologic Map of the Dakan Mountain Quadrangle, Douglas, Teller, and El Paso Counties, Colorado: Colorado Geological Survey, Open-File Report OF-08-16, scale 1:24,000.

Thorson, J. P., 2003, Geologic Map of the Greenland Quadrangle, Douglas and El Paso Counties, Colorado: Colorado Geological Survey, Open-File Report OF-03-09, scale 1:24,000.

Thorson, J. P., 2004, Geologic Map of the Castle Rock South Quadrangle, Douglas County, Colorado: Colorado Geological Survey, Open-File Report OF-04-05, scale 1:24,000.

Thorson, J. P., 2004, Geologic Map of the Cherry Valley School Quadrangle, Elbert, Douglas, El Paso Counties, Colorado: Colorado Geological Survey, Open-File Report OF-04-06, scale 1:24,000.

Thorson, J. P., 2005, Geologic Map of the Castle Rock North Quadrangle, Douglas County, Colorado: Colorado Geological Survey, Open-File Report OF-05-02, scale 1:24,000.

Thorson, J. P., 2006, Geologic Map of the Russellville Gulch Quadrangle, Douglas and Elbert County, Colorado: Colorado Geological Survey, Open-File Report OF-06-08, scale 1:24,000.

Thorson, J. P., 2007, Geologic Map of the Pondera Park Quadrangle, Douglas and Elbert Counties, Colorado: Colorado Geological Survey, Open-File Report OF-07-04, scale 1:24,000.

Thorson, Jon, Temple, Jay, Busacca, Alan, and Berg, William, 2008, Geologic Map of the Larkspur Quadrangle, Douglas and El Paso Counties, Colorado: Colorado Geological Survey, Open-File report OF-08-17, scale 1:24,000.

Varnes, D. J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J, eds., Special Report 176 – Landslides, Analysis and Control: Transportation and Road Research Board, National Academy of Science, Washington D.C., 11-33

Wills, C. J., Perez, F. G., and Gutierrez, C. I., 2011, Susceptibility to deep-seated landslides in California: California Geological Survey, Map Sheet 58 (https://maps.conservation.ca.gov/cgs/metadata/MS58_metadata.pdf).

Wilson, R. C., and Keefer, D. K., 1985, Predicting areal limits of earthquake-induced landsliding *in* J.I. Ziony, editor, Evaluating earthquake hazards in Los Angeles region—an earth-science perspective: U.S. Geological Survey, Professional Paper 1360, p 317-345 (https://pubs.er.usgs.gov/publication/pp1360).