LANDSLIDE INVENTORY AND SUSCEPTIBILITY OF JEFFERSON COUNTY, COLORADO

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INTRODUCTION

The CGS aims to provide geologic hazard susceptibility maps to state and local governments for use in planning processes and hazard mitigation plans. The Landslide Susceptibility Map of Jefferson County is part of a statewide effort to develop inventory and susceptibility maps for landslide-prone areas in Colorado. Jefferson County extends from the Rocky Flats area, north of Golden, to south of Buffalo Creek. It contains North Table Mountain, South Table Mountain, Green Mountain, and a section of the hogbacks. Much of the western part of the Denver Metro area lies within the county, as well as mountain towns like Evergreen, Conifer, and Pine. Extensive growth and development is taking place in Golden and the Rocky Flats region, where many landslides in Jefferson County are located. This study seeks to reevaluate existing landslide boundaries 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

There are a few major geographic features associated with landslides in Jefferson County. North and South Table Mountain are prominent features in the Golden area. These are mesas capped with Table Mountain Shoshonite underlain by Denver Formation. While landslides of varying size are mapped around both mountains, failures occur at or near the contact between these two units and are present on all sides of North Table Mountain and on west-, north-, and east-facing slopes on South Table Mountain.

Green Mountain in Lakewood is flanked by many landslides, some of which have affected homes and roadways. The Green Mountain Conglomerate caps the top of the mountain and is underlain by sandstones, conglomerates, and shales of the Denver Formation. Some landslides at Green Mountain fail out of the contact between the Green Mountain Conglomerate and the Denver Formation or from within the Denver Formation. Other landslides tend to initiate out of the Green Mountain Conglomerate.

Bedrock hogbacks trend north-south through the county and parallel the west extension of Colorado State Highway 470 (C-470). In places, there are two sets of hogbacks, the second set just west of the first. The first set (westernmost) of hogbacks consist of steeply dipping Dakota Group sandstones overlain by Benton Shale, Niobrara Formation, and Pierre Shale. These three units typically fail in shales of the Dakota Group, resulting in shallow earthflow landslides. The second set of hogbacks (easternmost) are less prominent, but still generate shallow landslides which commonly initiate near the contact between the Lyons Sandstone and Lykins Formation. Landslides typically occur on the dip slope (east-facing slopes) of the hogbacks. Rockfalls and debris flows are the dominant processes on the western-facing sides, although some landslides were mapped on the eastern sides as a part of this inventory.

The slopes surrounding the Rocky Flats alluvial surface are prone to landsliding and while some of this area is restricted from development, there have been subdivisions constructed in recent years. The relatively thick layers of gravel overlie the Cretaceous Arapahoe, Laramie, Fox Hills and Pierre formations which range in dip from overturned to less than 10 degrees in only a few miles. The shaly parts of these units are prone to failure within this range of dips and may fail at dips less than 10°.

There are some landslides 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 landslides not associated with any of these features mapped in Jefferson County. The majority of them are failures in the alluvium along stream channels in developed areas. Many others may be related to the contact between the crystalline bedrock in the foothills and the Fountain Formation, which tends to have older alluvium overlying it.

The major bedrock units and a brief description of each found in Jefferson County are shown below from youngest at the top to oldest at the bottom (Table 1). Quaternary surficial deposits include various alluviums and gravels.

METHODOLOGY

The landslide 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 separately. 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 1:100,000-scale geologic maps were used to develop the landslide susceptibility maps. A coverage map of geologic maps used for Jefferson County landslide susceptibility is shown in Figure 1.

Table 1. Rocks found in Jefferson 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 Paleocene Green Mountain Conglomerate	Andesite, gneiss, pegmatite, quartzite, and sandstone clasts with some interbedded sandstone, claystone, and siltstone. This formation caps Green Mountain.
Paleocene Table Mountain Shoshonite	Three porphyritic potassium-rich basalt flows that cap North and South Table Mountains.
Late Cretaceous-Paleocene Denver Formation	Claystone, siltstone, sandstone, and conglomerate.
Late Cretaceous Arapahoe Formation	Sandstone, siltstone, claystone, thin pebble beds, and conglomerate with sedimentary, igneous and metamorphic clasts.
Cretaceous Laramie Formation	Micaceous siltstone, silty claystone, lignitic claystone, sandstone, and conglomerate with sedimentary clasts.
Cretaceous Fox Hills Sandstone	Micaceous sandstone, shale, massive to thinly bedded sandstone, and claystone.
Cretaceous Pierre Shale	Three members with sandstones, silty sandstones, sandy shale, limestone, and shale.
Cretaceous Niobrara Formation	Two members with calcareous shale and limestone.
Cretaceous Benton Shale	Siltstone, calcareous shale, and limestone.
Cretaceous Carlile Shale	Sandy limestone, shale, silty limestone, and calcareous shale.
Cretaceous Greenhorn Limestone	Limestone, calcareous shale, and calcarenite.
Cretaceous Graneros Shale	Clayey shale, and siltstone.
Cretaceous Dakota Group	Sandstone, siltstone, claystone, and conglomerate.
Jurassic Morrison Formation	Siltstone, sandstone, claystone, and limestone.
Jurassic Ralston Creek Formation	Siltstone, sandstone, and limestone.
Triassic/Permian Lykins Formation	Four members of silty sandstone, siltstone, limestone, sandy limestone, and conglomerate.
Permian Lyons Sandstone	Conglomerate and sandstone.
Pennsylvanian Fountain Formation	Sandstone and conglomerate.

Table 2. Susceptibility developed for Jefferson County by the Colorado Geological Survey.

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

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. Units with multiple members were treated as a single rock unit. 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.

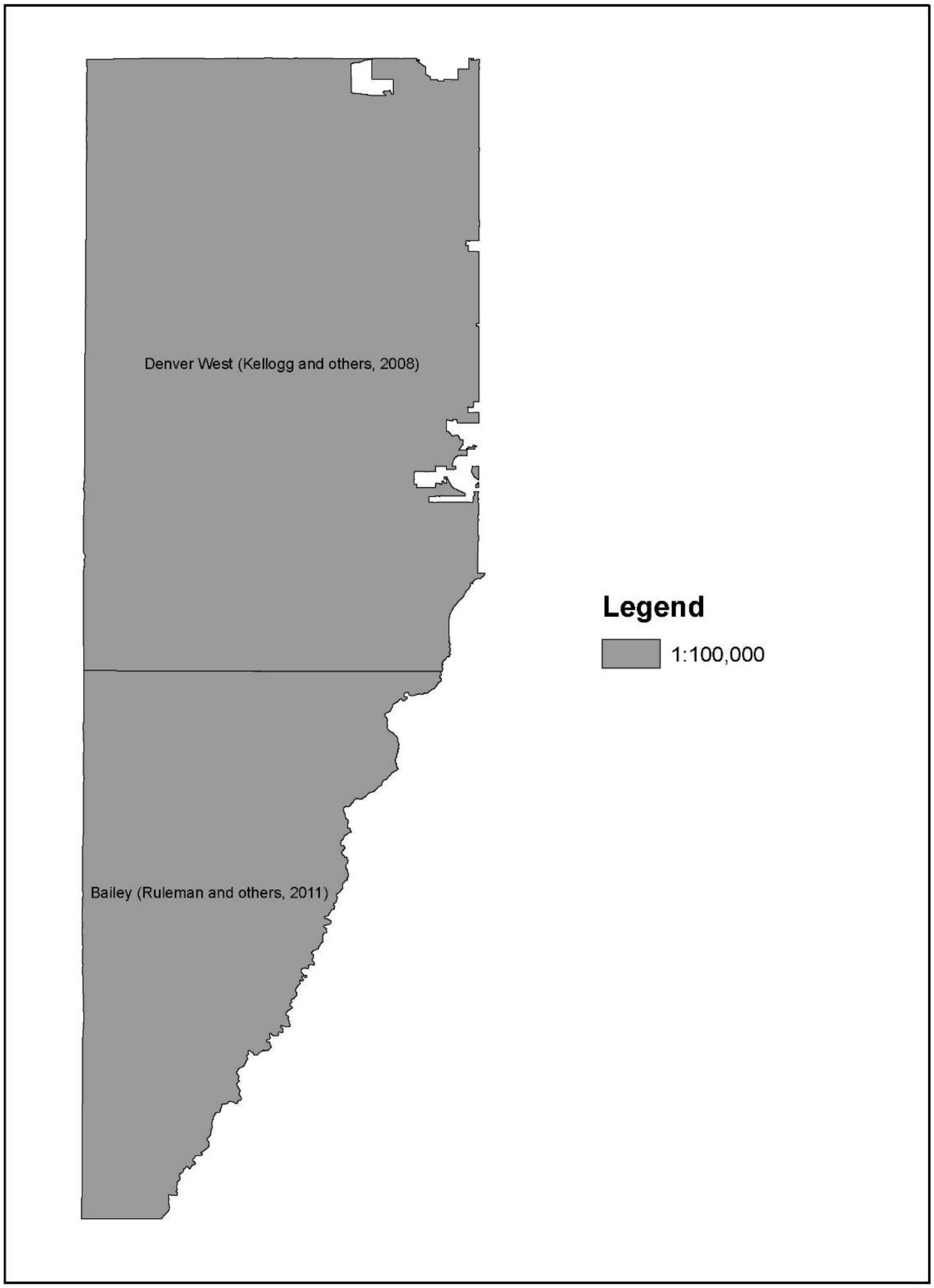

Figure 1. Geologic map name and coverage used for development of landslide susceptibility.

Table 3: Relative rock strength groups and the units assigned to each group.

Group A (High Strength)	**Group B (Moderate Strength)**	**Group C (Low Strength)**
Fountain Formation Lyons Sandstone Table Mountain Shoshonite	Dakota Group Fox Hills Sandstone	Arapahoe Formation Benton Shale Carlile Shale Denver Formation Green Mountain Conglomerate Graneros Shale Greenhorn Limestone Laramie Formation Lykins Formation Morrison Formation Niobrara Formation Pierre Shale Ralston Creek Formations

Intersections between the different slope groups and rock strength groups were assigned a level of susceptibility from 0-10, where 0-5 is considered low susceptibility, 6-7 is moderate, and 8-10 is high.

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 (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.

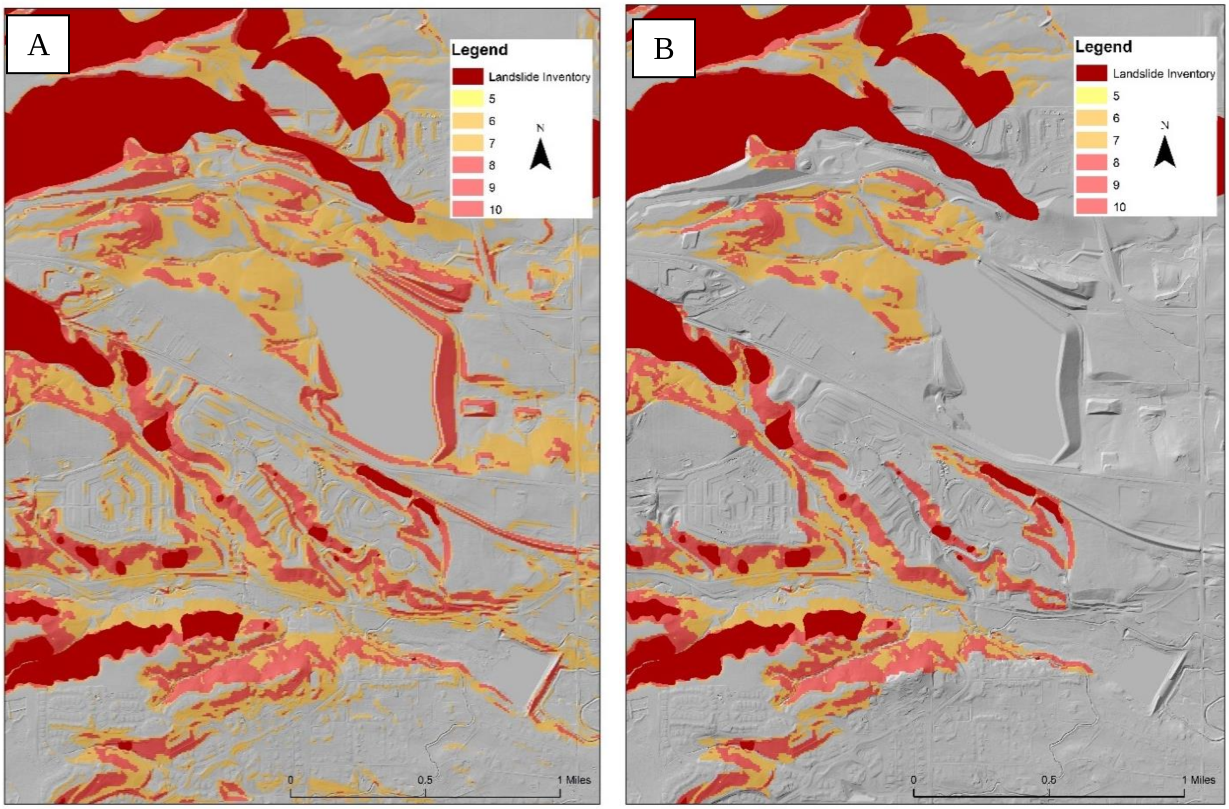

Figure 2. a) Susceptibility raster before any “noise” removal. b) Susceptibility raster after some “noise” manually removed by converting the raster to a point file, deleting necessary points, and converting back to a raster.

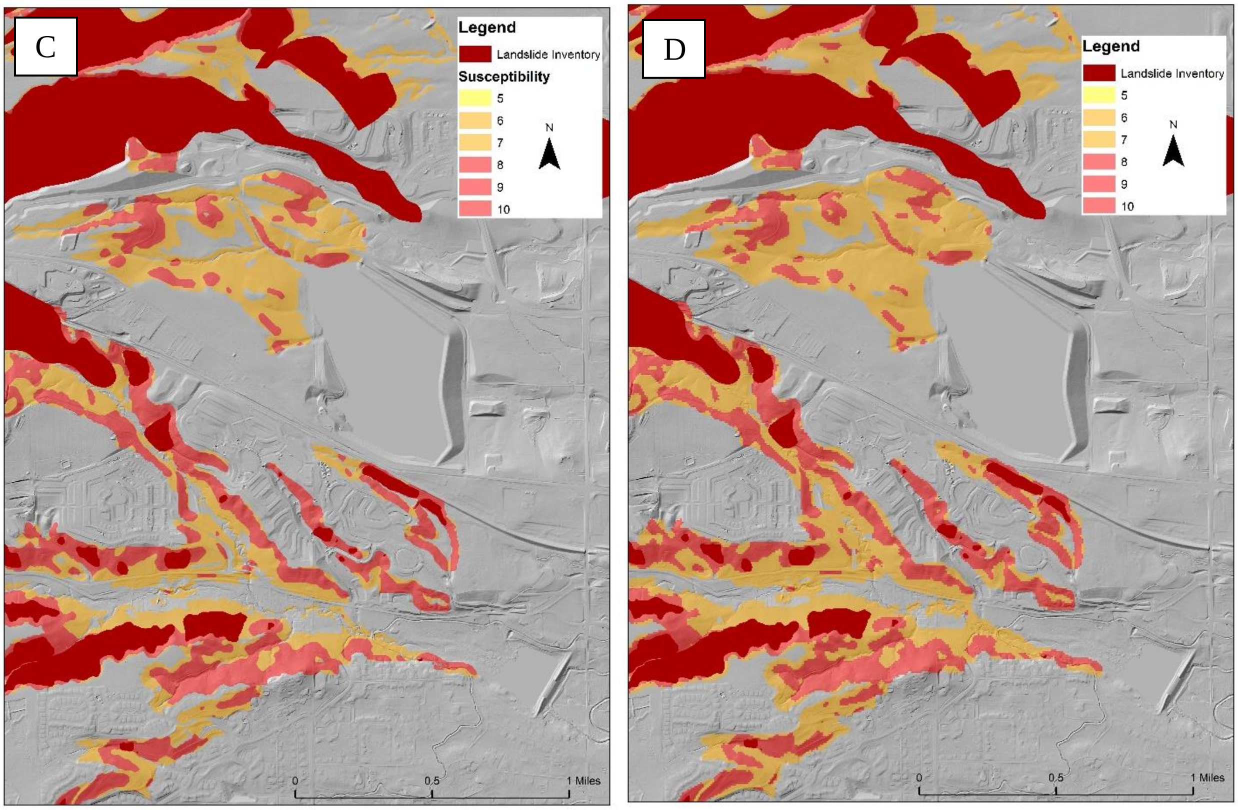

Figure 2. c) Susceptibility rater after being processed through the focal statistics tool and the majority filter tool twice. d) Susceptibility shapefiles with smoothed susceptibility polygons and the landslide inventory overlain on it.

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 Jefferson 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.

Kellogg, K. S., Shroba, R. R., Bryant, Bruce, and Premo, W. R., 2008, Geologic map of the Denver West 30' x 60' quadrangle, north-central Colorado: U.S. Geological Survey, Scientific Investigations Map SIM-3000, scale 1:100,000 (https://pubs.er.usgs.gov/publication/sim3000).

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: United States 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).

Varnes, D. J., 1978, Slope movement types and processes. In: Special Report 176 – Landslides, Analysis and Control (Eds: Schuster, R.L., and Krizek, R.J.): 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: United States Geological Survey, Professional Paper 1360, p 317-345 (https://pubs.er.usgs.gov/publication/pp1360).