Landslide25_03

Key Factors and Mechanisms of Landslide Formation in northeastern Nevada: A Case Study of the Spruce Mountain Landslide

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SUMMARY

Landslides are a significant natural hazard in the Basin and Range Province of the western United States, where an active tectonics, complex geological structure, and climatic conditions contribute to the development of landslide hazards. By integrating field observations, geological and geomorphological mapping, lithological analysis, and remote sensing data, the study aims to identify the main geological and geomorphological factors that influence slope failure and instability in the Spruce Mountain area. Structural morphometry was used to study the conditions for landslide formation and determine the tectonic and morphological factors of landslide formation. The development of morphostructural maps enabled the validation of conclusions regarding the total amplitudes of tectonic movements in the Spruce Mountain area and facilitated the identification of landslide material source zones. The Spruce landslide, based on the composition of the sediments, can be attributed to extremely rapid rock avalanches without signs of significant gradational layering. Approximate rate of movement was up to 3 m per second, which is considered as an extremely rapid mass flow. Its formation was caused by tectonic features with the significant faulting and a high rate of weathering processes that contributed to the preparation of the material for transportation. This landslide likely occurred at the boundary of the Late Pleistocene-Holocene (?). The findings contribute to a broader understanding of landslide dynamics in arid and tectonically extended regions such as Nevada.

Introduction

Landslides are a significant natural hazard in mountainous and geodynamically active regions, posing significant threats to infrastructure, geoecosystems, and local communities. In the Basin and Range Province of the western United States, active tectonics, complex geological structure, and climatic conditions contribute to the development of landslide hazards. Landslides are the result of various factors and mechanisms, the combination of which leads to the manifestation of landslides of different genetic types and structure. In Nevada, these are mainly large rock avalanches (LRA), rotational landslides, gravity rock collapses, and caldera collapses. Landslides also vary in age of formation, ranging from ancient to modern, from the Cretaceous to the Holocene, respectively. The Spruce Mountain area, located in Elko County, northeastern Nevada, has tectonic, geological, and geomorphological conditions that contribute to landslide activity. The mountain is composed of faulted Paleozoic sedimentary units intruded by Mesozoic and Cenozoic igneous rocks. These features, combined with steep terrain and extensive faulting, create a geologically complex environment prone to gravitational processes and mass movements.
This study aims to identify and analyze key factors and mechanisms of landslide formation in the Spruce Mountain area. By integrating field observations, geological and geomorphological mapping, lithological analysis, and remote sensing data, the study aims to identify the main geological and geomorphological factors that influence slope failure and instability.

Study area and characterization of landslide deposits

The study area (Figure 1) is located to the west of Spruce Mountain, the inferred source area of Spruce Mountain LRA. The area is predominantly composed of poorly consolidated Miocene volcanoclastic rocks, the Spruce Mountain LRA deposit, and unconsolidated Quaternary sediments forming a saddle between Pleistocene lakes Clover and Franklin.

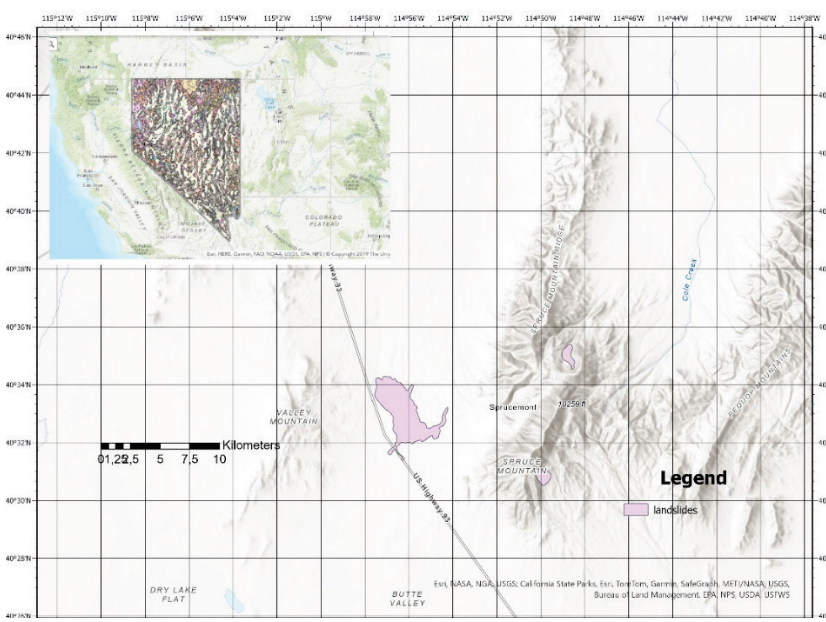


Figure 1 *Location of the study area, Spruce Mountain Landslide, Elko County, Nevada, USA. The landslide data is according to database of Belair et al., 2019.*

Structurally, the area has experienced significant extensional tectonics, particularly during Miocene to present Basin and Range deformation. This has resulted in numerous high-angle normal faults that segment

the mountain into tilted fault blocks. The recent extension has resulted in generation of numerous fault-bounded mountain ranges, which have been the source of hundreds of large-scale landslides since the Miocene (Sturmer and Micander, 2020).
Among different types of landslides in Nevada, LRA represent one of the most significant and hazardous types. Rock avalanches are rapid, large-scale movements of fragmented rock masses that typically occur on steep slopes and triggered by seismic activity or intense weathering. This study focuses on the LRA deposits, Spruce Mountain landslide deposits, exposed on both sides of highway US-93 in northeastern Nevada and is entirely within the Spruce Well quadrangle (Figure 2).

Figure 2. *Spruce Mountain landslide deposits, northeastern Nevada, the Spruce Well quadrangle*

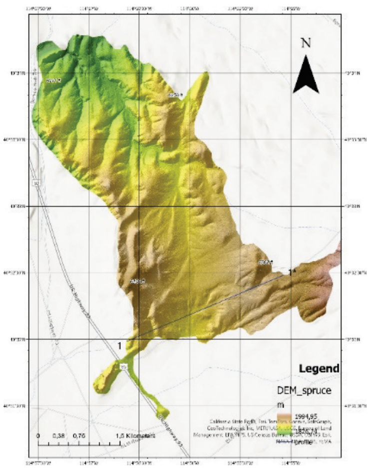
The landslide extends from an elevation of approximately 1826 m at its toe to 1994 m at its head opposite the inferred source area on Spruce Mountain (peak elevation 3129 m). Slope angles across the landslide deposits range from 2° to 27°, indicating a mix of gentle and moderately steep surfaces. Hope (Hope, 1972) described the landslide deposit as a resistant 15 m-thick layer with breccia clasts that are dominantly 4-7 cm across with clasts up to 30 cm common. The basal portion of the deposit is described as an undulatory band of fragmented limestone clasts and rounded quartz grains that is up to 1 m thick. Hope also states that the fragments are ~99% Devonian Guilmette Formation, based on distinctive fossils.

Method and/or Theory

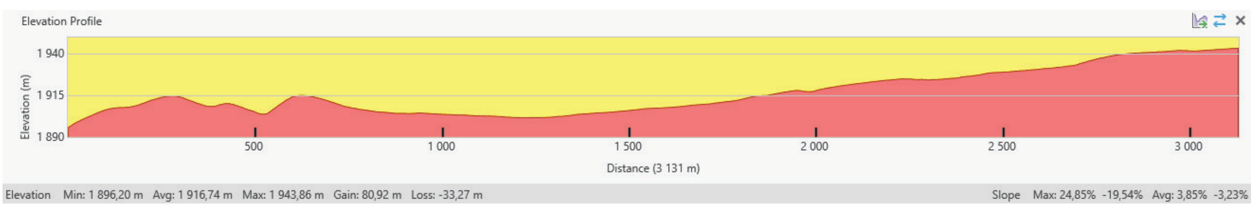
A three-dimensional terrain model of the landslide deposit was constructed using ArcGIS Pro to analyze its morphology and spatial characteristics (Figure 3a, 3b). The model was based on a high-resolution (1 m) digital elevation model (DEM) covering the entire extent of the landslide and surrounding terrain within the Spruce Well quadrangle (coordinate system WGS_1984_Web_Mercator_Auxiliary_Sphere). The DEM was imported into a 3D scene environment in ArcGIS Pro (Fig. 3b), where visualization and surface analysis tools were applied to highlight the topographic features of the landslide.
Structural morphometry was used to study the conditions for landslide formation and determine the tectonic and morphological factors of landslide formation in the study area. The method of structural morphometry (Filosofov, 1975) is based on the analysis of morphometry characteristics of relief. This method reproduces a morphology and tectonic evolution of the area, analyzes the amplitudes of tectonic movements, identify the stages of tectonic movement and relative rates of erosion and denudation. The workflow includes the determining stream and watershed orders, establishing the hierarchical classification necessary for identifying erosional patterns. This classification serves as the framework for constructing base, hilltop surfaces, generating maps of residual relief, calculating difference surfaces, and creating local erosion maps. These products enable geomorphological and geological interpretation of the morphostructural models, revealing tectonic influences on landslide distribution.

Results

The resulting 3D model demonstrates that the surface of the Spruce Mountain landslide deposit is distinctly irregular and hummocky, characterized by internal scarps, ridges, and depressions that reflect internal deformation during transport and deposition of landslide deposits, and following erosion processes. These features are clearly visible on the extracted topographic profile (Fig. 3c), which displays an undulating pattern of convex and concave segments typical of complex landslide movements involving sliding and spreading.



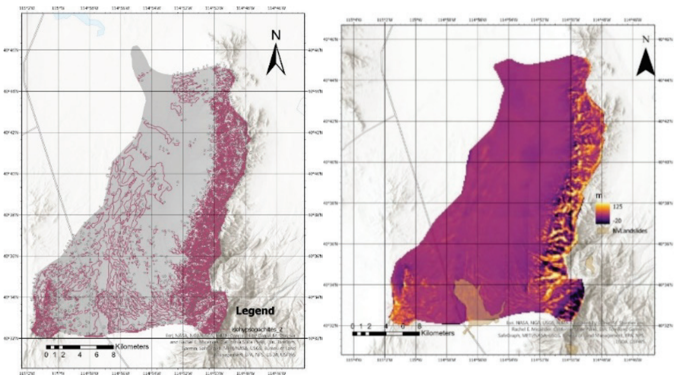
a) **b)**



c)

Figure 3. *Three-dimensional terrain model (a), scene overview (b) and topographical profile (c) of the Spruce Mountain landslide deposits within the Spruce Well quadrangle, created in ArcGIS Pro using a high-resolution DEM. The model reveals a distinctly hummocky and uneven surface morphology, with clearly defined headscarp, internal ridges, and depressions. Elevation ranges from 1826 to 1994 m, highlighting the structural and morphological complexity of the landslide. Topographic profile extracted across the southern part (line 1-1*) of the landslide body. The profile illustrates the morphology of the landslide deposit surface, with alternating concave and convex segments corresponding to internal deformation features. Slope angles vary from 2° to 27°, reflecting areas of secondary displacement.*

The development of morphostructural maps enabled the validation of conclusions regarding the total amplitudes of tectonic movements in the Spruce Mountain area and facilitated the identification of landslide material source zones (Fig. 4). These amplitudes, estimated at approximately 420 meters, correspond to the Pliocene–Quaternary stage of regional development. The constructed residual relief maps illustrate the relative elevation of positive landforms above the erosion base and indicate the volume of material that may be mobilized through future erosional processes (i.e., potential mass movement). Positive landforms situated above the regional erosion surface are defined as residual relief. The highest residual relief values, reaching up to 125 meters, are found in the Spruce Mountain area, as shown on the second-order residual relief map, which reflects the pre-Holocene geomorphic evolution of the region. Approximate rate of movement was up to 3 m (10 ft) per second, which is considered as an extremely rapid mass flow.



a) *b)*

Figure 4 *Maps of residual relief of the 2nd order and landslide deposits, northeast basin, Nevada: contours of isohypsopachytes of the 2nd order (a); map of residual relief surface of the 2nd order (b).*

Conclusions

The Spruce Mountain landslide site has a complex morphological structure, which is confirmed by both field research data and spatial modeling results. This landslide, based on the composition of the sediments, can be attributed to extremely rapid rock avalanches without signs of significant gradational layering. According to our data, its formation was caused by tectonic features with the significant faulting and a high rate of weathering processes that contributed to the preparation of the material for transportation. This landslide likely occurred at the boundary of the Late Pleistocene-Holocene (?). The findings contribute to a broader understanding of landslide dynamics in arid and tectonically extended regions such as Nevada.

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