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A LiDAR-Based Bedrock Landslide Inventory of the San Gabriel Mountains, California

A Thesis submitted in partial satisfaction
of the requirements for the degree of

Master of Science

in

Earth and Planetary Sciences

by

Terry Checkbun Li

September 2025

Thesis Committee:

Dr. Nicolas C. Barth, Chairperson

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Dr. David Oglesby

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2025

The Thesis of Terry Checkbun Li is approved:

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University of California, Riverside

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ABSTRACT OF THE THESIS

A LiDAR-Based Bedrock Landslide Inventory of the San Gabriel Mountains, California

by

Terry Checkbun Li

Masters of Science, Graduate Program in Earth and Planetary Sciences

University of California, Riverside, September 2025

Dr. Nicolas C. Barth, Chairperson

The San Gabriel Mountains (SGM) are one of the most tectonically active mountain ranges in the U.S., yet a comprehensive LiDAR-based landslide inventory (LSI) has not been completed at the range scale. This study presents a novel, high-resolution LSI of the SGM using 1 m LiDAR multi-hillshade imagery, mapping nearly 12,000 bedrock landslides and analyzing their relationships with geology, topography, tectonic blocks, and landslide susceptibility. Results show that crystalline rocks host the majority of large landslides, supporting prior hypotheses that stronger rocks can produce larger landslides. Landslides sourced in schist display disproportionately high abundance and distinctive morphology, with internally deformed, topography-mantling deposits that differ from more blocky, coherent failures in other lithologies. Fault-bounded structural blocks show varied landslide behavior, with notably high landslide density along the range-front area, suggesting possible reactivation of the San Gabriel Fault or complex deformation within

the Sierra Madre and Tujunga blocks. While landslide density generally increases with landslide susceptibility (He & Beighley, 2008), the distribution deviates from an expected linear trend suggesting potential to improve landslide susceptibility and hazard models. A region of Tertiary volcanics stands out for its disproportionately high density of landslides, including a $>1 \text{ km}^2$ deposit, highlighting complex multi-factor influences. Comparison of landslide deposit and lineament density reveals little correlation in the western SGM, but strong positive correlation in the east, likely due to lithologic and geomorphic controls. Observations made in this study suggest that Holocene-scale rates of $>1 \text{ km}^2$ landslide rates share similarities to those estimated by Lave & Burbank (2004), but may be underestimated as the topographic expression of bedrock landslides can be removed over Holocene timescales. Findings made by this study underscore the need for further refinement of geologic mapping, susceptibility models, and tectonic investigations to better assess landslide hazards in active orogens such as the SGM.

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1.0 Introduction



Fig. 1. Overview of California with the study area outlined in red.

California's diverse geologic history has resulted in a complex landscape shaped by active tectonics, steep topography, and varying lithology. This is apparent in the San Gabriel

Mountains (**Fig. 1**), where rapid uplift, seismic activity, and highly fractured bedrock contribute to widespread landsliding. Advances in active remote sensing technologies, such as LiDAR, have significantly improved high-resolution topographic mapping, allowing for more detailed and accurate landslide identification. While shallow debris flows driven by fire and flood cycles have been extensively studied in the San Gabriel Mountains (Lavé & Burbank, 2004; Cannon et al., 2009; Kean et al., 2011; Schmidt et al., 2011; Gartner et al., 2015), research on bedrock landslides and their potential risk implications remains limited. Recent exposure dating suggests that bedrock landslides in the San Gabriel Mountains are up to several orders of magnitude younger than previously anticipated, with some landslide deposits revised from early Pleistocene ages (> 2 Ma) to as recent as 0.6–1 ka (Scherler et al., 2016; Del Vecchio et al., 2018; Barth & Gentile, 2020; Nourse et al., 2020; cf. Morton & Miller, 2006). Understanding the extent and frequency of these bedrock landslides, as well as related hazards such as increased sediment generation and landslide damming, is crucial for improving mitigation strategies and risk management practices as bedrock landslides pose a significant risk to residential communities, commercial properties, and infrastructure.

1.1 Landslides

1.1.1 Definition

Hungr et al. (2013) expand on the widely used Varnes (1978) landslide classification system and define a landslide as a representation of a physical system of mass movement that progresses over time through multiple stages. The progression of mass movement,

consisting of pre-failure deformation, the failure event, and subsequent post-failure displacement, is outlined by Hungr et al. (2013). “Failure,” as defined by Leroueil et al. (1996) and further expanded by Hungr et al. (2013), refers to the most significant movement event in a landslide’s known or anticipated history. A rupture surface typically forms during this event, representing either a discrete slip plane or a thin, localized shear or deformation zone within the material. Post-failure displacement may also occur numerous times with periods of inactivity of varying lengths in between. The Varnes (1978) definition of “displaced material” will be used to define the term “deposit” in this study as the mappable volume of material displaced from its original source position on the slope through the process of landsliding.

1.1.2 Types and Triggers

Although the expanded Varnes (1978) landslide classification system lists 32 landslide types, this study will focus on rotational rockslides, translational rockslides, and rock avalanches within the San Gabriel Mountains (SGM). Scree deposits produced from composite rockfall events and debris flow deposits are deliberately excluded. Due to the complex geomorphic expressions of most landslides identified, a catch-all term of “bedrock landslide” will be utilized throughout this study.

Rockslides

Rotational and translational rockslides account for the majority of bedrock landslides identified within the SGM. Both types of rockslides involve large, mostly coherent blocks of rock that do not travel far from their source (**Fig. 2**).

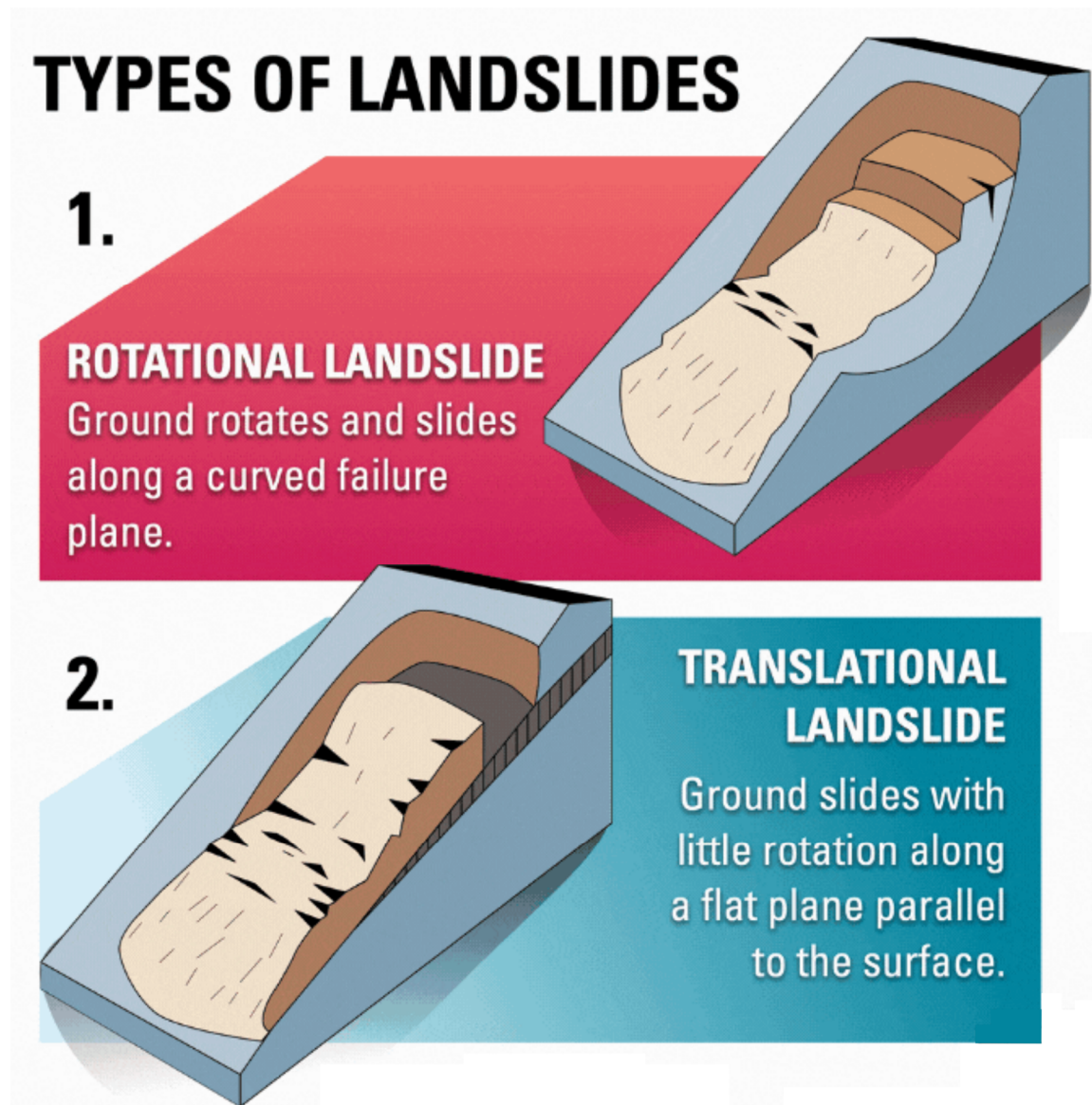


Fig. 2. Schematic cartoon depicting both a rotational landslide and a translational landslide. Cartoon obtained from <https://www.usgs.gov/media/images/types-landslides>.

Rotational rockslides are the downslope movement of rock masses along a curved, concave-up failure surface and are typically characterized by a steep, arcuate headscarp, back-tilted benches, and minor to no internal deformation, though these features may be obscured by topography, vegetation, and erosion. Due to the geometry of a curved failure surface, rotational rockslides tend to have a slow or moderate velocity as the rotational mechanism upon a curved surface is self-stabilizing (Hungr et al., 2013). In the SGM, rotational rockslides primarily occur in both homogenous and heterogenous igneous and non-foliated metamorphic rocks.

Translational rockslides, by contrast, are the downslope movement of rock masses along a planar failure surface and are typically characterized by ridge top trenches, side hill trenches, and minor to no internal deformation, though complex topography, vegetation, and erosion can obscure or eliminate these features. Due to the geometry of a planar failure surface, translational rockslides tend to have a high velocity as the planar sliding mechanism is not self-stabilizing (Hungr et al., 2013). In the SGM, translational rockslides primarily occur on failure surfaces associated with foliated metamorphic rocks, layered or folded sedimentary rocks, and fault planes.

Rock Avalanches

Rock avalanches are a continuation of displacement from a large rockslide and are typically dominated by macroscopic flow-type movements. These differ from rotational and translational rockslides due to differences in emplacement characteristics as well as general

morphology: rock avalanche deposits often preserve the original stratigraphy, exhibit inverse grading, contain jigsaw-fractured clasts and longitudinal hummocks, and are covered by a bouldery carapace (Dufresne et al., 2016). The travel path of rock avalanches in the SGM are predominantly controlled by the surrounding topography, which confines their movement and often limits their runout distance. In the SGM, rock avalanches are restricted to high-relief areas underlain by crystalline rock. Notable examples include the Alpine Canyon, Antelope Canyon, and Manker Flat rock avalanches.

Mountain Ridge Deformation

Ridgetop spreading and sackungen are ubiquitous, mountain ridge-scale gravitational deformations expressed as uphill-facing scarps and benches, cracks, bulges, and trenches, typically striking parallel to ridges (Beck, 1968; Morton & Sadler, 1989; Cruden & Varnes, 1996; Hunger et al., 2013; McCalpin & Hart, 2003). Sackung (plural: sackungen) are large, deep-seated slope failures that feature a well-defined slide plane near the headscarp that transitions to broad, downslope creep or bulging. They form gradually through ductile deformation or deep creep, often lacking a clear rupture surface or landslide mass (Zischinsky, 1969; Morton & Sadler, 1989). Sackungen scarps identified in the SGM can be up to several kilometers long; in contrast to faults, sackungen are expected to be rooted into the base of the topography. Lithology, rock strength, and orientation of the discontinuities all influence the expression of sackungen scarps.

Causes and Triggers

The rapid exhumation, uplift, and orographic process of the SGM have resulted in a dynamic and evolving landscape characterized by high relief, steep slopes, and extensively fractured bedrock, with fracture densities approximately five times greater than those found in the nearby north San Jacinto Mountains (DiBiase et al., 2018). These conditions create an environment highly susceptible to bedrock landsliding. Fractured crystalline bedrock with discontinuity planes (joints, bedding, foliations, cleavages, faults) are prevalent throughout the SGM and impact local rock strength, reducing cohesion and increasing landsliding susceptibility (e.g., Morton & Miller, 2006; McColl, 2022).

Long-term variability in precipitation through climate change or the removal of vegetation can raise groundwater levels, further reducing rock strength by increasing pore pressure within fractures and decreasing friction (Terzaghi, 1950; Varnes, 1978). On decadal timescales, mass wasting in the SGM is primarily driven by fire-flood-debris flow cycles, which facilitate denudation through the generation of dry ravel and debris flows (Lavé & Burbank, 2004). At centennial to millennial timescales, it is expected that extreme precipitation events and earthquake shaking are likely the primary dynamic failure trigger of bedrock landslides in the SGM, given the region's strong rainfall gradient and proximity to major fault systems (e.g., Bookhagen et al., 2005; Scherler et al., 2016).

1.1.3 Landslide Hazards

The proximity of failure-prone slopes, active faults, and pre-existing bedrock landslide deposits to the Los Angeles metropolitan area, local infrastructure, and numerous mountain communities, such as Wrightwood and Mount Baldy Village, pose significant hazards. Residential communities, commercial properties, and infrastructure situated downslope, downstream, or close to failure-prone slopes and pre-existing landslide deposits face an immediate risk of severe damage in the event of slope failure. Pre-existing landslide deposits, compared to bedrock source slopes, likely have a higher chance of activation as these deposits often consist of poorly consolidated debris and sediment. Wrightwood experiences recurring landslide and mudslide events due to precipitation and the proximity of the Wright Mountain Landslide, located less than 2 kilometers away (Morton & Campbell, 1978). Many Mount Baldy Village buildings are located either less than 2 kilometers downstream from the toe of the rock avalanche deposit at Manker Flat or directly atop it, placing them at immediate risk should the deposit reactivate. Furthermore, major roads and access roads cross over landslide deposits throughout the SGM, which could inhibit access to remote mountain communities during emergency situations should the deposits reactivate. As an illustrative example, a landslide in 1978 forced the closure of Highway 39, severing this major cross-range link up to 2024 when CalTrans began investigating options to reopen this 5 mile section of highway between Crystal Lake and Islip Saddle. Landslide mapping is timely to assess the feasibility of Highway 39 reopening by identifying potential slope hazards, assessing terrain stability, and guiding future mitigation efforts.

Additional hazards related to bedrock landslides include landslide damming, increased sediment generation, and drainage reorganization, which can further impact downstream areas. Landslide damming has occurred within the SGM, most notably the Hogback bedrock landslide as it previously dammed the San Antonio Canyon and formed a transient lake immediately upstream (e.g., Gentile, 2018). The breaching of a landslide dam can be catastrophic, as massive quantities of water and sediment are released downstream (Xia et al., 2020). Drainage reorganization, whether caused by stream capture or landslide dams, can also alter sedimentation, as changes to catchment areas affect river profiles, stream properties, and erosional patterns (Xia et al., 2020). Increased sediment generation from loose deposit sediments may exceed the storage and removal capacities of range-front debris basins. Scherler et al. (2016) document over 150-meter thickness of rapid valley-fill and subsequent downcutting following a major 4–5 ka landslide event in the North Fork San Gabriel Canyon; a similar event today would overtake highways, flood control, and reduce the volume of the reservoir downstream.

1.1.4 Landslide Inventory

A landslide inventory (LSI) typically documents landslide extents along with metadata such as activity, landslide type, direction of movement, deposit thickness, age, and interpretation confidence. The detail and accuracy contained within a LSI varies depending on the mapping method used, the scale, and purpose. Advancements in active remote sensing technologies have significantly reduced the uncertainty that previous aerial imagery mappers faced, particularly in heavily vegetated areas (e.g., Wills & McCrink,

2002). Landslide inventories have been widely utilized for: (1) assessing landslide susceptibility, seismic hazard, risk, distribution, and frequency (Harp et al., 2010; Guzzetti et al., 2012); (2) cross-correlating landslide morphometry with geomorphic and geologic information (Guzzetti et al., 2012); and (3) studying the impact of landslides on landscape denudation and evolution (Guzzetti et al., 2012). Notable examples include: (1) examining the effects of deep-seated landslides on the Southern Alps, New Zealand (Korup, 2006; Korup, 2010); (2) evaluating the influences of lithology, climate, topography, and tectonics on large landslides on northern margin of the Anatolian Plateau (Görüm, 2018); and (3) mapping coseismic landslides from the 1994 Northridge, California earthquake for seismic landslide hazard analysis (Harp & Jibson, 1996).

1.1.5 Previous Studies in California

Regional-scale mapping for the Los Angeles 30' x 60' Quadrangle (Yerkes & Campbell, 2005; Campbell et al., 2014) and the San Bernardino and Santa Ana 30' x 60' Quadrangle (Morton & Miller, 2006) has provided foundational geologic data for understanding the structural framework, lithology, and tectonic history of the region. Mapping of Quaternary surficial deposits (including landslides) in southern California was done by Bedrossian et al. (2012) to identify geologic hazards and natural resources that could affect development on alluvial fans. The California Geological Survey (CGS) has also been compiling and digitizing landslide maps into a web-based, statewide database (CGS Preliminary Landslide Inventory), an ongoing effort.

Additionally, many case studies on individual landslides have been conducted in California. The Blackhawk Rock Avalanche (Johnson, 1978) and Eureka Valley Rock Avalanche (Shaller et al., 2020) were examined to assess the mechanics behind long runout rock avalanches. The Minor Creek Landslide (Iverson & Major, 1987) was examined to assess rainfall and groundwater influence on landslide creep rates; creeping landslides on the Palos Verdes Peninsula were mapped by Bouali et al. (2017) using a combination of interferometric synthetic aperture radar (InSAR) and CGS LSI data, while Calabro et al. (2010) assessed seasonal deformation on the Portuguese Bend Landslide through InSAR. Several coastal landslides were assessed to determine failure factors, geomorphic characteristics, and climatic influences (Hapke & Green, 2006; Hapke et al., 2009; Young, 2015; Warrick et al., 2019). Several studies in Yosemite National Park assessed hazards and risks associated with rock falls, such as airblasts (e.g., Wieczorek et al., 2000; Guzzetti et al., 2003; Stock et al., 2011; Stock et al., 2014).

1.2 San Gabriel Mountains

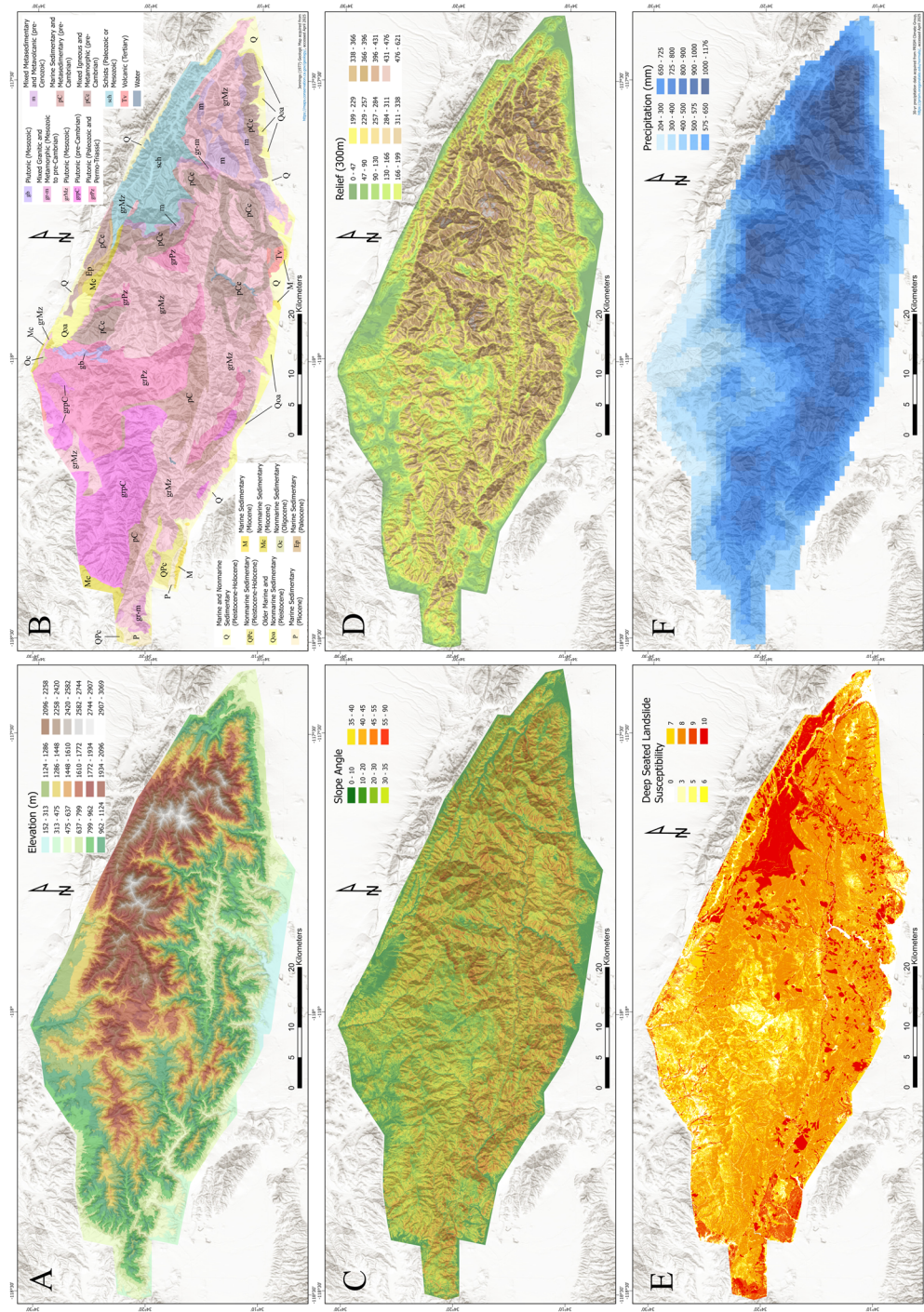


Fig. 3. Study area from **Fig. 1.** shown with several factors overlay on grayscale topography of the SGM. (A) elevation, (B) Jennings (1977) geologic map, (C) slope, (D) relief within 300 m radius, (E) deep-seated landslide susceptibility (Wills et al., 2011), (F) 30-year mean annual precipitation (PRISM Group).

The San Gabriel Mountains (SGM) are a roughly 2,400 km² tectonically active mountain range that is a prominent part of the Transverse Ranges of southern California, a distinct and anomalous group of mountain ranges rotated to an east-west trend in contrast to the northwest-southeast trend of the California Coast Ranges to the north and Peninsular Ranges to the south (e.g., Morton & Miller, 2006; Campbell et al., 2014). Mount San Antonio, colloquially known as “Mount Baldy,” is the highest peak within the SGM at 3,049 m (**Fig. 3A**). The SGM are situated adjacent to a restraining bend in the San Andreas Fault (SAF) and is bound by the SAF to the north and the Sierra Madre-Cucamonga Fault system and San Fernando Fault to the south. The San Gabriel Fault, a precursor to the modern SAF, and the associated San Gabriel catchment make up a significant portion of the SGM. The SGM borders the Los Angeles metropolitan area to the north and approximately 90% of the range drains south directly through the Los Angeles metropolitan area due to preferential coast-facing precipitation, erosion, and the general geometry of the SAF (Campbell et al., 2014).

The SGM are situated within a Mediterranean climate with seasonal variations between hot, dry summers and mild, wet winters (Eschel, 2002). Mean annual precipitation (**Fig. 3F**) between 1991–2020 falls between ~0.4 m/yr and ~1 m/yr with a snowline elevation of 2,000 m (DiBiase et al., 2010; PRISM Group, accessed February 2025). Vegetation type consists primarily of chaparral with minor regions of hardwood, shrub, conifer, and grassland (CALFIRE WHR13, accessed February 2025).

1.2.1 Bedrock Geology

Previous work has shown that the occurrence of landslides in the SGM are partially a function of the bedrock geology (Morton & Campbell, 1978). The SGM represent over a billion years of plutonic igneous and metamorphic rock, intrusive suites, sedimentary deposits, and volcanics (Blythe et al., 2002; Morton & Miller, 2006; Campbell et al., 2014). The following ages and rock types are summarized based on the geologic map of Jennings (1977) shown in **Fig. 3B**. The Jennings (1977) geologic map used in this study is sufficiently accurate for regional-scale analysis and was cross-validated with more recent geologic maps of the SGM. Its use also simplifies interpretation, as it excludes landslide deposit mapping, allowing for clearer assessment of the underlying bedrock geology associated with newly identified landslide deposits.

The Proterozoic rocks consist of plutonic anorthosite, gneiss, and mixed metamorphic and plutonic rock. The plutonic anorthosite and gneiss make up a large, uninterrupted portion of the western SGM while the mixed metamorphic and plutonic rock make up a moderate portion of the central and southeastern SGM. Bedrock landsliding, depending on local relief, is fairly prolific and several large bedrock landslide deposits are found to be sourced from Proterozoic rocks (e.g., Manker Flat Rock Avalanche, Crystal Lake Rock Avalanche). The Proterozoic rocks make up approximately 694 km² (~28%) of the SGM.

The Paleozoic rocks consist of plutonic rock, schist, and metasedimentary schist and gneiss. Most of the gently sloped relict topography—remnants of past environments or

geological periods—in the central western SGM, as well as small regions in the southwestern and central eastern SGM, is comprised of Paleozoic rock, though the relict topography is likely preserved by the relatively slow exhumation and uplift history of the central western SGM. Several large bedrock landslide deposits are found to be sourced from Paleozoic rocks (e.g., Alpine Canyon Rock Avalanche, Bichota Canyon bedrock landslides). The Paleozoic rocks make up approximately 384 km² (~16%) of the central SGM.

The Mesozoic rocks consist of early to middle Mesozoic mixed granitic and metamorphic rock, plutonic rock, granodiorite, tonalite, Pelona Schist of varying facies, and Cretaceous plutonic and metamorphic rock. The Pelona Schist predominates in the northeastern portion of the SGM, whereas the granitic and metamorphic rock are extensively distributed throughout the southwestern, southern, central, and eastern portions of the SGM. Notably, regions of Pelona Schist exhibit widespread and complex bedrock landslides (Morton & Campbell, 1978). The Mesozoic rocks make up approximately 1,097 km² (~44%) throughout the SGM.

The Tertiary units consist of marine and nonmarine sedimentary rocks, granitic rock, and volcanic rock. Oligocene granodiorite is found near Telegraph Peak in the easternmost region of the SGM (Morton & Miller, 2006). The Miocene volcanics, consisting of tuff breccia, andesite flow breccia, fine grained andesite, and basalt flows, are found on the southern range-front east of Big Dalton Canyon. Several Middle Pleistocene to Late

Miocene marine and nonmarine sedimentary formations (conglomerates, massive and interbedded sandstones, siltstones, and mudstones) are found in the westernmost region of the SGM. Holocene to Pleistocene-age alluvial deposits are found on the northern, eastern, and southern flanks of the SGM. The Tertiary units make up approximately 291 km² (~12%) of the SGM.

The CGS Deep-Seated Landslide Susceptibility map (**Fig. 3E**) utilizes rock strength and slope data to assess and categorize landslide susceptibility within California (Wills et al., 2011). In general, landslide susceptibility increases with slope and in weak, foliated rock where foliation is oriented parallel or sub-parallel to the slope. Within the SGM, large regions of high landslide susceptibility are associated with preexisting landslide deposits, Pelona Schist in the northeastern SGM, Tertiary marine and nonmarine sedimentary rocks in the western SGM, and steep valley walls.

1.2.2 Tectonic History

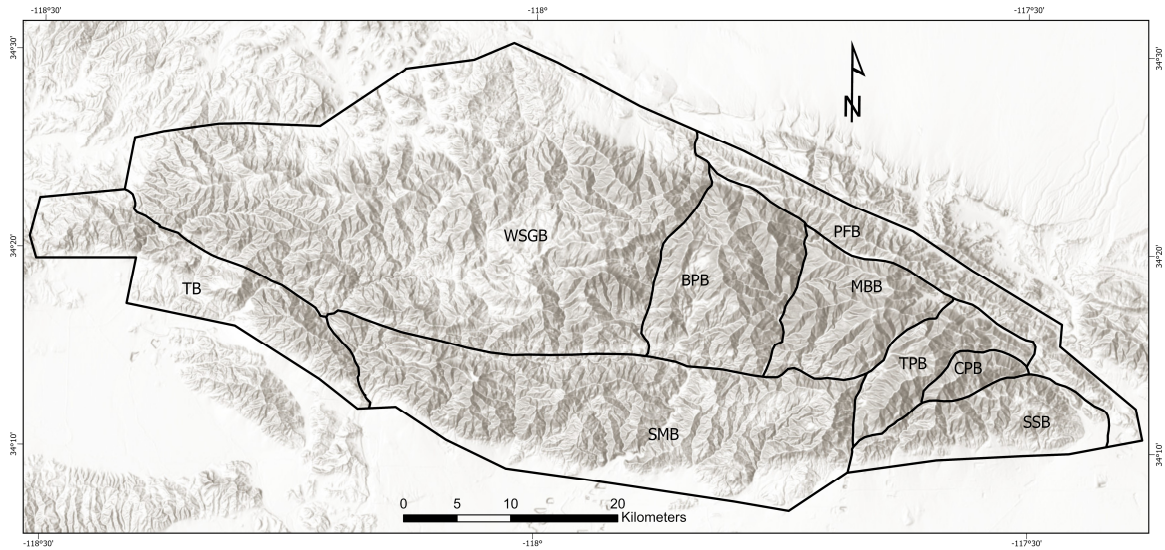


Fig. 4. Overview map of the San Gabriel Mountains, CA, showing topography in grayscale overlain with a modified version of the Blythe et al. (2002) fault blocks. Shown in this figure are the Tujunga block (TB), Western San Gabriel block (WSGB), Sierra Madre block (SMB), Baden-Powell block (BPB), Mount Baldy block (MBB), Punchbowl Fault block (PFB), Thunder Peak block (TPB), Cucamonga Peak block (CPB), and San Sevaine block (SSB).

The SGM, as with other components of the Transverse Ranges such as the San Bernardino Mountains, are closely tied to the activity of the SAF system. Differences in exhumation rate, history, and lithology between the SGM and the San Bernardino Mountains suggest that the structural evolution of both mountain ranges occurred independently of each other (Blythe et al., 2002; Spolita et al., 2002).

Table 1

Fault block topography and bedrock landslide description (this study after Blythe et al., 2002).

Name of Block	Topography	Bedrock Landslide Deposits
Western San Gabriel	In general, elevation and relief increase from west to east. Most of the central region is relict topography with low relief, smooth topography, and an elevation range between ~1,500–1,900 m. Peak elevation is 2,504 m at Mount Williamson.	Deposits are either extremely modified or do not exist in the relict topography region. Deposits are found mostly in the central and western regions. Deposit frequency does not increase with relief.
Tujunga	In general, elevation and relief increase from west to east. Elevation and relief is similar to the Western San Gabriel block, but does not reach similar peak elevations. Low relief and elevation exist between Pacoima and Big Tujunga Canyon with elevation decreasing slightly from west to east. Peak elevation is 1,548 m at Mount Lukens.	Deposits are generally concentrated in high relief regions, sedimentary rocks, and along the Lakeview fault of the Sierra Madre fault zone. Deposits are also found in the low relief region, which may explain the abnormal change in elevation and relief from west to east.
Sierra Madre	Elevation decreases slightly from west to east until San Dimas Canyon, where elevation increases slightly from west to east. Relief remains high from west to east and decreases slightly east of San Gabriel Canyon. The San Dimas catchment, located on the easternmost region, exhibits abnormally low elevation and relief. Peak elevation is 1,767 m at Sunset Peak.	Deposits generally do not coincide with high relief. Deposits are highly concentrated between San Gabriel and San Dimas Canyon, with moderate frequency west of San Gabriel Canyon. Rock avalanche deposits exist (e.g., Brown's Flat) and may explain the abnormal topography in the San Dimas catchment.
Baden-Powell & Mount Baldy	Elevation increases from south to north. Relief is moderate to high. Contains the highest elevation and relief of the SGM near Mount Baden-Powell and Mount San Antonio. Vincent Fault does not affect topography, but instead divides lithologies. Peak elevation is 3,049 m at Mount San Antonio.	Contains the largest rock avalanches in the SGM (e.g., Crystal Lake, Alpine Canyon, Manker Flat, Cow Canyon, Doe Flat) as well as bedrock slumping of moderate relief Pelona Schist in the northern regions.
Punchbowl	Elevation increases inward towards the central region. Relief is low with moderate to high relief towards the central region. Region consists primarily of Pelona Schist. Peak elevation is 2,294 m at Table Mountain.	Deposits likely cover most of the slopes, but are modified to the point of obscurity. Mapped deposits cover most NE-facing slopes in the eastern half of the block. Bedrock slumping is observed for most of the deposits, except for larger, more catastrophic landslides, such as the Mount Wright Landslide (Morton & Campbell, 1978).
Thunder Peak, Cucamonga Peak, & San Sevaine	Elevation increases from south to north until Cucamonga Peak, where elevations slightly decrease northward. Relief varies from low to high depending on region; relief is high near mountain peaks and South Fork Lytle Creek, while San Sevaine Flats exhibits relict topography and moderate elevation between ~1,400–1,700 m. Peak elevation is 2,740 m at Telegraph Peak.	Several rock avalanche deposits sourced from the Thunder Peak block are located in San Antonio Canyon. Deposits, otherwise, are scarce throughout all blocks and are either extremely modified or do not exist in relict topography regions.

Fault-Bounded Blocks

In a thermochronology study, Blythe et al. (2002) divide the SGM into nine fault-bounded blocks with distinctive thermal histories, rock types, and topography: the Western San Gabriel, Tujunga, Baden-Powell, Sierra Madre, Baden-Powell, Mount Baldy, Punchbowl, Thunder Peak, Cucamonga Peak, and San Sevaïne blocks. This study slightly modifies the boundaries of the blocks defined by Blythe et al. (2002) based on modern mapping techniques and an expanded geographic scope (**Fig. 4; Table 1**).

Evolution of Fault Blocks

Paleomagnetism data indicate that the SGM rotated roughly 50 degrees clockwise from ca. 25 Ma to 10 Ma and roughly 16 degrees counterclockwise from ca. 12 Ma; this totals to approximately 35 degrees of clockwise rotation (Terres & Luyendyk, 1985; Hornafius et al., 1986; Blythe et al., 2002). The SAF restraining bend controls the overall tectonic setting of the SGM, however the main SAF trace does not directly cut through the SGM; strain was instead transferred from the SAF to the San Gabriel Fault (SGF), then the Punchbowl-Wilson Creek Fault during the exhumation of the SGM (Blythe et al., 2002).

The most recent phase of exhumation in the SGM began approximately 12 Ma with the activation of the southern strand of the SGF, currently known as the Sierra Madre Fault (SMF), which primarily exhibited strike-slip motion until 7 Ma. This phase was particularly pronounced in the Sierra Madre block (SMB), where exhumation was driven by a constraining bend along the active southern brand of the SGF. Initially, exhumation

rates remained relatively low (<0.35 mm/yr) across the Western San Gabriel block (WSGB), Baden-Powell block (BPB), and SMB (Blythe et al., 2002).

Approximately 7 Ma, exhumation intensified, particularly in the SMB and Mount Baldy block (MBB). The Tujunga block (TB) experienced less cooling, suggesting that by this time, the SMF had transitioned into a reverse fault as activity switched from the southern strand of the SGF to the northern strand. Between 7 and 5 Ma, exhumation rates exceeded 0.3 mm/yr in the SMB and TB, with the Mount Baldy block (MBB) reaching rates of ~ 0.7 mm/yr. Similar rates may have affected other northeastern SGM blocks during this time, as inferred by depositional patterns in the Los Angeles Basin. By 5 Ma, the Cucamonga Peak block (CPB) and MBB underwent >0.4 mm/yr exhumation, with the San Gabriel Canyon region of the SMB reaching rates of ~ 0.7 mm/yr. Exhumation rates near Mount Wilson of the SMB appear much lower (~ 0.3 mm/yr). Around this time, the Punchbowl-Wilson Creek fault strand of the SAF became active and replaced the SGF, stopping all strike-slip motion on the SGF by 5 Ma.

Exhumation rates mostly remain unchanged from 5 to 3 Ma, with the Thunder Peak block (TPB) exhibiting the highest rates (>1.1 mm/yr) (Blythe et al., 2002). During this time, the active strand of the SAF switched from the Punchbowl-Wilson Creek strand to the Mission Creek strand (Matti & Morton, 1993). The San Seivaine block (SSB) did not experience significant exhumation until 3 to 1.5 Ma, implying that the block-bounding Cucamonga Fault (CF) was not active previously. At approximately 1.5 Ma, the CF and San Jacinto

Fault (SJF) became active along with potentially high exhumation rates for the SSB. Composite InSAR, GPS, leveling, and tide gauge data by Hammond et al. (2017) show that the areas of the SGM are actively uplifting at a rate of up to ~2 mm/yr concentrated in the eastern SGM. In contrast, Mere & McPhillips (2024) argue that uplift along the range front is more uniform compared to previous work.

Major Active and Inactive Faults

Active, high angle, reverse faults along the southern SGM range front, such as the Sierra Madre-Cucamonga Fault system and the San Fernando Fault, are the primary drivers of modern uplift and account for approximately 1 mm/yr of vertical slip with a progressive increase of dip-slip fault motion from west to east, generally consistent with topographic relief of the SGM (Blythe et al., 2002; Spolita et al., 2002; Lindvall & Rubin, 2008; DiBiase et al., 2009; Burgette et al., 2020). Secondary active faults within the SGM, such as the San Antonio Fault and San Jacinto Fault system, accommodate Quaternary slip (Blythe et al., 2002; Mere & McPhillips, 2024). Several anomalous major north-south trending channels within the SGM, such as the headwaters of the Bear Creek and North Fork San Gabriel River, may be controlled by faults; San Antonio Canyon, a major north-trending drainage located in the eastern SGM, is controlled by the San Antonio Fault (Blythe et al., 2002).

The Late Miocene SGF and Punchbowl Fault (PF), both of which are thought to be inactive right-lateral strike-slip faults, accommodated tens of kilometers of SAF motion during different periods of the SGM exhumation (Blythe et al., 2002). The northern strand of the

SGF, active prior to the PF, is subparallel to the Sierra Madre-Cucamonga Fault system and is expressed as a major physiographic boundary within the SGM as topography, relief, and elevation typically differ drastically across the fault. The PF lies subparallel to the main strand of the SAF and, like the SGF, is expressed as a major physiographic boundary within the SGM. Unlike the SGF and PF, the Tertiary Vincent Fault, an inactive fault located in the central-eastern SGM, is expressed mostly as a lithologic boundary (e.g., Morton & Miller, 2006).

1.2.3 Previous San Gabriel Mountains Landslide Studies

A handful of studies have investigated landslides within the San Gabriel Mountains, focusing on their characteristics, contributing factors, and impact on landscape evolution. Early work by Morton & Campbell (1978) documents recurring landslide and mudslide cycles caused by precipitation on the Mount Wright Landslide. McCalpin & Hart (2003) document and categorize sackungen along with their relationship to landslides. Morton & Miller (2006) discusses the characteristics, lithology, and topographic influence of landslides in the SGM for the San Bernardino and Santa Ana 30' x 60' Quadrangle. More recent work by Scherler et al. (2016) suggests a bedrock landslide origin for multi-leveled terraces within the North Fork of the San Gabriel Canyon, while Del Vecchio et al. (2018) assesses whether landslide deposits dominate long-term chemical solute flux. Nourse et al. (2020) build on data acquired by Scherler et al. (2016) and Del Vecchio et al. (2018) and highlights significant hazards associated with late Quaternary-Holocene landslides in the

SGM, specifically San Antonio Canyon. Several MSc theses have also investigated prominent bedrock landslides (Cortez, 2006; Gentile, 2018; Agunwah, 2020).

1.3 High-Resolution Topography and LiDAR

Light Detection and Ranging (LiDAR) is a remote-sensing technology that employs the use of rapidly emitted lasers to measure distance by calculating the time differential between the emitted laser and its reflection. LiDAR is utilized in two ways: ground level measurements via Terrestrial Laser Scanning and airborne measurements via Airborne Laser Scanning (ALS).

Ground level measurements allow for highly detailed scans at outcrop scale as well as the ability to survey vertical surfaces as the device remains stationary. Given the precision and accuracy of Terrestrial Laser Scanning techniques, repeat surveys can be conducted to assess spatio-temporal variation in the landscape. In contrast, ALS is best utilized for landscape-scale surveying and provides less detail compared to Terrestrial Laser Scanning as ALS can survey large swaths of area relatively broadly and quickly. Although both generate a cloud of points in 3D space, which can be strategically filtered to generate different products, ALS is preferred to Terrestrial Laser Scanning in this study; detailed landscape-scale surveying via Terrestrial Laser Scanning is highly time and labor intensive, difficult to conduct in rugged and/or heavily forested terrains, and can lead to subpar surveying as a ground level view can obscure visibility due to the vegetation and topography of the landscape.

In ALS surveys, a small portion of the LiDAR emissions penetrate gaps in vegetation and return from the underlying ground surface. Filtering algorithms are then applied to classify the point cloud and isolate the lowest ground-classified points (Wehr and Lohr, 1999). This subset of ground points can then be triangulated and gridded to create a bare earth high-resolution LiDAR-derived digital elevation model (DEM) with typical pixel resolutions of 1 m, bypassing the typical vegetation obfuscation encountered with other remote-sensing methods (e.g., Meigs, 2013).

LiDAR-derived products have been proven to be integral to the study of tectonically active regions and the understanding of fault kinematics, fault zone structure, long term fault slip rates, earthquake hazards, and paleoseismic history (Meigs, 2013; Sun et al., 2022). These products are also indispensable for various geomorphological modeling processes (e.g., floods, debris flow, avalanches; Höfle & Rutzinger, 2011), fieldwork (Roering et al., 2013), and the production of highly detailed LSI, which in turn can be utilized for assessing landslide activity, susceptibility, hazard, and risk (Chen et al., 2014; Meigs, 2013; LaHusen et al., 2016; Görüm, 2019).

1.4 Motivation of Thesis

This study aims to quantify the role of bedrock landsliding in shaping the SGM, which is critical for understanding the drivers of landscape evolution. Previous studies have suggested that fire and flood cycles primarily govern modern erosion and denudation in

the region (Lavé & Burbank, 2004). However, a more comprehensive assessment of bedrock landsliding is needed to better understand its contribution to sediment generation, drainage reorganization, and long-term geomorphic changes, such as drainage reorganizations and epigenetic gorges. Additionally, a detailed investigation into lithologic controls on bedrock landsliding will work towards testing a seemingly counterintuitive hypothesis based on an unpublished observation by Doug Morton: that the strongest rocks in the SGM produce the largest landslides. This hypothesis challenges the conventional assumption that weaker, more erodible lithologies are inherently more landslide-prone. Instead, it suggests that competent crystalline rocks, while generally stable, can accumulate large volumes of stress over time and fail catastrophically when thresholds are exceeded. By comparing landslide area, volume, and frequency across contrasting lithologies, this study aims to evaluate whether material strength correlates with larger failure magnitude.

Using the LSI generated, this study assesses the location, abundance, and recurrence of bedrock landsliding, as well as their potential impacts on residential communities, commercial properties, and infrastructure. Landslide-induced sedimentation and damming present significant hazards as increased sediment generation can overwhelm debris basins, and the potential breaching of landslide dams can trigger catastrophic downstream flooding and sediment release (Fan et al., 2020). Identifying potential triggers, such as precipitation and seismic activity, is crucial for improving mitigation strategies and risk management practices.

This study presents a novel, systematic LSI of an active orogen, utilizing high-resolution, range-scale LiDAR coverage to produce what is likely the most detailed and comprehensive LSI of an active orogen—surpassing those by Delgado et al. (2022) in the Central Western Andes and Lazzari & Gioia (2015) in the Southern Apennines of Italy. The CGS LSI for the SGM currently consists of a patchwork of multiple generations of landslide maps and mappers, resulting in inconsistent coverage, detail, and mapping styles. While informed by the CGS *Landslide Mapping Operations Guide* (2021, unpublished), this study applies a methodical and systematic approach to produce a consistent, range-wide inventory, which will ultimately contribute to and enhance the CGS LSI. A standardized approach is critical for ensuring data accuracy, reducing mapping inconsistencies, and improving hazard assessment, particularly in an active orogen like the SGM. The framework established here can serve as a model for future regional-scale LSI efforts in active orogens.

2.0 Methods

2.1 LiDAR Datasets & Processing

Available airborne LiDAR (ALS) point clouds of the ~2,470 km² study area were downloaded and processed into visualization products that could be used to identify and map the locations and boundaries of bedrock landslide deposits located in the SGM. Several ALS LiDAR survey datasets were required to cover the entire area of study:

Los Angeles County: CA LosAngeles 2016. ALS data. Survey area: 11,077 km². Encompasses the Los Angeles County portion of the study area (~2,134 km²). Point Density: 6.79 pts/m². Survey Date: 09/27/2015–10/18/2016.

San Bernardino County: CA SoCal Wildfires B1 2018. ALS data. Survey area: 8,075 km². Encompasses most of the San Bernardino County portion of the study area (~ 333 km²). Point density: 5.86 pts/m². Survey Date: 05/27/2018–10/12/2018.

Wrightwood: CA SanBern EMRI 2 2021. ALS data. Survey area: 7,751 km². Encompasses part of the Wrightwood area that is not covered by the two previous datasets (~ 3 km²). Point density: 4.00 pts/m². Survey Date: 11/07/2021–11/16/2021.

The pre-classified point clouds for the regions of interest were downloaded from OpenTopography (<https://opentopography.org/>) or USGS The National Map (<https://apps.nationalmap.gov/downloader/>). Using the blast2dem script of LAStools software (<https://lastools.github.io/>), the ground classed points (classification = 2) were used to create a seamless TIN that was then rastered into a DEM with 1 m pixels. These separate tiled raster products were then merged into a new raster with manageable file sizes. The large individual, and subsequently cumulative, file sizes of the LiDAR data required careful management and significant processing resources. A 1 mi² tile of the raw point cloud in the LAZ file format is ~200 MB (~43 million points) with the ground-only file size being ~115 MB per tile (~4 million points). The Los Angeles County-extent DEM product is ~24 GB in size with some derivative products like the multi-hillshade being ~13 GB. Relatedly, computers with capable computational and graphical processing needed to be used at all times.

Several first and second-order derivatives of the DEM (e.g., aspect, slope, multi-hillshade) were then generated with Relief Visualization Toolbox (<https://iaps.zrc-sazu.si/en/rvt>) or ArcGIS Pro 3.4.3 for data visualization and the manual interpretation of curvilinear features and bedrock landslides. These products were also used for terrain analysis. The multi-hillshade visualization uses colored light from multiple directional sources to illuminate details that are obscured in traditional, single-source grayscale hillshade methods. Traditional hillshading typically obfuscates features parallel to the direction of the light source as well as details in shadows due to undersaturation (Kokalj & Somrak, 2019). Multi-hillshades are particularly effective at visualizing both scarp-like features and surface textures.

2.2 Landslide Inventory Methodology

To generate a detailed and systematic landslide inventory (LSI) of the SGM, several sequential steps were taken, as detailed below.

Given the effectiveness of multi-hillshade visualization as described by Kokalj & Somrak (2019), grayscale hillshading was not used for manual interpretation and mapping in contrast to its standard use. The multi-hillshade visualization itself was the primary visualization method used within ArcGIS Pro 3.4.3, though a translucent grayscale slope raster was overlain occasionally as an additional visualization method. Web-served satellite imagery linked within ArcGIS Pro and aerial imagery from Google Earth Pro were also often used to aid in the manual interpretation of bedrock landslides. Although the

majority of the bedrock landslides in the SGM are identified based on geomorphology partially obscured by vegetation in aerial imagery, bedrock landslides can occasionally be identified by visible angular carapace boulders and changes in vegetation patterns.

ArcMap 10.8 was initially used as the primary interpretation and mapping program, but due to ESRI ending support for ArcMap in 2024, this study migrated to ArcGIS Pro 3.4.3 partway through the mapping process. The multi-hillshade rasters were imported to ArcGIS Pro 3.4.3 to function as the basemap for the study area. The 1 m DEM was also imported for analysis with ArcGIS Pro 3.4.3 tools and to serve as a high-resolution elevation source for the program's 3D Scene function; the 3D Scene function functions similarly to the 3D visualization and navigational capabilities of Google Earth Pro. Supplementing 2D mapping with 3D visualization was indispensable as the complexities of the SGM topography and travel paths and deposition of bedrock landslides often led to counterintuitive landslide deposit extents (**Fig. 5**).

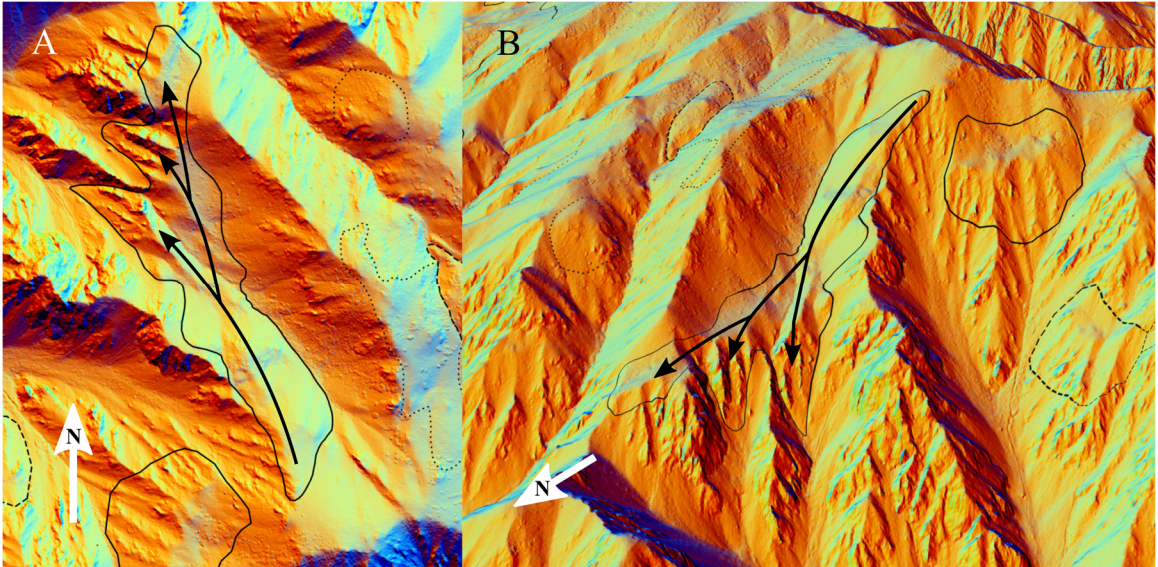


Fig. 5. Multi-hillshade view of a complex landslide extent found in Cherry Canyon, east of San Antonio Canyon. The deposit sits atop several steep ridges. Black arrows denote the travel path of the deposit. (A) plan view, (B) perspective view.

The 3D visualization capabilities of both ArcGIS Pro 3.4.3 and Google Earth Pro (with 1.5x vertical exaggeration) were utilized to aid in the interpretation of curvilinear features and bedrock landslide deposits. ArcGIS Pro 3.4.3 became the primary 3D visualization method once the author migrated from ArcMap 10.8 to ArcGIS Pro 3.4.3 as Google Earth Pro uses far lower resolution elevation sources for the area of study compared to the 1 m DEM used in this study.

The initial step towards generating the LSI was to identify and map all curvilinear features associated with slope failure which, in this study, refers to any downward movement of bedrock under the influence of gravity. This encompasses various modes of movement, including bedrock landsliding, where rock slides along a defined failure surface. This approach is analogous to creating a lineament map for tectonic studies. Generating the LSI

was done by manually interpreting and mapping curvilinear features as polylines in ArcGIS Pro 3.4.3 to a “landslide curvilinear features” shapefile. Examples of curvilinear features include sackungen scarps, headscarps, pronounced deposit edges, and internal deposit features such as fissures and transverse ridges (**Fig. 6**).

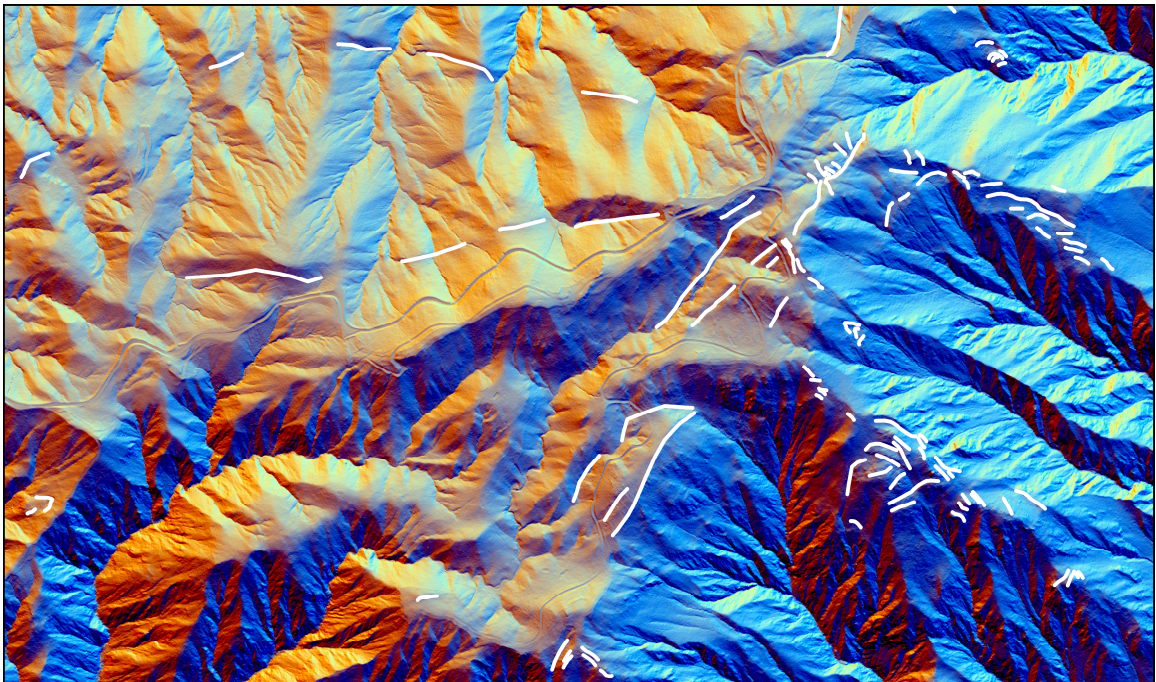


Fig. 6. Multi-hillshade view of several curvilinear features (white lines), such as sackung scarps, headscarps, and transverse ridges. Note that curvilinear features are not necessarily indicative of landslide deposits and often represent slope failure instead. These features are located at 34.300994°N, -118.302892°W.

The non-specific nature of this classification enables high confidence curvilinear features to be mapped and reduces the need for subjective interpretation. The generated curvilinear feature shapefile provides a comprehensive view of all areas affected by slope failure and serves as an important foundation for more detailed traditional polygonal mapping of bedrock landslide deposit extents and source areas. The author and his advisor

independently mapped curvilinear features and the resulting maps were refined and merged into a “UCR” curvilinear feature polyline shapefile.

The extents of bedrock landslide deposits were then interpreted and manually mapped as polygons in ArcGIS Pro 3.4.3 to a “landslide deposit” shapefile. Geologic maps, such as Campbell et al. (2014) and Morton & Miller (2006), and the CGS LSI were used to assist in bedrock landslide interpretation and mapping. Shapefiles for these maps were downloaded to isolate and extract polygons related to landslides. Unlike the CGS mapping procedures—CGS *Landslide Mapping Operations Guide* (2021, unpublished), an unpublished internal document obtained directly from CGS staff—this study did not apply a minimum landslide deposit size threshold based on screen resolution (e.g., 1:2000 scale), minimum map unit width (e.g., 30 m), or area (e.g., 0.2 acres). Given the consistent quality of the LiDAR data across the 2400 km² study area and its 1 m resolution, this study prioritized mapping directly to the data resolution, with the understanding that smaller deposits could be filtered by area during post-processing. All bedrock landslide deposits were assigned one of three confidence levels: Definite, Probable, and Questionable (**Fig. 7**).

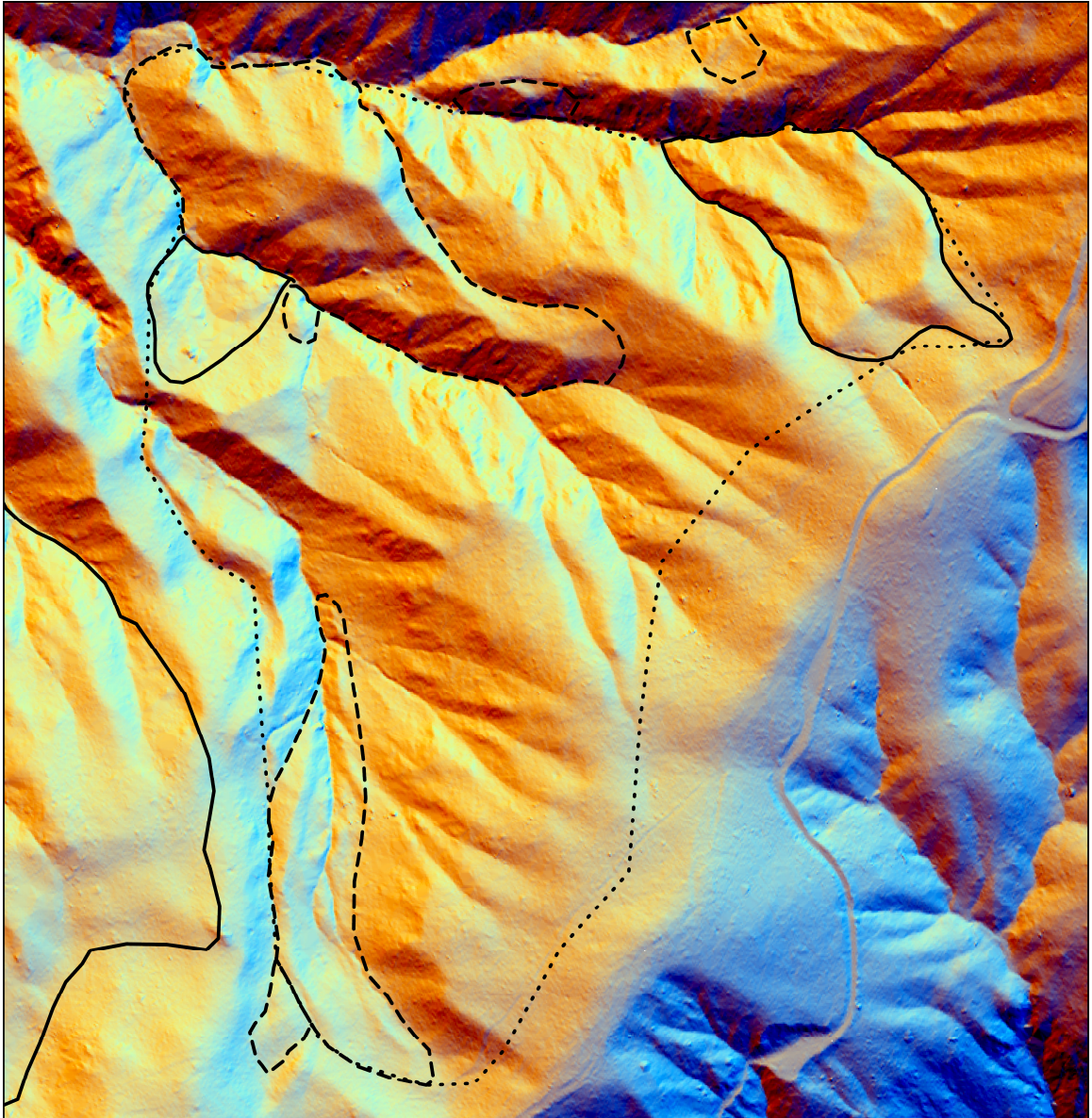


Fig. 7. Multi-hillshade view of a landslide complex which exhibits all three confidence levels: Definite (solid line), Probable (dashed line), and Questionable (dotted line). The landslide complex is located at 34.273611°N, -118.083611°W.

A confidence level of “Definite” indicates that the landslide deposit exhibits multiple diagnostic landforms—such as prominent scarps, deposit edges, or internal hummocky topography—and is interpreted with high certainty (100% confidence). These features often correspond with recent, historic, or active slope movement. A confidence level of

“Probable” applies to deposits with one or more geomorphic features indicative of landsliding, though they may be modified by erosion or obscured; the deposit is interpreted as a landslide with moderate confidence (75%). A confidence level of “Questionable” is assigned when geomorphic indicators are few, subtle, or ambiguous, and alternative explanations (e.g., erosional or depositional processes) are plausible; these deposits are interpreted with low confidence (50%) and may require field validation. These definitions are based on the *Landslide Mapping Operations Guide* developed by CGS (2021, unpublished).

Given that older bedrock landslide deposits often reactivate, overlapping polygons were utilized to delineate the different generations of landslides within the same deposit if the geomorphic “freshness” was distinct enough to suggest separate events. Previous LSI, such as the CGS LSI, incorporated headscarps of larger deposits in their polygon mapping. In contrast, this study deliberately excluded mapping excavated headscarp areas to more accurately assess landslide deposit area and volume, with the exception of instances where landslide debris was observed on the headscarp. Like the curvilinear feature polyline shapefile, the author and his advisor independently mapped landslide deposits and the resulting maps were refined and merged into a combined “UCR” landslide deposit polygon shapefile.

2.3 Spatial Analyses

All spatial analyses performed for this study were done in ArcGIS Pro 3.4.3. Standard tools referenced below are italicized and included in toolbox suites available in ArcGIS Pro.

Landslide Density: Total length (or count) of features per unit area. Lineament and landslide density analyses were performed on the lineament polyline and landslide polygon dataset, after using *Feature to Point* set to “Inside,” with the *Line Density* and *Kernel Density*. For landslide area density analysis, the landslide polygon dataset was rasterized at 1 m resolution using the *Polygon to Raster* and assigned a value of 1 per pixel. *Focal Statistics* (set to the “Sum” Statistic type and a 1 km radius circular neighborhood) was then applied to generate broad-scale density patterns; a radius of 1 km was selected to avoid overrepresenting the fine-scale structure of the original features.

Landslide Volume: To accurately assess landslide volume, several steps were taken to identify the total amount of landslides that exclude overlapping landslides; a negative buffer of 1 m was applied to the landslide polygon dataset with *Buffer* in order to separate and isolate adjacent landslide polygons which share the same boundary. *Dissolve* was used to merge overlapping polygons and *Buffer* was used again to apply a positive buffer of 1 m to restore the landslide polygons to their original extent. The resulting merged dataset was used to estimate cumulative landslide area and volume. To approximate the volume of landslide deposits without comprehensive in-field measurements, the empirical equation from Guzzetti et al. (2009) was utilized with the merged landslide area:

$$V_L = 0.074 \times A_L^{1.450}$$

with A_L in m^2 and V_L in m^3 . The volume-area relationship established by Guzzetti et al (2009) is based on 677 well-documented landslides from a global database and demonstrates a robust empirical correlation expressed as a power law with a scaling of 1.45. Despite the diverse lithologic, morphologic, and climactic settings—and varying landslide triggers such as rainfall, earthquakes, and snowmelt—their dataset exhibits limited scatter, supporting the validity and broad application of the relationship (Guzzetti et al., 2009). The parameters for the equation ($\alpha = 1.450$ and $k = 0.074$) have also been validated by Jaboyedoff et al. (2020) for large landslides.

Slope: The rate of change of elevation expressed in degrees. Analysis of slope across the SGM was performed with *Slope* applied to the 1 m LiDAR DEM, and slope values across the landslide-affected area were extracted using *Extract by Mask*. Given that the generated SGM and landslide slope rasters excluded Attribute Tables, both datasets were passed through *Int* to convert floating-point values to integers to enable Attribute Table generation via *Build Raster Attribute Table*—this tool only accepts integer values.

Geology: Landslide polygons were assigned geologic units by clipping the Jennings (1977) geologic map to the landslide extents with *Pairwise Clip*, and determining the dominant unit per polygon with *Summary Statistics* set to the “Maximum” Statistic type.

Deep-Seated Landslide Susceptibility: Combines slope, lithology, and historical landslides in weighted classes. Numerical categories for deep-seated landslide susceptibility were obtained from Wills et al. (2011; <https://data.ca.gov/dataset/cgs-map-sheet-58-deep-seated-landslide-susceptibility>) and extracted to landslide points using *Extract Value to Points*, and to lineament polylines using *Intersect*.

Relief: The vertical difference between the highest and lowest elevation within a given area. *Focal Statistics* set to a 300 m radius “Circle” neighborhood and the “Range” Statistic applied to the 1 m LiDAR DEM captured relief with minimal distortion from nearby ridges and drainages. The resulting SGM relief raster was clipped to the extent of the merged landslide dataset using *Extract by Mask*. Both the SGM relief raster and the merged landslide relief raster were then processed with *Int* to convert floating-point values to integers and enable Attribute Table generation.

Ridge Density: Local concentration of ridge-classified terrain. Topographic Position Index (TPI), implemented via *TPI (Weiss)* from Dilts (2023) Topographic Toolbox Pro, was used to evaluate ridge density as a proxy for drainage density (desirable since ridges and their slopes are the source of landslides). TPI classifies terrain by comparing the elevation of nearby data points to distinguish topographic features ranging from ridges to valley floors (Fig. 8).

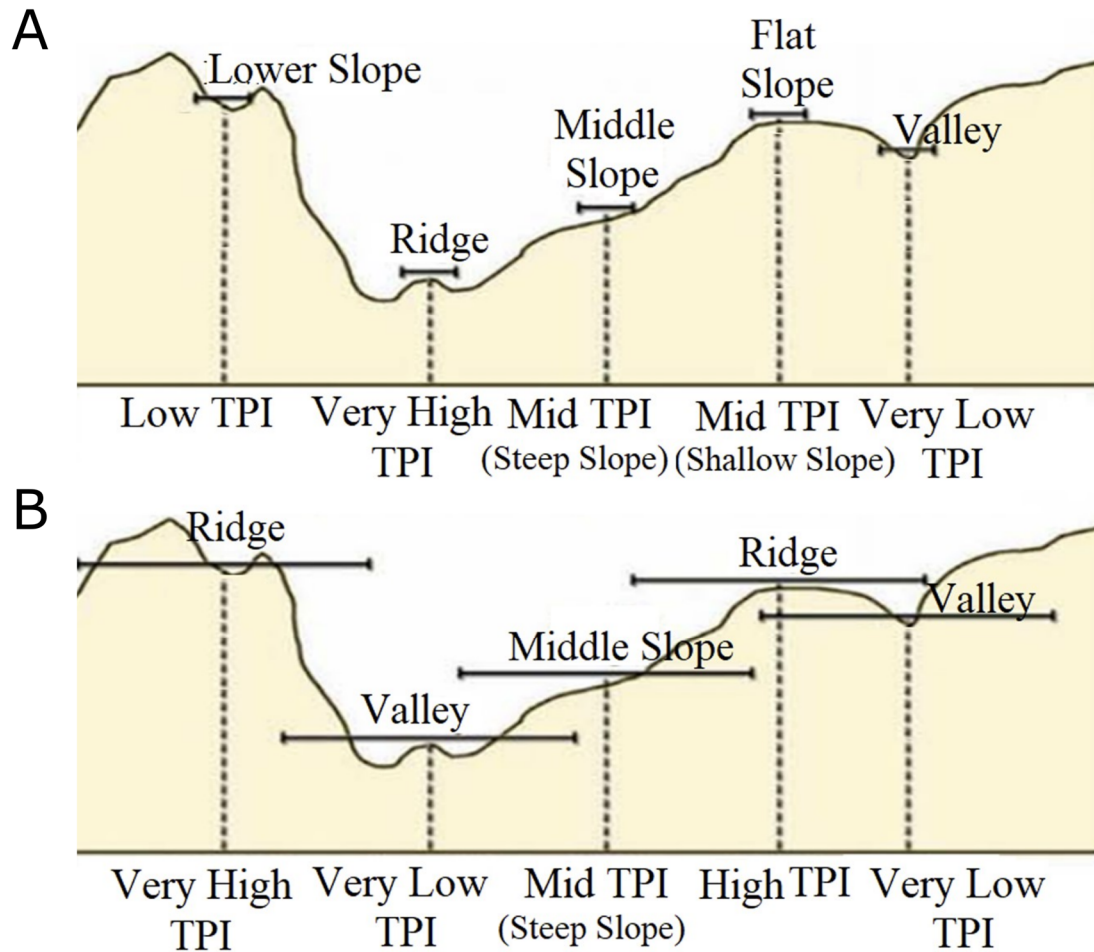


Fig. 8. Figure acquired from Al-Sababhah (2023). The size of the neighborhood used for TPI dictates the scale at which topographic features are to be interpreted. (A) small scale neighborhood and its relation to TPI, (B) large scale neighborhood and its relation to TPI.

The SGM TPI raster was derived from the 1 m LiDAR DEM using the “Rectangle” neighborhood set to 125 m × 125 m. A 125 m neighborhood and threshold TPI value > 9 were selected to isolate ridge features while minimizing overrepresentation and ensuring the inclusion of smoothed, relict ridges. These ridge pixels were isolated and assigned a value of 1 with *Raster Calculator* and ridge density analysis was calculated with *Focal Statistics* with the “Sum” Statistic type and a 300 m radius. This radius was chosen to

reduce distortion from adjacent terrain features. TPI-derived ridge density serves as a topographically consistent substitute for drainage density across the SGM.

Spectral Acceleration (SA10): The maximum acceleration response of a structure within a 1.0-second period subjected to a given ground motion and is represented in units of g (acceleration due to Earth's gravity). Although not directly related, this study used SA10 as a proxy for surface motion. Numerical values for spectral acceleration were obtained from Branum et al. (2016), and extracted to landslide points using *Extract Value to Points*.

Precipitation: Mean annual precipitation data (30-year average at 800 m areal resolution) was acquired from the PRISM Group (accessed February 2025), vectorized using *Raster to Polygon*, and clipped to the merged landslide extent with *Pairwise Clip*.

Roads and Buildings: Road, path, and building footprint datasets were obtained from OpenStreetMap (accessed March 2025) and Microsoft US Building Footprints (accessed April 2025). Both datasets were clipped to the merged landslide extent using *Pairwise Clip* to assess anthropogenic presence in landslide-prone areas. Definitions of roads were obtained from OpenStreetMap.

3.0 Results

3.1 Lineament Statistics

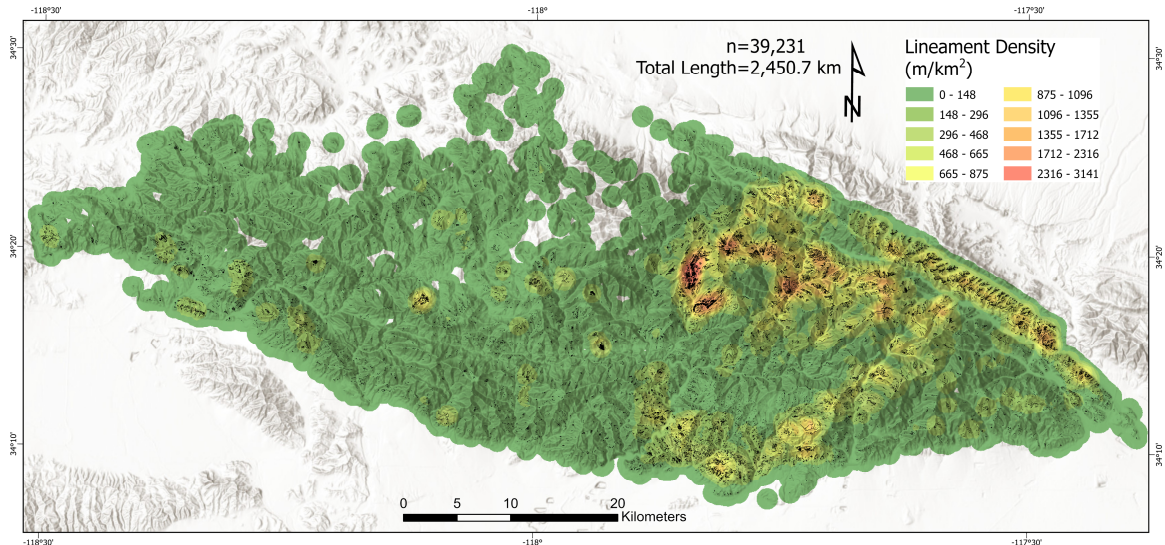


Fig. 9. Overview map of the San Gabriel Mountains, CA, showing topography in grayscale overlain with a density map of landslide lineaments produced with a 1km radius and a 50m cell size. Lineaments (black lines) show curvilinear features associated with slope failure.

This study mapped 39,231 individual landslide lineaments, resulting in a cumulative length of 2,450.7 km (**Fig. 9**). Lineament frequency is heavily biased towards high contrast curvilinear features found in young landslides and rock avalanches, such as the Crystal Lake and Alpine Canyon rock avalanches, as well as the Pelona Schist “bedrock slumps,” a term coined by Morton & Campbell (1978) to describe the abnormally slow displacement of schist landslide deposits found near Wrightwood, CA. This study interprets that regions of high lineament density generally correspond with areas of high landslide density. In particular, the San Antonio Canyon, the San Dimas Experimental Forest, and the southwestern range front all display varying but consistently overlapping patterns of lineament and landslide density.

3.2 Landslide Inventory Statistics

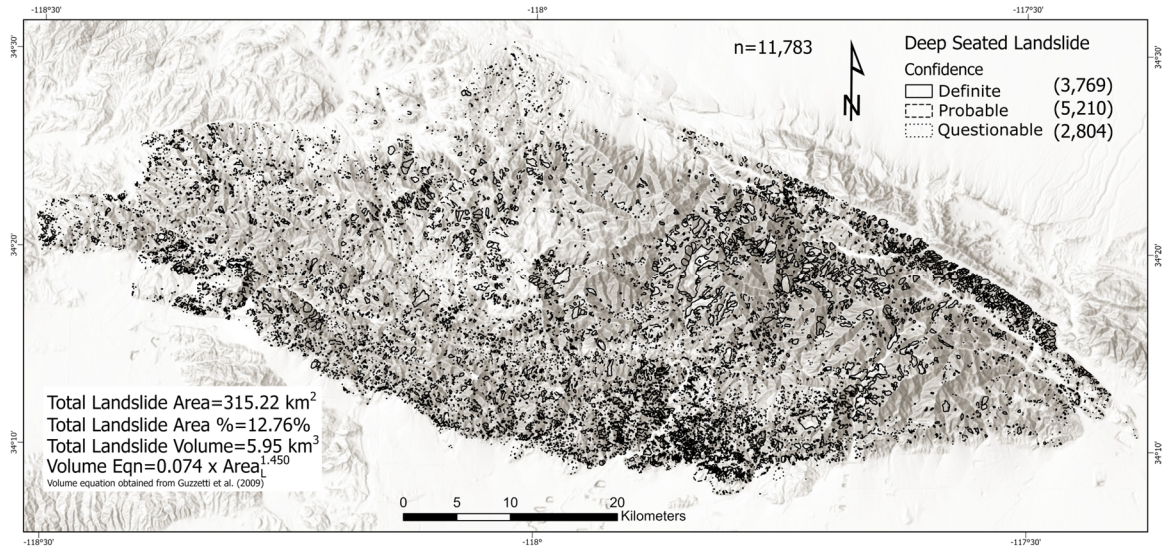


Fig. 10. Overview map of the San Gabriel Mountains, CA, showing topography in grayscale overlain with mapped landslides (black polygons) of varying degrees of assigned confidence (Definite, Probable, and Questionable for solid, dashed, or dotted polygon boundaries, respectively).

11,783 individual bedrock landslides were mapped with 3,769 landslides assigned a confidence of Definite, 5,210 landslides to a confidence of Probable, and 2,804 landslides to a confidence of Questionable (**Fig. 10**). Approximately 10,433 merged landslides remain after excluding overlapping, or nested, landslides. Inconsistencies in mapped landslide boundary extents and landslide interpretation affect the true number of merged landslides. The cumulative area affected by merged landslides total to 315.22 km², approximating 12.76% of the SGM area. Volume of the merged landslides, calculated with Equation 1, total to 5.95 km³. Landslide area density, seen in **Fig. 11**, is dominated by rock avalanche deposits and regions of schist outcrops.

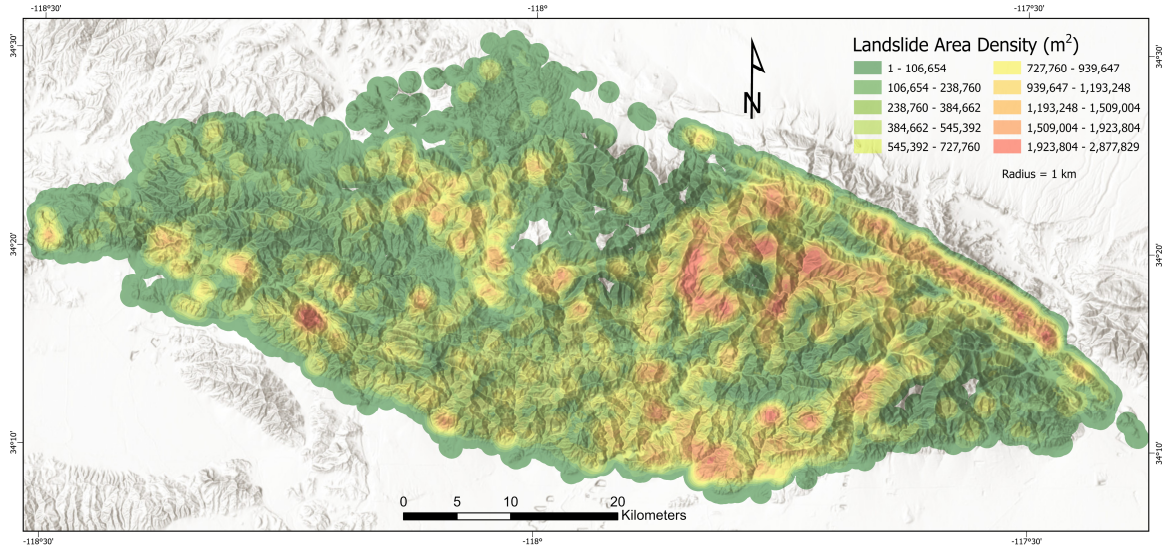


Fig. 11. Overview map of the San Gabriel Mountains, CA, showing topography in grayscale overlain with landslide area density of 1 km radius. Landslide area density refers to the area distribution of all mapped landslides. Rock avalanches and regions composed of schists comprise highest landslide area density.

The landslide area distribution exhibits a weakly positively skewed landslide area-frequency distribution with a steeper decline below the median and more gradual tapering above the median (**Fig. 12**). While the majority of landslides have relatively small areas, the distribution is influenced by a small number of large landslides that increase the overall mean area ($28,904.3 \text{ m}^2$) well above the median area ($6,528.6 \text{ m}^2$). Deposit areas between approximately $1,000 \text{ m}^2$ and $3,000 \text{ m}^2$ also show an anomalous distribution where landslide frequency remains relatively constant.

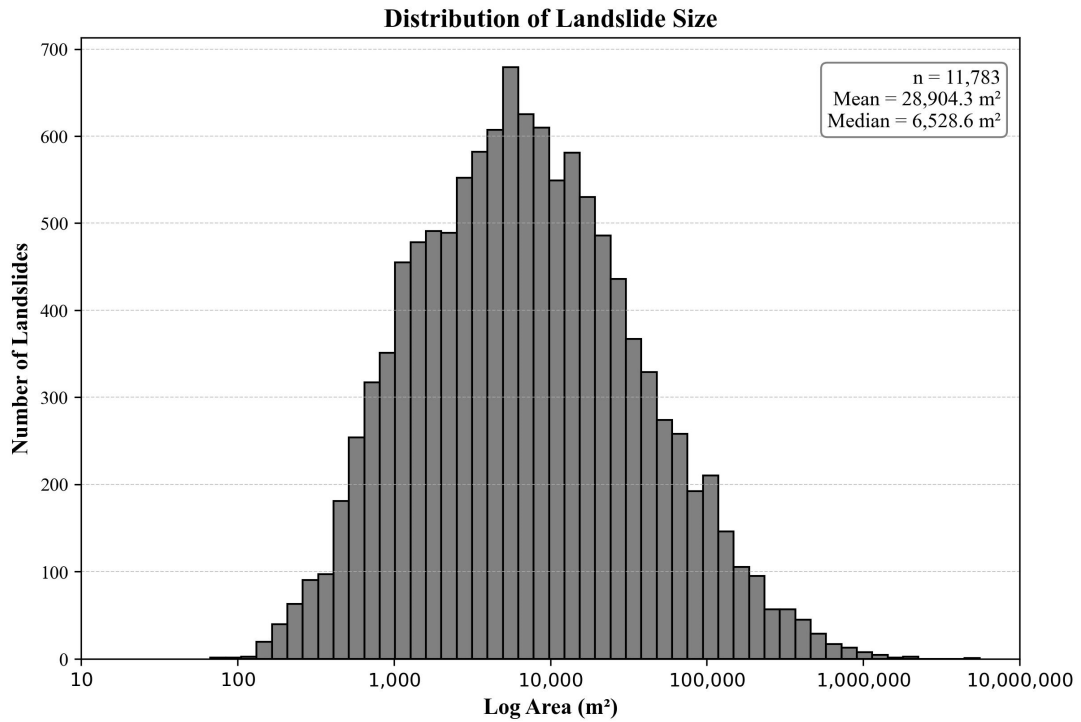


Fig. 12. Distribution of landslide size plotted across logarithmic area. The Crystal Lake Rock Avalanche (5,576,331.5 m²) is significantly larger than the second-largest bedrock landslide deposit (Alpine Canyon Rock Avalanche, 2,044,918.7 m²).

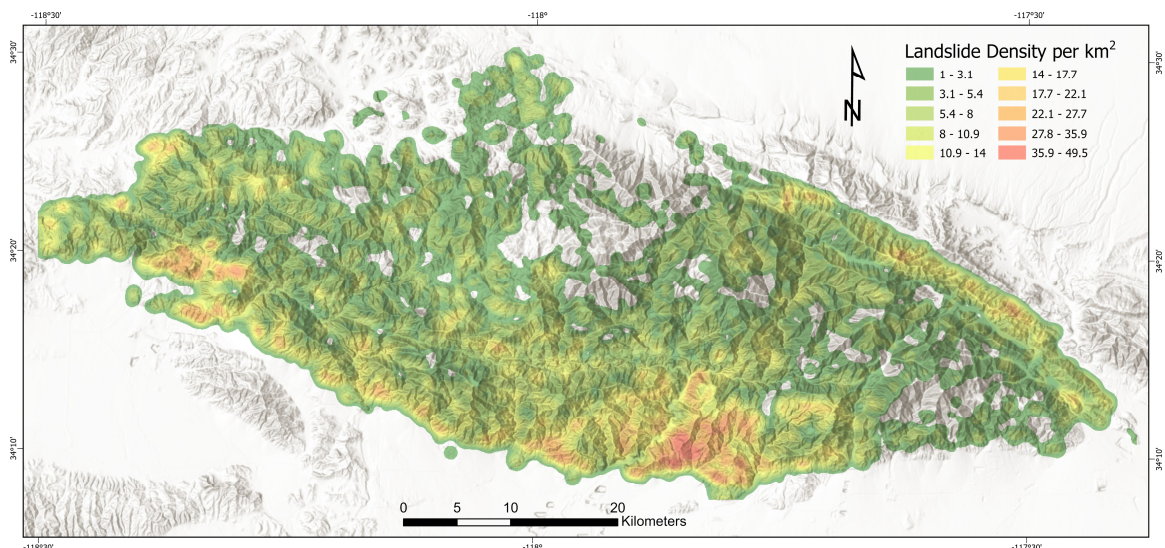


Fig. 13. Overview map of the San Gabriel Mountains, CA, showing topography in grayscale overlain with landslide deposit point density of 1 km radius. Landslide density refers to the density distribution of individual landslide deposits irrespective of landslide area.

Because a majority of the approximately 1,000 m² to 3,000 m² landslides are located along the range front fault-bounded blocks (SMB and TB fault blocks seen in **Fig. 4**), this study suggests that ridge density has a notable influence on landslide size. The deviation from a normal distribution may also be attributed by post-failure obfuscation of smaller deposits via erosion or geologic influences on landslide size. This will be further expanded upon below in subsection 3.7. High landslide density along the range front is also visible in **Fig. 13**.

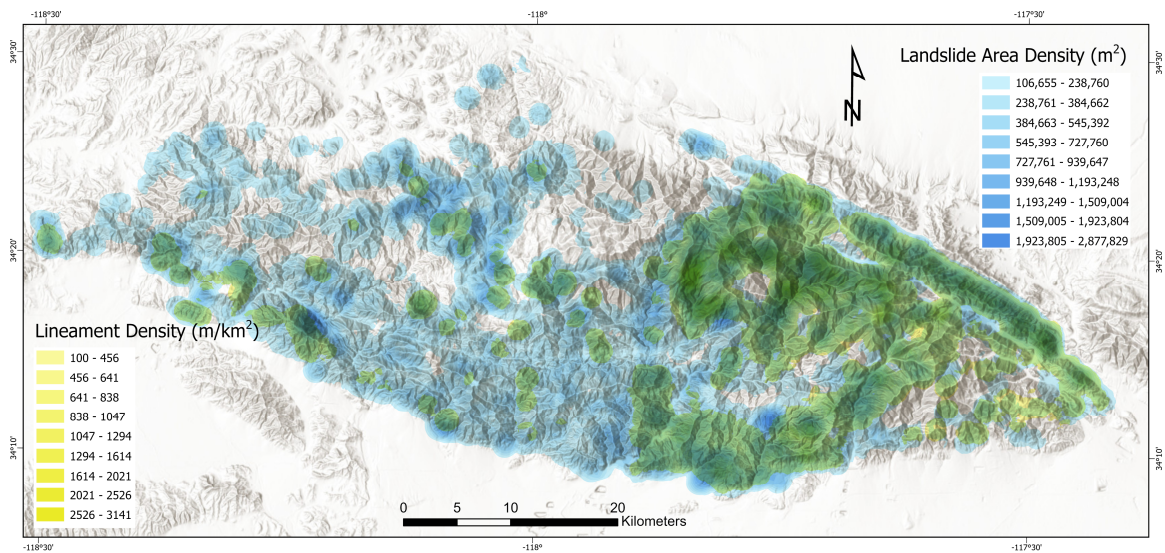


Fig. 14. Overview map of the San Gabriel Mountains, CA, showing topography in grayscale overlain with landslide area density (yellow) and lineament density (blue) with thresholds of 100 m/km² and 106,655 m², respectively. Note that the overlap of both datasets produces the color green; this aids in interpreting correlation between lineament density and landslide area density.

Shown in **Fig. 14** is the spatial relationship between landslide area density and lineament density across the SGM. Notably, regions of high lineament density do not consistently align with regions of high landslide density. In the western SGM, landslide area density is

moderate, yet lineament density remains relatively low. Conversely, in the eastern SGM, both datasets exhibit a strong positive correlation. This uneven relationship suggests that the generation of lineaments is influenced by additional factors beyond landslide area alone and is heavily biased by schistose regions and rock avalanches.

3.3 Lithology / Geologic Unit

Lineaments:

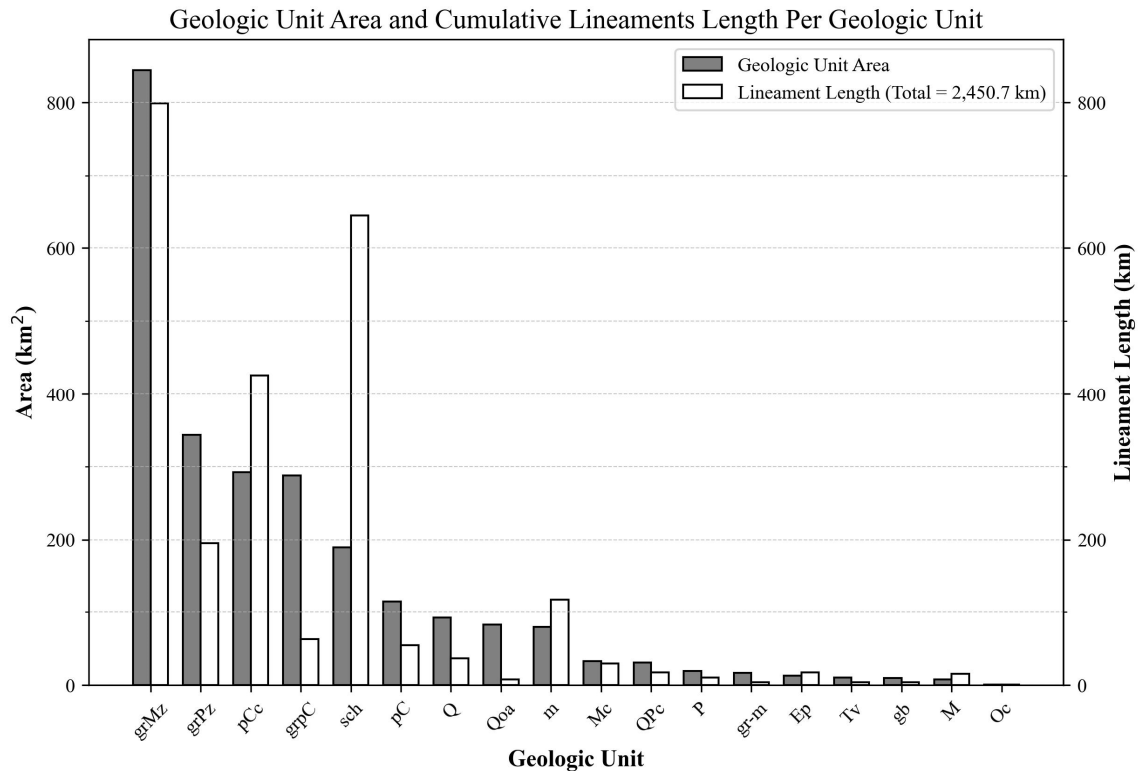


Fig. 15. Comparison of geologic unit area (gray) and cumulative lineament length (white) plotted across geologic units. Geologic units are ordered based on the total area covered on the SGM.

Crystalline units constitute the majority of the total area of the SGM, and frequently exhibit proportionately high cumulative lengths of mapped lineaments (**Fig. 15**). Among these, the

plutonic unit grMz occupies the largest area (844.0 km²) and contains the highest cumulative lineament length (798.9 km). This high value is likely a consequence of both the extensive coverage of the unit and the high landslides frequency (n=4,584), many of which contain lineament-generating features. Similarly, the pCc unit displays a high cumulative lineament length (426.0 km) relative to its area (292.7 km²), further reinforcing this trend.

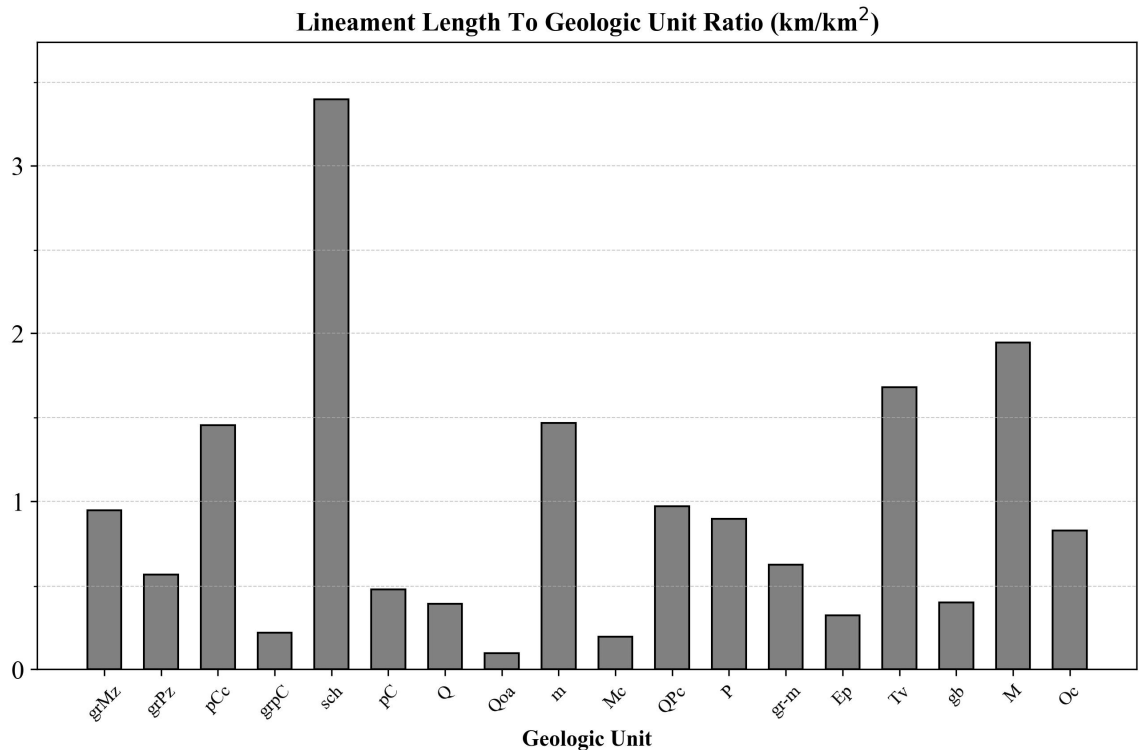


Fig. 16. Ratio of cumulative lineament length to geologic unit area plotted across geologic units.

However, other crystalline units such as grPz, grPc, gr-m, and gb do not follow this proportional relationship, exhibiting comparatively lower lineament densities despite their lithologic similarities. Notably, these units are primarily located in regions of lower relief,

which may limit the development of slope failure features and associated lineaments. This observation suggests that significant relief may be a prerequisite for lineament formation in crystalline lithologies. These same low-relief regions also exhibit relatively sparse landslide distributions (**Fig. 13**), reinforcing the correlation between topographic relief and both lineament and landslide occurrence in crystalline bedrock.

In contrast, sedimentary and metasedimentary units comprise a smaller fraction of the SGM's total area but display notably high cumulative lineament lengths relative to their extent. Units such as sch, m, Tv, and M demonstrate disproportionately large lineament totals, suggesting that landslide processes in these lithologies produce more readily observable geomorphic expressions than those in crystalline terrains. The most prominent example is the sch unit, which spans only 189.6 km² yet contains 644.2 km of cumulative lineaments. This highlights the schist's elevated susceptibility to landsliding and the development of lineament-forming features, regardless of slope or aspect. These differences are likely related to mechanical contrasts in rock strength, internal structure, and weathering behavior. Further discussion of slope characteristics influencing schist behavior is presented in Subsection 3.4. The disparity in area-lineament ratios between crystalline and sedimentary/metasedimentary units is further illustrated in **Fig. 16**.

Landslides:

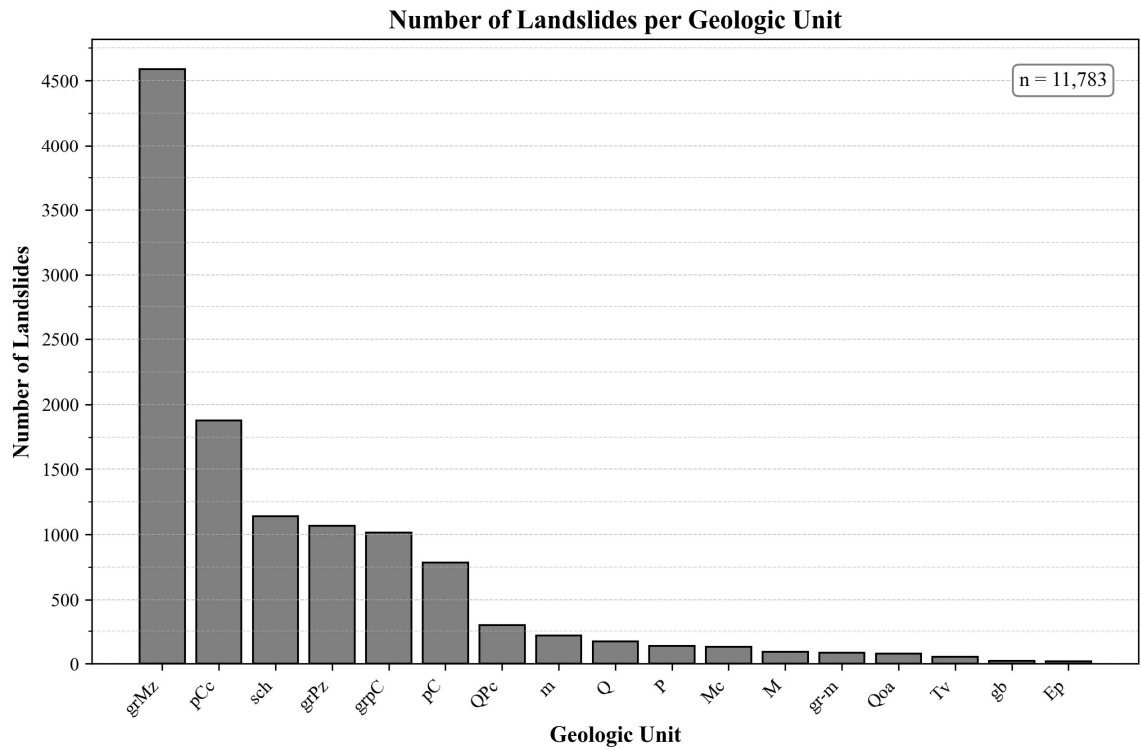


Fig. 17. Cumulative number of landslides plotted across geologic units. Landslide count contains all mapped landslides, including overlapping landslides.

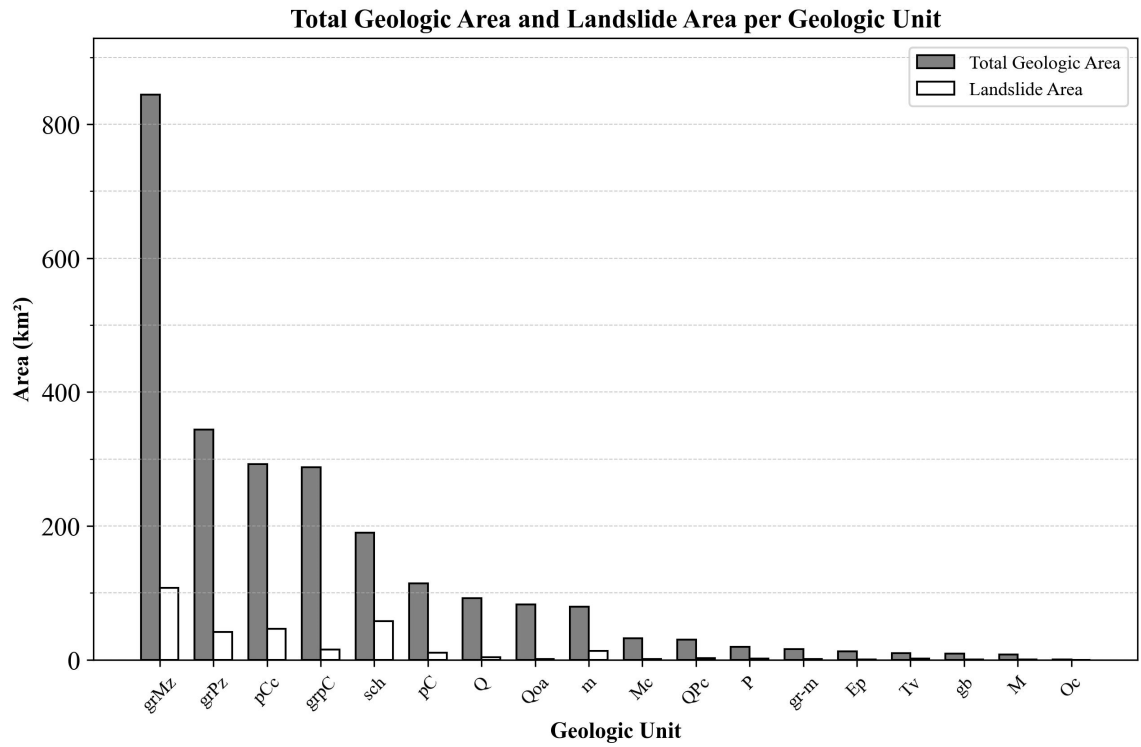


Fig. 18. Comparison of geologic unit area (gray) and landslide-affected area (white) plotted across geologic units. Geologic units are ordered based on the total area covered on the SGM. The landslide area does not contain overlapping landslides and only considers the area of the SGM affected by landsliding.

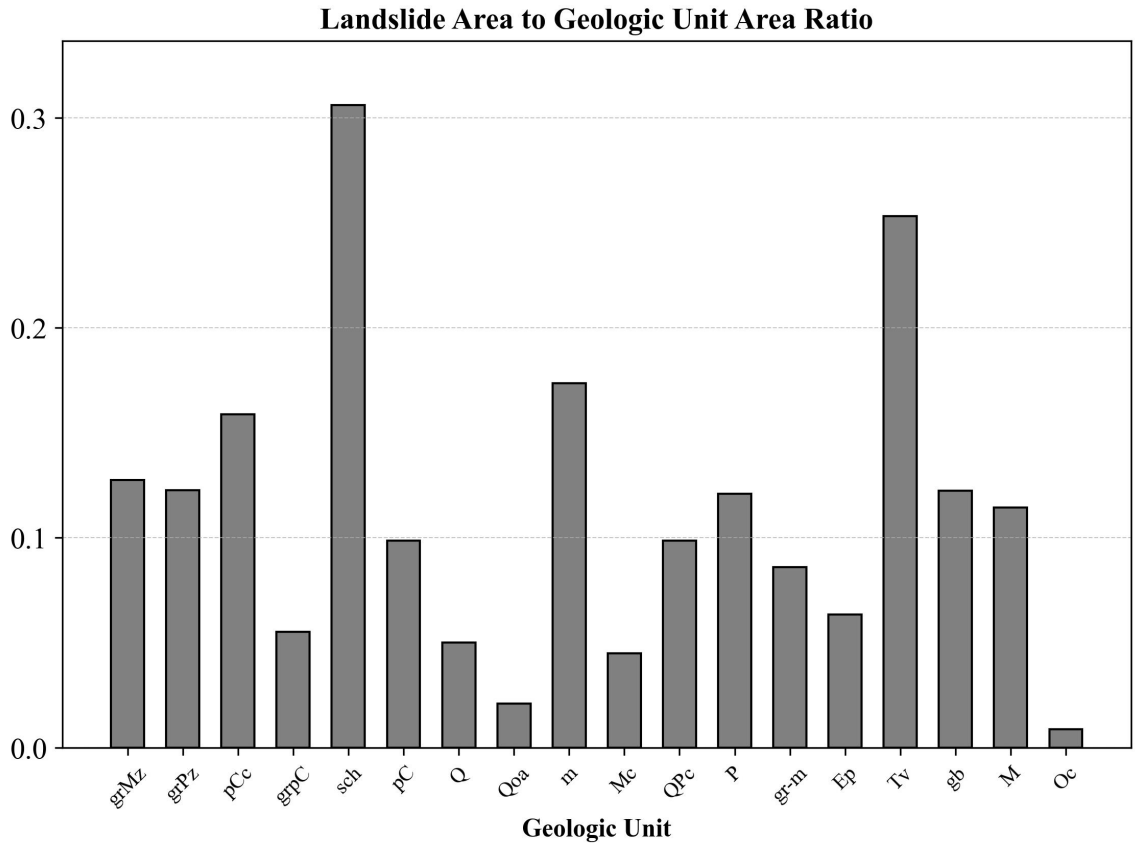


Fig. 19. Ratio of geologic unit area and landslide area plotted across geologic units. The landslide area does not contain overlapping landslides and only considers the area of the SGM affected by landsliding.

Mirroring the lineament distribution, crystalline units account for a majority of the mapped landslide deposits in the SGM (**Fig. 17**). However, several sedimentary and metasedimentary units host a disproportionately large number of landslides and landslide areas with respect to their relatively small geologic area (**Fig. 18**). These patterns align closely with the lineament-to-area ratios, indicating a consistent relationship between landslide generation and lineament-forming features (**Fig. 19**). One exception is the Tv unit, a 10.2 km² volcanic region situated along the range-front between Big Dalton Canyon and San Dimas Canyon (**Fig. 3B**). Tv exhibits relatively low relief but contains

approximately 2.6 km² of mapped landslide deposits, a notably high proportion given its limited geologic area. This anomaly suggests that, in this instance, relief is not the dominant control on landslide generation. Instead, proximity to the SMF and lithologic characteristics of the Tv unit likely play a more significant role in the observed landslide density.

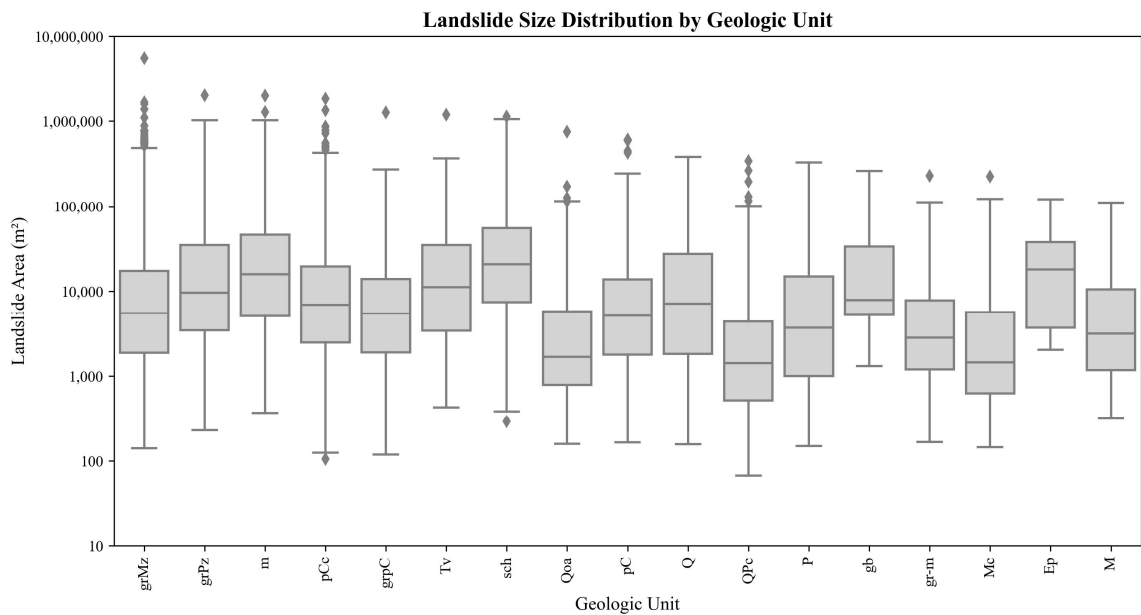


Fig. 20. Distribution of landslide size across geologic units ordered by largest landslide, shown as a box plot. Large individual landslides are marked as outliers. Landslide size contains all mapped landslides, including overlapping landslides. Generated using Seaborn in Python. Median, mean, and max values are found in **Table 2**.

Landslide size distributions across the SGM are highly variable (**Fig. 20**). All units exhibit right-skewed distributions, with mean landslide areas consistently exceeding their respective medians (**Table 2**).

Table 2

Geologic area and median, mean, and maximum area values of individual landslide (LS) deposits for each geologic unit. The table is ordered by the maximum landslide area.

Geologic Unit	Landslide Count	Geologic Area (km ²)	LS Median (m ²)	LS Mean (m ²)	LS Max (m ²)
grMz	4584	844.0	5,500.8	24,811.3	5,576,331.5
grPz	1065	343.7	9,595.0	41,182.8	2,044,918.7
m	218	79.5	15,761.6	71,157.9	2,032,270.2
pCc	1877	292.7	6,893.9	27,339.3	1,875,291.8
grpC	1011	287.9	5,441.1	15,955.2	1,254,302.8
Tv	53	10.3	11,143.7	59,327.7	1,186,374.4
sch	1137	189.6	20,638.7	58,748.9	1,130,668.7
Qoa	79	82.5	1,675.6	21,986.8	750,260.9
pC	782	113.9	5,102.3	15,569.6	607,692.1
Q	171	92.2	7,130.2	30,684.5	380,984.7
QPc	298	30.7	1,419.6	9,909.5	341,895.1
P	137	19.6	3,687.4	19,913.0	326,804.8
gb	22	9.8	7,909.0	43,345.2	260,326.7
gr-m	85	16.6	2,828.0	12,375.6	227,503.6
Mc	130	32.8	1,440.4	10,814.1	223,568.3
Ep	20	12.8	18,237.0	27,363.8	121,231.5
M	92	8.1	3,157.5	10,934.5	109,896.5

Units such as grMz, grPz, and m contain the largest individual landslides, with maximum areas exceeding 2 million m². The elevated mean-to-median ratios observed in grPz, m, Tv, sch, and gb indicate the occurrence of a small number of very large landslides that skew the overall size distribution. Conversely, units including grpC, pC, QPc, gr-m, Mc, and M display both lower median and mean values, indicating a predominance of less extensive landslides. These observed patterns are likely a result of contrasting lithologic strength, weathering susceptibilities, and structural controls such as slope steepness, ridge density, and proximity to major fault zones.

3.4 Slope

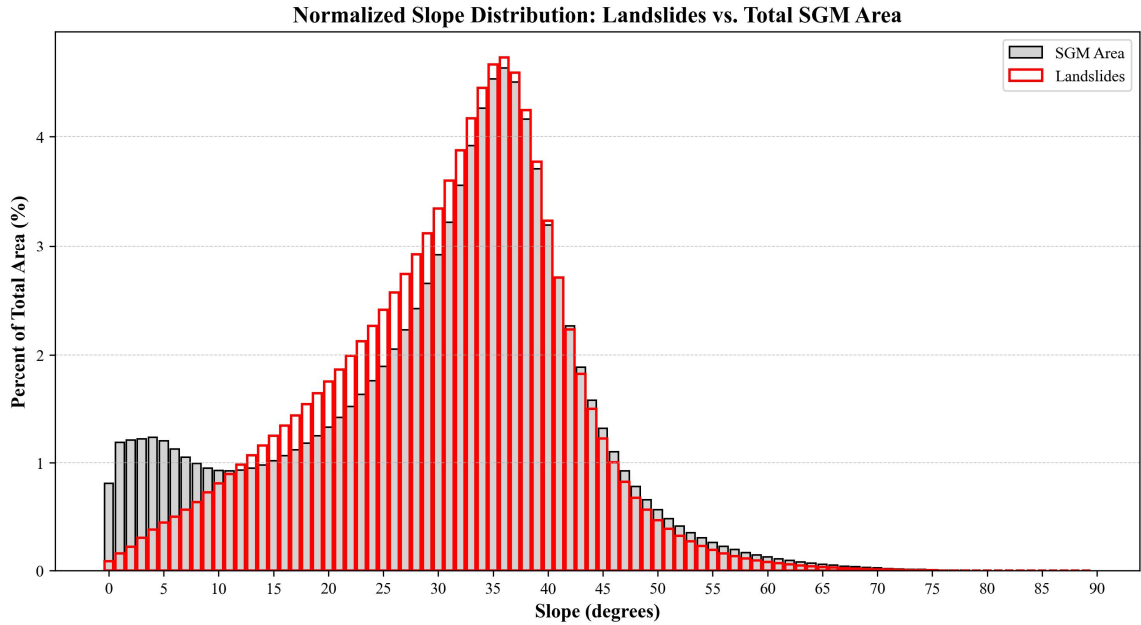


Fig. 21. Comparison of slope between the total SGM area (gray) and landslide-affected area (red), normalized by percent of total area. High percentages in the lowest slope bins ($0\text{--}6^\circ$) are attributed to the inclusion of low-slope margins in the overall SGM boundary.

Both landslide-affected area and overall slope values in the SGM exhibit negatively skewed distributions (**Fig. 21**), characterized by a gradual increase in frequency up to a peak slope value of 36° , followed by a rapid decline resembling an inverse function curve. While the overall shapes of the two distributions are broadly similar, subtle differences are present. The landslide slope distribution exhibits a more gradual rise leading to the peak and a steeper post-peak decline relative to the general SGM slope distribution. This suggests landslides predominantly occur on moderate to steep slopes, but become less common on the most extreme slopes. An alternative explanation is that slope values within landslide deposits may not reflect the original slope conditions at failure initiation.

Artificial inflation of low slope values (0–6°) within the SGM slope distribution likely affects the overall shape of the SGM curve, particularly in the 10–35° slope range, and may obscure finer-scale differences between the two distributions. Regardless, the distribution curve suggests that landslide activity in the SGM is concentrated within a relatively narrow slope range, with decreasing frequency on both lower and higher slope values, consistent with mechanical and geomorphic thresholds governing slope stability.

Table 3

Mean slope values of individual landslide deposits for each geologic unit ordered by mean slope.

Geologic Unit	Mean Slope (°)
grMz	34.9
pC	34.8
pCc	34.3
gr-m	33.5
m	32.7
sch	32.6
Ep	31.0
grpC	31.0
Qoa	30.7
grPz	30.6
M	30.6
Q	30.1
gb	29.7
P	29.7
Tv	29.5
QPc	28.4
Mc	27.9

Mean slope values of individual landslides across all geologic units span between approximately 28° and 35° (**Table 3**). Landslides of crystalline lithology, particularly grMz and pC, display the highest mean slope values of 34.9° and 34.8°, respectively. These elevated slope values may reflect the steep topographic characteristics of crystalline regions within the SGM—which are more structurally competent than sedimentary lithologies but still prone to failure given enough stress or disturbance—as well as the conditions required for landsliding in these units. Other crystalline units, such as pCc (34.3°), gr-m (33.5°), and m (32.7°), follow similar trends. One outlier which does not follow this trend is gb, which has a mean slope value of 29.7°. This value, however, is based on a small sample size of 22 landslides (0.19%) distributed across only 9.8 km² (0.40% of the SGM). The low relief topography within the gb region suggests that the mean slope may not accurately reflect the lithology’s mechanical behavior and is instead influenced by local geomorphic factors.

In contrast, most sedimentary and volcanic units, particularly Tv, QPc, and Mc, tend to show lower mean slope values which range from 27.9° to 30.7°, suggesting that landslides within these structurally weak units often occur on more gentle slopes. Exceptions to this are Ep and sch. As Ep spans approximately 12.8 km² of the SGM (0.52%) and contains only 20 mapped landslide deposits (0.17%), the calculated mean slope value (31.0°) may suggest an inaccurate representation of its mechanical characteristics. The sch unit, however, exhibits a relatively high mean slope value of 32.6° despite its foliated characteristic. This likely reflects the widespread instability of schistose terrain in the

SGM, where entire slopes composed of schists are often mapped as landslide deposits. In such cases, landslide deposits preserve the steepness of the original slope surface, which likely contributes to the higher mean slope values observed for this unit.

3.5 Relief

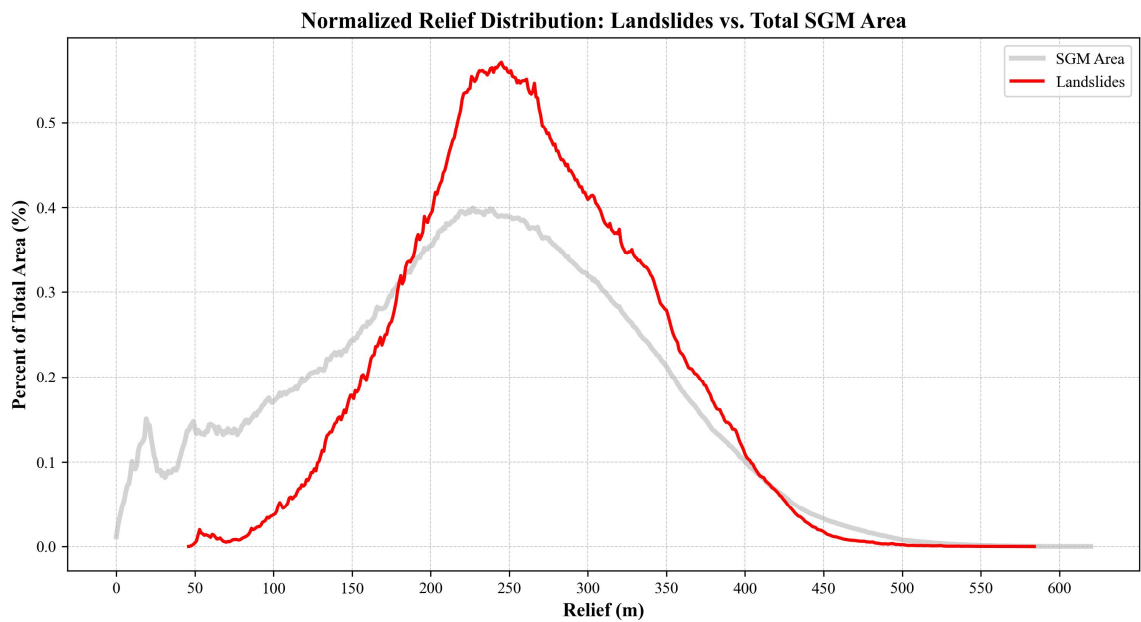


Fig. 22. Comparison of relief within 300 m between the total SGM area (gray) and landslide-affected area (red), normalized by percent of total area. Elevated frequency in the lowest relief values (0-25 m) are attributed to the inclusion of low-relief margins within the overall SGM boundary.

Relief values for both landslide-affected areas and the SGM exhibit slightly positively skewed distribution, with an exponential increase to a peak frequency followed by a gradual decline (**Fig. 22**). While the overall shapes of the distributions are similar, the landslide-specific relief distribution displays a more pronounced and narrower peak, centered between approximately 225–260 m, compared to the broader peak of the SGM distribution, which spans roughly 210–270 m. This difference suggests that landslides in

the SGM are more tightly constrained to a specific relief range. The landslide distribution curve also exhibits steeper slopes leading to and descending from the peak, indicating a higher concentration of landslides occurring within a relatively narrow range of intermediate relief. This steepness may reflect the presence of critical geomorphic conditions in this relief range that are optimal for slope failure. In contrast, areas of lower relief may not support landslide initiation as frequently due to insufficient force required for failure or increased rock stability, and areas of higher relief may have already undergone slope failure with no immediate identifiable landslide deposit nearby.

A small, but anomalous, secondary protrusion in the landslide distribution curve around 340 m may reflect the influence of local topographic features—such as steep, incised hillslopes—or specific lithologic units that are prone to failure at higher relief. The SGM distribution curve, by contrast, appears more uniform, with a gradual rise and fall in frequency that reflects the natural variation in SGM topography. The abundance of low relief values (0-25 m), primarily caused by the inclusion of low-relief foothills within the SGM boundary, contributes to the broader base of the SGM distribution and may obscure more localized relief variations within the distribution curve.

3.6 Deep-Seated Landslide Susceptibility Category

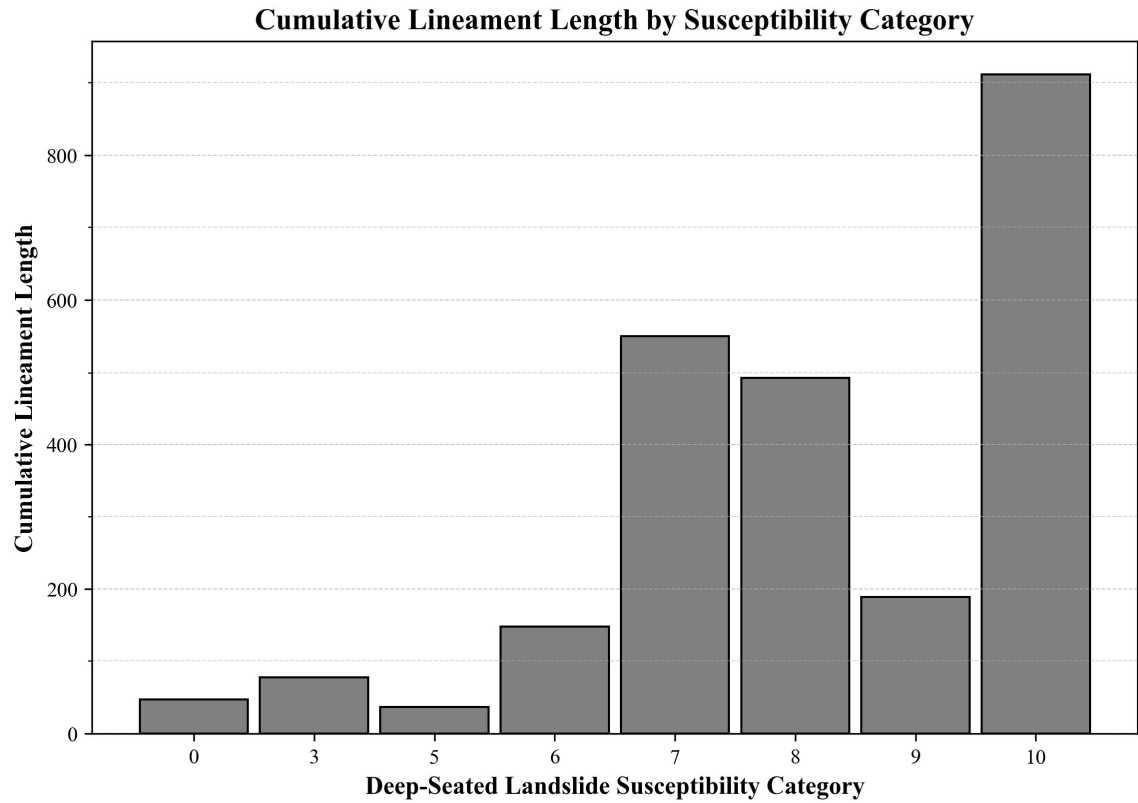


Fig. 23. Cumulative length of lineaments plotted across deep-seated landslide susceptibility category.

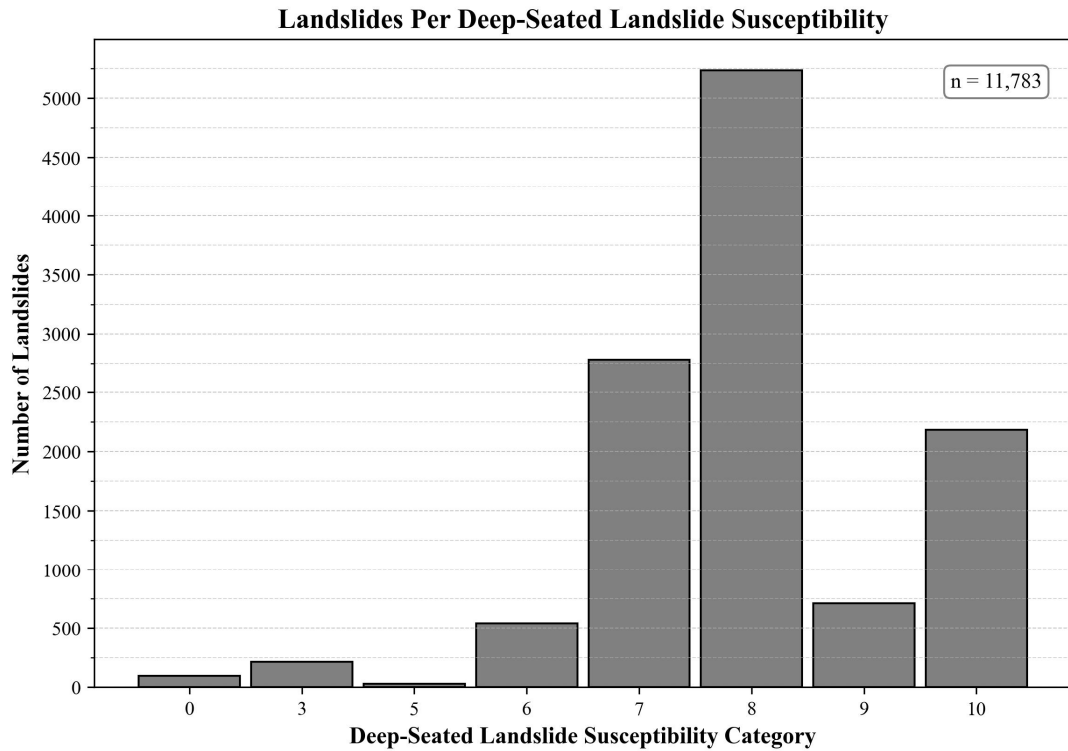


Fig. 24. Total landslide count plotted across deep-seated landslide susceptibility categories.

Cumulative lineament length and landslide frequency, as shown in **Fig. 23** and **Fig. 24**, both display bimodal peaks within deep-seated landslide susceptibility categories 7-8 and category 10. While this bimodal distribution is consistent across both figures, the relative shapes of each distribution differ significantly. Notably, susceptibility category 10 contains the highest proportion of cumulative lineament length; however, landslide frequency peaks in susceptibility category 8 instead of susceptibility category 10. This discrepancy suggests that landslides occurring in susceptibility category 10, though fewer in number, are associated with a disproportionately high number of lineament-forming features. These features are related to bedrock slump characteristics found within schistose regions and internal deformation within rock avalanche deposits (**Fig. 9**). The inverse is also apparent

where high frequencies of susceptibility category 8 landslides produce disproportionately few lineament-forming features.

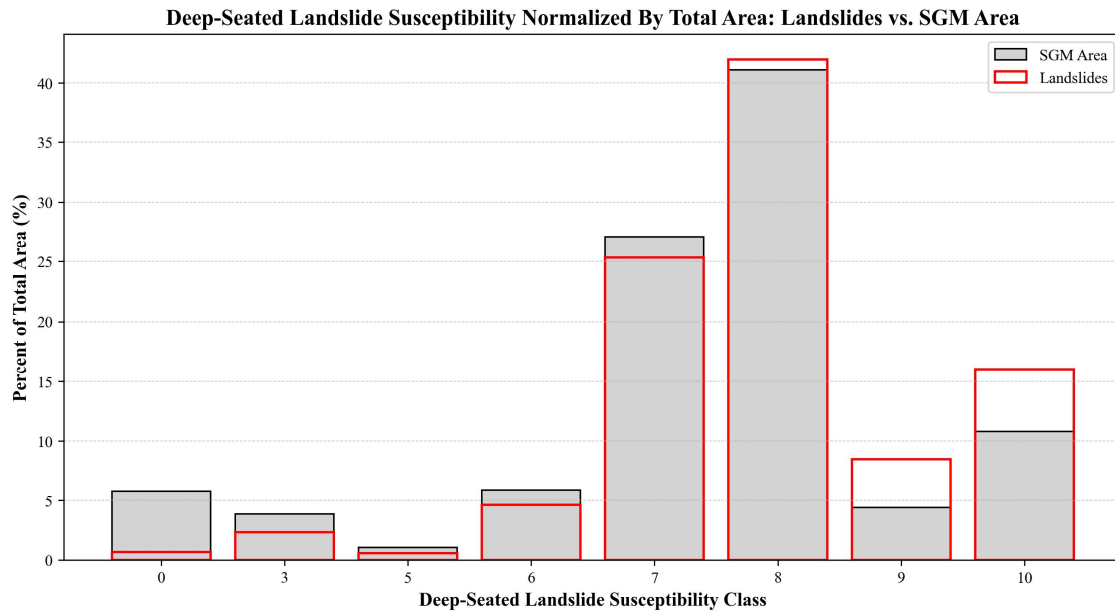


Fig. 25. Comparison of deep-seated landslide susceptibility categories between the total SGM area (gray) and landslide-affected area (red), normalized by percent of total area. Elevated frequencies in the lowest susceptibility category are attributed to the inclusion of low susceptibility regions along the margins of the SGM boundary.

Table 4

Total area, landslide area, and landslide density for all landslide susceptibility categories in the SGM.

Landslide Susceptibility Category	Area (km ²)	Landslide Area (km ²)	Landslide Density
0	143.606	2.157	0.015
3	94.802	7.331	0.077
5	26.253	1.793	0.068
6	145.726	14.549	0.100
7	669.238	79.813	0.119
8	1014.968	132.187	0.130
9	108.399	26.786	0.247
10	266.813	50.602	0.190

In contrast, the relatively small cumulative lineament length and landslide frequency are unexpectedly low in susceptibility category 9, which aligns with the small area extent of that category. Landslide density, however, peaks in category 9 with a value of 0.247, contrasting the notion that landslide density should generally increase with higher susceptibility values (**Table 4**). The relatively low landslide density value for susceptibility category 10 (0.190) may reflect limitations in the susceptibility model inputs—such as generalized rock strength assignments or the use of low-resolution slope data. Additionally, variability in susceptibility values assigned to individual landslides, particularly those that span multiple susceptibility zones, may introduce some degree of misrepresentation when values are extracted using point-based or centroid methods in ArcGIS Pro.

3.7 Ridge Density

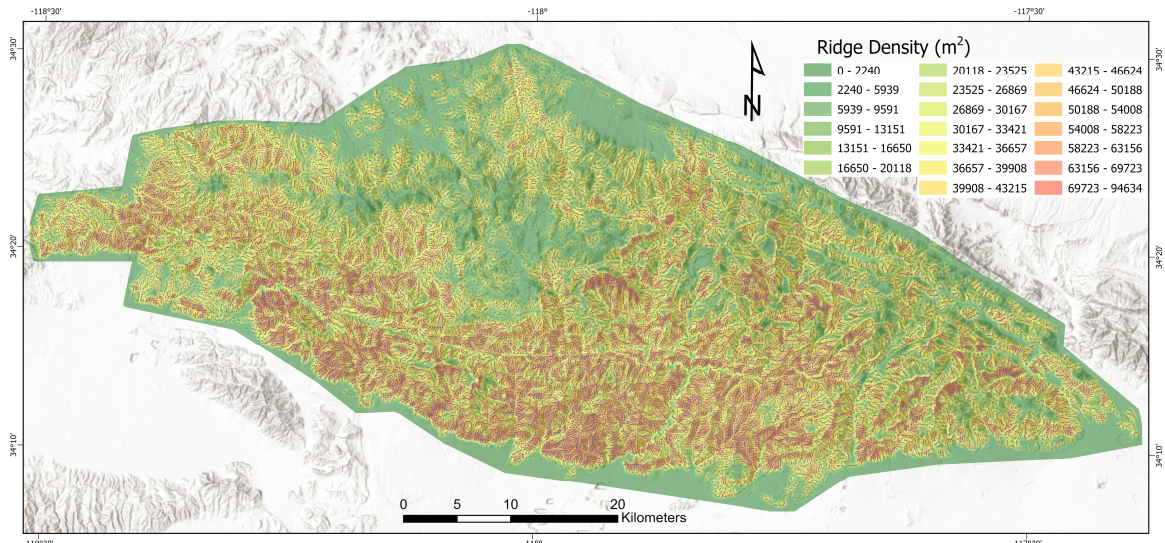


Fig. 26. Overview map of the San Gabriel Mountains, CA, showing topography in grayscale overlain with TPI-derived ridge density.

Although not a traditional method for assessing drainage density, the ridge density map (**Fig. 26**) generated using TPI-derived ridge polygons offers a systematic and compelling proxy for understanding drainage patterns across the SGM. While this method tends to emphasize steeper and more prominent ridgelines, often associated with younger topography, the spatial patterns it reveals are still relevant and reflective of the underlying terrain.

A notable feature of **Fig. 26** is a subtle north-south divide, where southern portions of the range exhibit much higher ridge density values. Furthermore, **Fig. 26** shows partial spatial congruence with the landslide density distribution (**Fig. 13**), particularly along the range front and relict topography region for high and low ridge density values, respectively. This congruence suggests that steep, dissected ridgelines serve as initiation zones for deep-seated slope failures and gently sloped ridgelines are not conducive to deep-seated slope failures.

3.8 Spectral Acceleration (SA10)

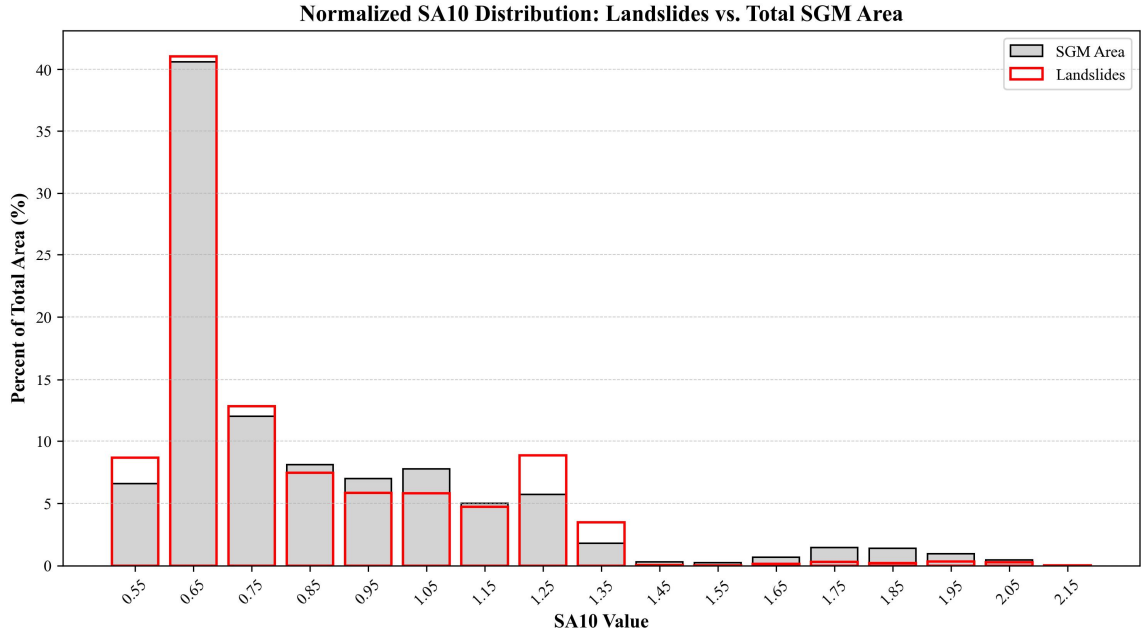


Fig. 27. Comparison of SA10 values between the total SGM area (gray) and landslide-affected area (red), normalized by percent of total area.

Despite SA10 being implemented to model building response to seismic ground motion, it serves as a useful proxy for evaluating ground shaking intensity over time, which is a critical factor influencing deep-seated landslide initiation. In the SGM, the distribution of SA10 values closely mirrors the distribution of SA10 within landslide-affected areas, suggesting that landsliding is generally consistent with the regional seismic hazard pattern (**Fig. 27**). However, landslide SA10 values show a slight increase compared to SGM SA10 values at 0.55, 0.65, 0.75, 1.25, and 1.35, which may suggest that these SA10 values are more conducive to triggering landslides. SA10 values greater than 1.45 are relatively rare in the landslide dataset. This is likely because the highest SA10 values tend to coincide with low-relief depositional environments—such as alluvial basins or Quaternary valley

fill—where landslides are less likely to occur due to gentle slopes and limited relief. The near alignment of the SGM and landslide SA10 distribution may be a result of the coarse resolution of the SA10 dataset provided by CGS. Additionally, because SA10 values tend to decrease with distance roughly parallel to the SAF, naturally similar SA10 distributions across both datasets may occur due to their shared spatial distribution.

3.9 Fault Blocks

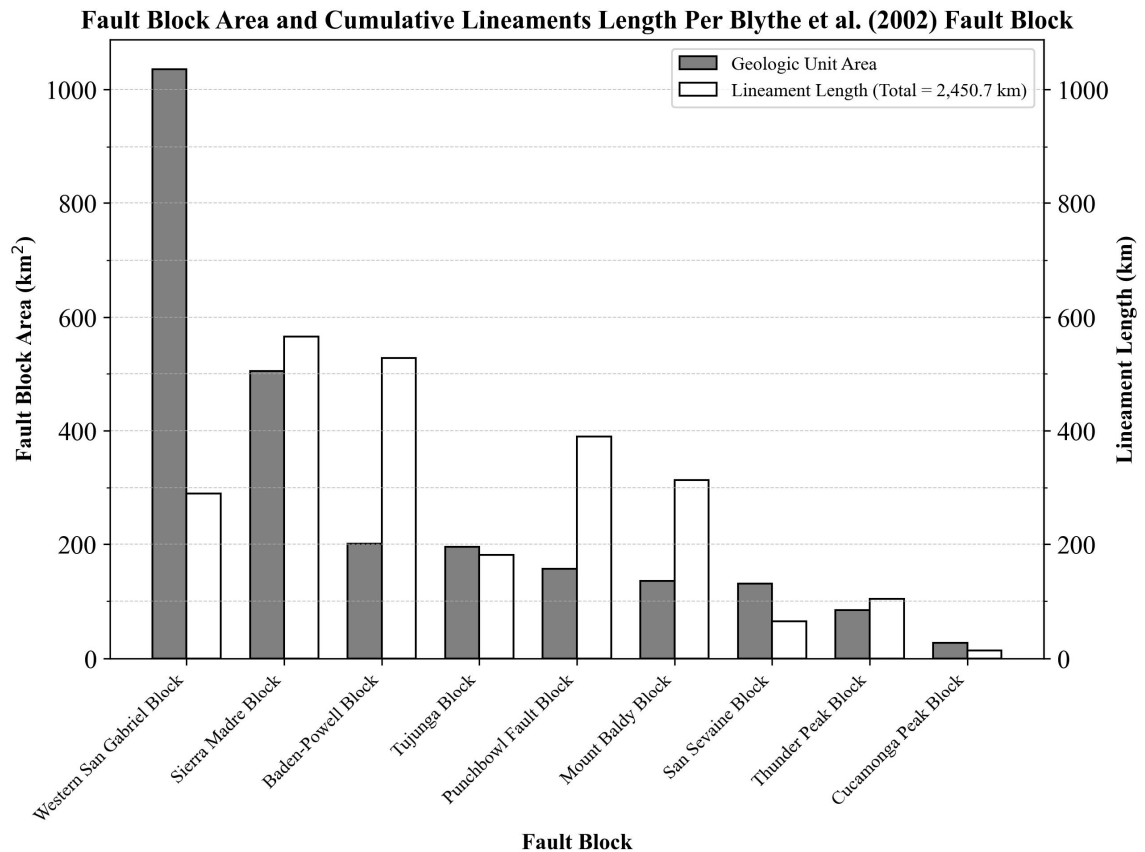


Fig. 28. Comparison of fault-bounded block area (gray) and cumulative lineament length (white) plotted across geologic units. Fault blocks are ordered based on the total area covered within the SGM.

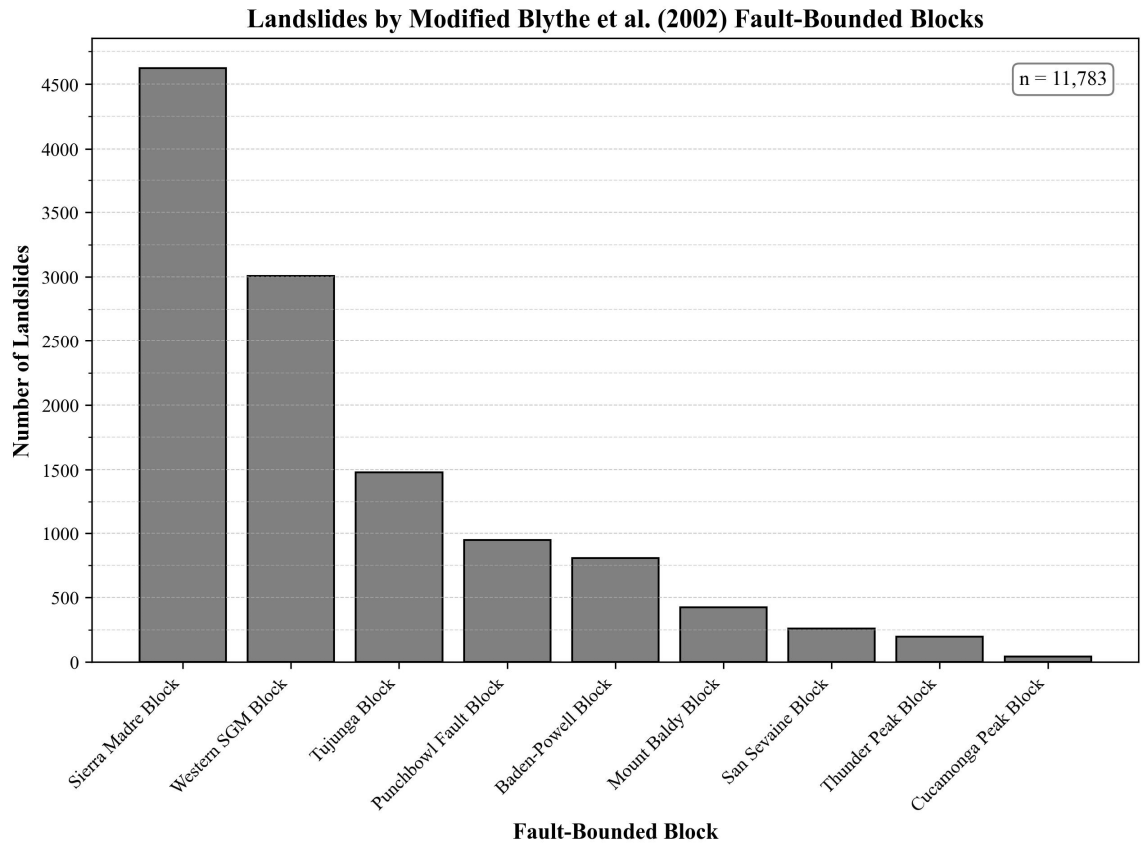


Fig. 29. Total landslide count plotted across fault-bounded blocks.

Analysis of fault-bounded blocks within the SGM reveals variability in both cumulative lineament length and landslide distribution (**Fig. 28**). Notably, the WSGB (1,036 km²) contains only 290 km of cumulative lineaments. This anomalous low lineament density is attributed to the included relict topography region in the northern SGM, which is characterized by smoothed, less dissected terrain with minimal landslides and lineaments. In contrast, smaller blocks such as the BPB, PFB, and MBB exhibit disproportionately high lineament-to-area ratios. The BPB includes both the Crystal Lake and Alpine Canyon rock avalanches, whose extensive runouts contribute to an abundance of lineament-generating features. The PFB and half of the MBB are also dominated by schist, a lithology prone to

lineament generation. Landslide count distributions offer a different perspective (**Fig. 29**). Despite its moderate area (504 km²), the SMB contains the highest number of individual landslides (4,618) while the WSGB, despite its size, hosts only 3,007. The relatively low landslide count in the WSGB aligns with the lineament data as the inclusion of relict topography is not conducive to landslide initiation.

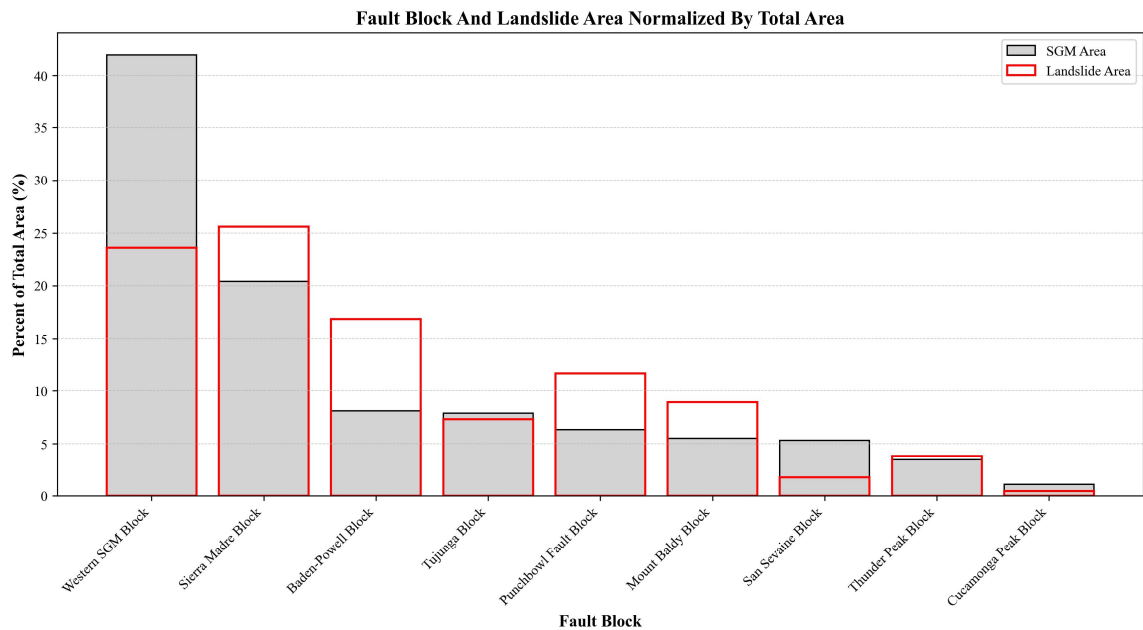


Fig. 30. Comparison of area between fault-bounded block (gray) and landslide-affected area (red), normalized by percent of total area.

When normalizing landslide-affected area and fault block areas, the SMB, BPB, PFB, and MBB all exhibit disproportionately high amounts of landslide coverage relative to their local block extent (**Fig. 30**). In the case of the SMB, its high ridge density and range front position likely increase landslide susceptibility. The PFB and MBB again reflect the prevalence of schist, while the elevated values in the BPB is driven by the presence of large rock avalanche deposits. Conversely, the TB and TPB show near-equivalent normalized

values for landslide and block area, suggesting more balanced geomorphic processes. The WSGB, SSB, and CPB, however, display disproportionately lower landslide area relative to block size. The CPB and SSB have experienced later-stage exhumation compared to the other blocks, possibly affecting landslide-prone slope generation, and exhibit low ridge densities.

3.10 Precipitation

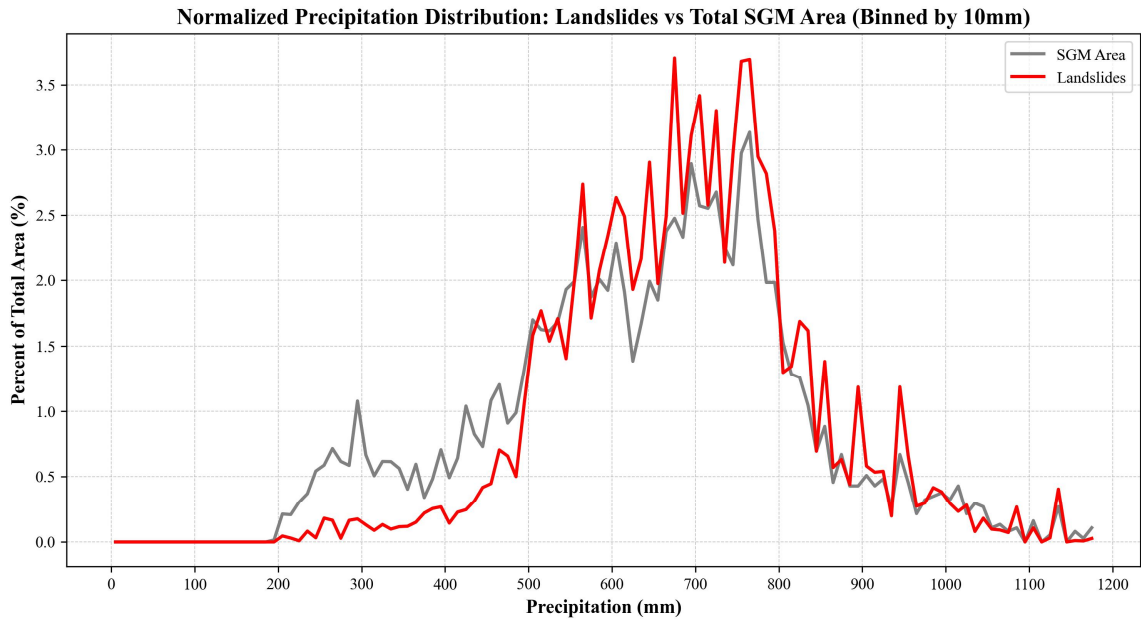


Fig. 31. Comparison of precipitation values between the total SGM area (gray) and landslide-affected area (red), normalized by percent of total area.

Average precipitation values across the SGM show a strong similarity to the landslide-affected area precipitation distribution (**Fig. 31**). Both datasets exhibit similar patterns, with matching peaks and troughs in precipitation values above 500 mm. The similarity in shape between the two curves indicates that precipitation, at least average precipitation, while an important condition for slope failure, may not be the sole controlling factor in

landslide occurrence. Instead, factors such as slope, ridge density, and lithology likely have greater influence on landsliding. Areas in the SGM with precipitation values below 500 mm lie primarily in the northern, relict topography region of the range. As a result, the low landslide occurrence in this area is likely due not only to limited rainfall, but the absence of steep or unstable topography. Above a precipitation value of 500 mm, the higher relative frequency of landslides reflects the exclusion of these low-activity areas, rather than any excess concentration of landslides in wetter regions.

3.11 Roads & Buildings

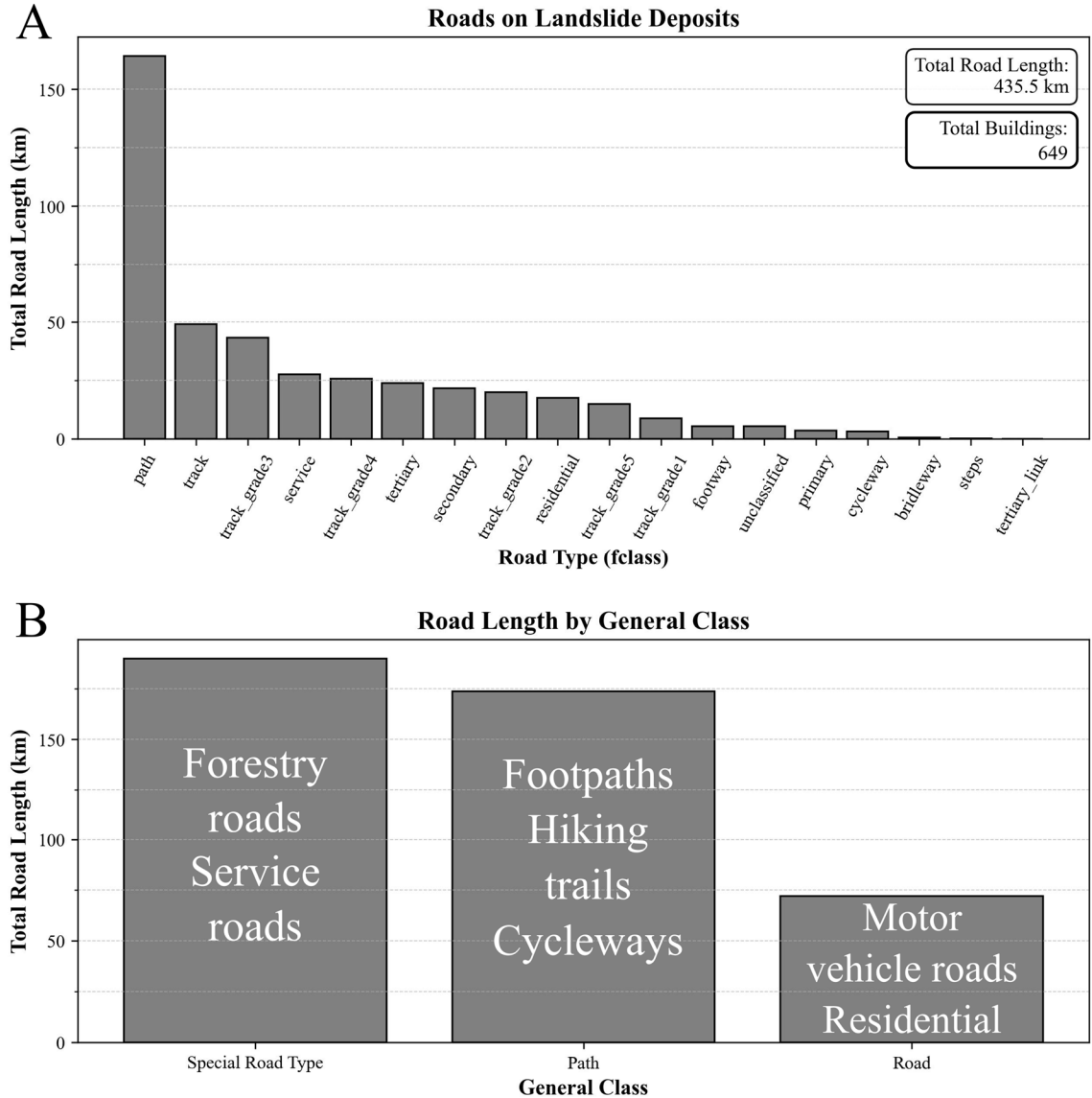


Fig. 32. Distribution of road types which sit atop bedrock landslide deposits. (A) cumulative road length by road type, (B) cumulative road length of generalized classes as defined by OpenStreetMap.

Landslide deposits across the SGM host a significant amount of infrastructure, including 435.5 km of roads and 649 buildings (**Fig. 32**). The most notable road types atop landslide deposits consist of 164.2 km of hiking trails, 189.8 km of forestry and service roads, and

72.1 km of motor vehicle and residential roads. These high values are often due to the gentler slopes typical of depositional areas, which encourage the construction of switchbacks for both roads and trails. However, building on or traversing landslide deposits present serious hazards. Should these deposits reactivate, critical access routes—particularly forestry and service roads—could be severely impacted (Turner, 2018). This would be especially disruptive in mountainous areas, such as the SGM, where alternative routes are limited or nonexistent. Rapidly moving landslides are of particular concern, as even small volumes of displaced material can result in injury or death and pose serious economic, operational, legal, and public safety risks (Turner, 2018)

4.0 Discussion

Limitations and Uncertainties

Several limitations affected this study and are primarily related to data resolution and classification methods. Slope statistics were derived from values atop mapped landslide deposits rather than their source areas. Because landslide deposits often settle across a wide range of terrain, the resulting slope values may not accurately reflect the failure conditions or mechanics at the source zone. Similarly, landslide susceptibility assignments were based on central points of deposit polygons, which may not represent the dominant conditions across each landslide, especially for large or irregularly shaped deposits.

The geologic data and susceptibility classification are also uncertain as they both rely on older and lower resolution datasets. Much of the geologic mapping used, particularly from older quadrangle maps, contains outdated, generalized, or inaccurate geologic and landslide boundaries which affect the assignment of susceptibility categories. This may contribute to unexpected trends, such as the unusual decrease in landslide density between susceptibility categories 9 and 10. Future work in the SGM would benefit from incorporating modern geologic maps for rock strength assignment, high-resolution DEMs, and this study's LSI. Inclusion of this study's LSI and a refined rock strength model with more nuanced categories, based on recent geologic maps, would likely enhance the accuracy and predictability of susceptibility models for the SGM. Incorporating machine learning for landslide detection or surface roughness may also improve the susceptibility model.

Morton's Hypothesis

Utilizing both the Yerkes & Campbell (2005) Los Angeles and the Morton & Miller (2006) San Bernardino 30' x 60' quadrangle geologic maps in conjunction with the Jennings (1977) geologic map, this study supports Morton's hypothesis that the hardest rocks produce the largest landslides in the SGM: the source areas for the three largest rock avalanches—Crystal Lake (5.58 km²), Alpine Canyon (2.05 km²), and Browns Flat (1.88 km²)—consist of monzogranite, quartz monzodiorite, and mixed metamorphic and granitic rock, respectively. For definite and probable landslides above an area of 1 km² (1.02–1.69 km²), eleven of fifteen are likely composed of crystalline rock. Of the remaining

four landslides, three are Pelona Schist, siliceous schist, and metasedimentary schist and gneiss and one is volcanic tuff and andesite flow breccia.

The association of large landslides with strong crystalline lithologies may reflect a mechanism analogous to that observed in earthquake rupture: in earthquake physics, large-magnitude ruptures often nucleate in strong, competent rock where elastic strain can accumulate over long periods before being released catastrophically (Scholz, 2019). Similarly, in the context of slope failure, while these rocks are highly fractured due to active orogenic processes, their rock mass strength—a function of both the strength of the intact rock and the frictional resistance along these fractures—is likely still sufficient to sustain steep slopes and allows them to sustain steep, oversteepened slopes and large potential failure volumes. When failure finally occurs, due to a triggering event such as seismic shaking or oversteepening, the release is more catastrophic, producing a larger landslide. In contrast, weaker lithologies tend to fail more frequently but at smaller scales, dissipating stress through shallow or distributed deformation. However, the observation that weak and foliated rocks like schist and volcanic breccia also host large landslides suggests that local topographic or tectonic conditions (e.g., fault proximity, relief, or ridge density) may increase deposit area and volume. Notably, approximately one-third of landslides above an area of 0.5 km² occur in the Pelona Schist within 8 km of the San Andreas Fault, underscoring the potential for structurally weak terrain to produce large failures in the presence of additional geologic or tectonic influences.

Approximate Rate Estimates

^{10}Be , ^{14}C , and IRSL dating done by Scherler et al. (2016), Del Vecchio et al. (2018), and Barth & Gentile (2020) on several prominent rock avalanches in the SGM range between 0.6-46 ka, however Barth & Gentile (2020) note that Cat Canyon Rock Avalanche ($<14.6 \pm 1.3$ ka), located within San Antonio Canyon, was only identified through road cuts and is completely obscured in aerial and LiDAR imagery. This shows that geomorphic expression of landslide deposits within the SGM can be removed over Holocene timescales and seriously undermines the robustness of the morphometric approaches. If we were to assume that all bedrock rock avalanches in the dataset are of Holocene age (<14 ka)—a reasonable assumption given that landslide deposits can be geomorphically erased within Holocene timescales—a rate of approximately 0.84 landslides per year would occur. If this assumption is also applied to the area and volume of landslide-affected regions, we find a rate of approximately 22,500 m² and 425,000 m³ per year. Lavé & Burbank (2004) estimate a return period of approximately 700 years for a single >1 km² landslide in the SGM, equating to roughly 20 such events over a 14,000-year span. If the 17 mapped landslides exceeding 1 km² in this study are assumed to have occurred within the last ~ 14 ka, this observed frequency aligns fairly closely with their estimate. This Holocene age estimate, however, is fairly conservative as it can be argued that the majority of the bedrock landslides identified in this study are younger than 14 ka given the observed expression of deposit surface and source features, so these ballpark estimates may be markedly inaccurate.

Decadal and Millennial Processes

Decadal- and millennial-scale erosional processes in the SGM reflect fundamentally different controls and landscape responses. Numerous studies (e.g., Lavé & Burbank, 2004; Cannon et al., 2009; Kean et al., 2011; Schmidt et al., 2011; Gartner et al., 2015) suggest that on decadal timescales, sediment flux is primarily driven by post-wildfire debris flows and flood events, which rapidly remove material from the hillslopes and channels following vegetation loss and intense precipitation. Although frequent, these events primarily mobilize surficial sediments and relatively small sediment volumes. In contrast, on millennial timescales, the dominant process of erosion is likely bedrock landslides—particularly large-scale failures that episodically release massive sediment pulses. These are often linked to rapid uplift rates, such as those found in the SGM, and produce long-lasting topographic changes, including slope readjustment and drainage reorganization (Morton & Miller, 2006; Scherler et al., 2016; Xia et al., 2020; McColl, 2022). The distinction between these two timescales underscores the variable nature of sediment production and landscape evolution in the SGM: short-term, climate-driven events rapidly evacuate relatively small volumes of sediment with limited geomorphic impact, while bedrock landslides likely dominate long-term hillslope evolution and sediment supply.

Lineament Mapping

While time consuming and not universally applicable, lineament mapping offers valuable insight in regions where slope failures are evident but formal landslide deposits are absent. In this study, lineament density and orientation provided structural context that helped

identify areas of potential instability—particularly where geomorphic evidence suggests slope deformation, but no mapped landslide deposits are present. Although the process requires detailed manual interpretation and is not practical for all mapping efforts, it supports a more systematic evaluation of slope failure by highlighting fracture-controlled terrain and possible preconditioning factors.

Unexpected Findings and Key Takeaways

Several surprising patterns emerge from this study’s systematic mapping and analysis of landsliding across the SGM. Most notably, landslide susceptibility category 9 shows an unexpectedly low area and landslide frequency, despite a local peak in landslide density (**Table 4**). This is especially unusual when compared to category 10, which has greater area and higher landslide frequency, but an abnormally low landslide density (He & Beighley, 2008). These trends contrast with the distribution patterns observed in the Sikkim Himalaya (Sarkar et al., 2008), where susceptibility area exhibits a unimodal distribution and landslide density increases with susceptibility (**Table 5**).

Table 5

Sikkar Himalaya susceptibility data acquired from Table 3 of Sarkar et al. (2008).

Susceptibility Zones	Area (km ²)	Landslide Area (km ²)	Landslide Density
Very Low	33.396	0.051	0.002
Low	189.526	0.607	0.003
Moderate	194.895	1.09	0.006
High	99.431	0.971	0.01
Very High	31.551	0.473	0.015

The bimodal peak in susceptibility area and nonlinear trend in landslide density observed in the SGM suggest limitations in how the CGS susceptibility model characterizes hazard. These issues likely stem not from the concept of susceptibility itself, but from the low-resolution and generalized input data used in the model. For example, much of the SGM is assigned a rock strength value of 1, yet susceptibility category 9 requires a rock strength of 2; similarly, the model's slope data is derived from a 10 m DEM, which lacks the spatial resolution of the 1 m LiDAR data used in this study. These low-resolution inputs likely constrain the model's ability to capture localized terrain features that strongly influence slope failure. In addition, susceptibility values were extracted using centroid points for each landslide deposit, which can misrepresent the conditions associated with large or complex landslides. Together, these factors likely reduce the model's effectiveness in accurately depicting where landslides are most likely to occur—not due to flaws in the susceptibility framework, but due to the limitations of the input data and methods used to assign values.

Other anomalies are the high landslide density observed along the range-front, particularly in the SMB and TB (**Fig. 13**), and large landslide sizes in areas underlain by Tertiary volcanics (**Fig. 11**). This also highlights an anomalous north-south divide in landslide density, excluding the highly susceptible schist regions in the northeastern SGM. Although both the SMB and TB exhibit moderate to high relief, regions in the central and eastern SGM contain higher relief values with markedly lower landslide density values (**Fig. 2D**). These patterns may point to localized uplift, activity along the northern strand of the SGF, or internal deformation within sub-blocks which likely accommodate thrusting or rotation

in the SMB and TB (Mere & McPhillips, 2024). Given that both the range-front blocks and high relief regions in the central and eastern SGM share similar lithologies, factors such as localized uplift, proximity to an active fault, and sub-block deformation likely have a greater impact on landslide initiation than single variables like relief or lithology—and may play a role in explaining the abnormal landslide density and size observed in the Tertiary volcanics.

This study also helps quantify long-standing observations about the behavior of schist deposits within the SGM. While earlier work (e.g., Morton & Campbell, 1978) referred to these deposits as “bedrock slumps,” later studies (e.g., Morton & Sadler, 1989) identified distinctive deposit morphologies associated with Pelona Schist landslides, which are supported by observations in this study. Schist-dominated landscapes produce atypical landsliding: landslide deposits often appear to drape over the underlying topography, conforming closely to the landscape rather than forming discrete, blocky deposits. This morphology suggests more ductile or viscous flow-like behavior (i.e., sackungen, as noted by Morton & Sadler, 1989) which typically does not fail catastrophically compared to rigid, coherent downslope failure patterns observed in crystalline bedrock landslides. This depositional style persists across a range of scales, suggesting it is a fundamental characteristic of schist-related mass wasting rather than a function of landslide size. Repeat LiDAR or InSAR surveys may reveal ongoing movement within these deposits, though this study has not assessed the available datasets which can determine this.

Comparison With Other Landslide Inventories

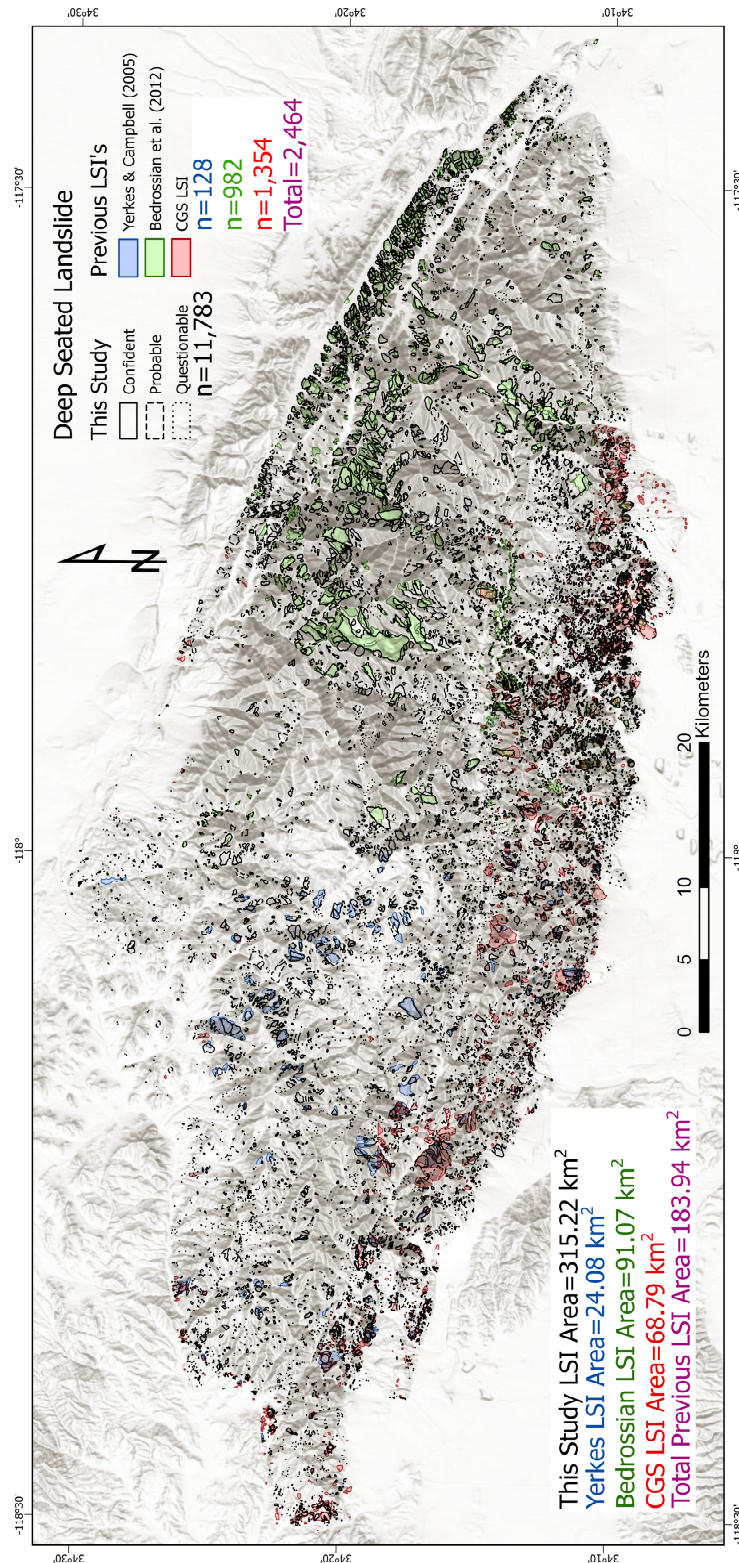


Fig. 33. Comparison of this study's LSI (black) with the Yerkes & Campbell (2005) LSI (blue), Bedrossian et al. (2012) LSI (green), and CGS LSI (red). Landslide extents for Yerkes & Campbell (2005) and Bedrossian et al. (2012) were extracted from their respective geologic maps.

Compared with previous LSIs in the SGM, the LSI generated in this study represents a significant increase in both resolution and extent (**Fig. 33**). The Yerkes & Campbell (2005) geologic map includes 128 landslides covering 24.08 km², while the Bedrossian et al. (2012) surficial deposit map contains 982 landslides totaling 91.07 km², and the preliminary CGS LSI includes 1,354 landslides covering 68.79 km². Combined, these three inventories account for 2,464 landslides and a total area of 183.94 km², including overlapping landslides. In contrast, this study's LiDAR-based inventory identifies 11,783 individual landslides and a non-overlapping affected area of 315.22 km²—nearly five times the number of mapped landslides and a substantially larger area than all prior inventories combined.

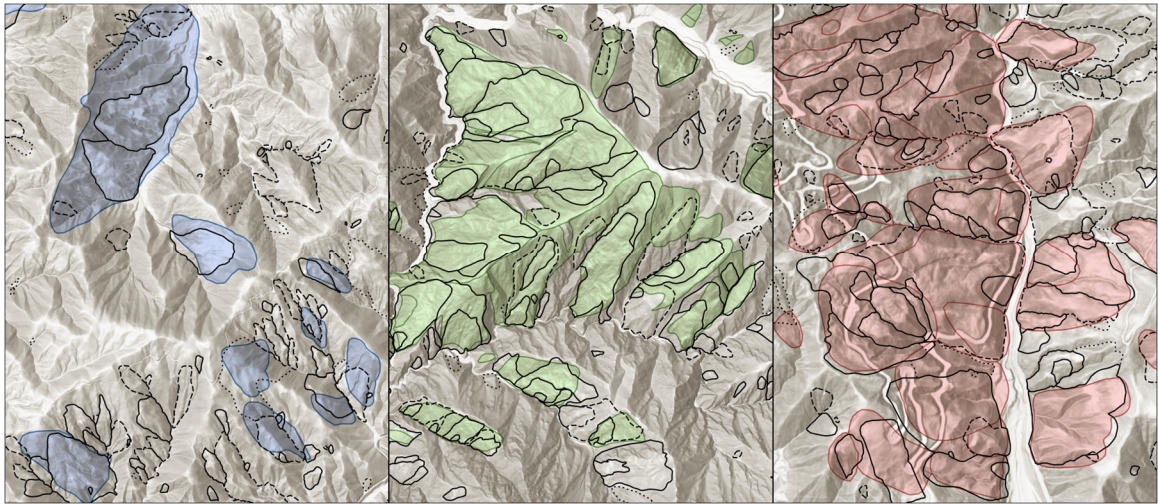


Fig. 34. Landslide deposit differentiation of this study's LSI (black) compared with the Yerkes & Campbell (2005) LSI (blue), Bedrossian et al. (2012) LSI (green), and CGS LSI (red). Locations of these examples are found at 34.3928051°N, -118.1222457°W; 34.3214486°N, -117.7083586°W; and 34.1671071°N, -117.8408540°W, respectively.

This increase reflects the benefits of high-resolution LiDAR imagery for detecting subtle or previously unmapped features, particularly in steep or vegetated terrain where field mapping and aerial imagery interpretation is limited. The improved spatial resolution of the LiDAR imagery also allowed for the differentiation of individual landslide deposits that were previously mapped as single deposits (**Fig. 34**). As such, this study's LSI provides a more consistent and spatially extensive basis for evaluating landslide distribution and characteristics across a range-wide scale.

5.0 Conclusion

This study presents one of the first range-wide landslide inventories that utilizes high-resolution LiDAR data. It highlights how landslide occurrence is influenced by lithology, topography, and tectonic structure as would be anticipated. The landslide inventory includes a total of 11,783 landslide deposits and 39,231 individual landslide lineaments mapped across 2,470 km², revealing that approximately 13% of the San Gabriel Mountains (SGM) by area are landslide deposits. The results show that broadly speaking the largest landslides initiate in strong crystalline rock, while also quantifying how schist and volcanic lithologies produce distinct, high-density landslides with unique morphologies. Landslide deposit and lineament densities do not completely correlate, particularly in the western SGM, reflecting differences in lithologic behavior and landslide deposit expression; this highlights the potential added value of landslide lineament mapping in anticipating future landslides. Anomalies in the landslide susceptibility statistics, such as the unexpectedly

low landslide density in category 10, suggest misclassification likely driven by outdated geologic and topographic inputs, and the potential for improved estimates of landslide hazard. The high landslide density identified along the range-front raises new questions about tectonic activity in blocks previously thought to be less active. The LSI generated by this study also provides a valuable foundation for refining susceptibility models and assessing infrastructure risk, particularly in planned roads and areas with roads and buildings atop deposits. Compared to previous inventories, this LSI identifies nearly five times as many landslide features and achieves spatial coverage and resolution not previously possible. More broadly, the systematic, high-resolution approach demonstrated in this study offers a framework for landslide mapping in other active orogens.

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