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IMPORTANCE OF DETAILED GEOMORPHIC INTERPRETATION IN THE LANDSLIDE CHARACTERISATION COMPONENT OF LANDSLIDE RISK ASSESSMENT

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ABSTRACT

Inventories are foundational to landslide hazard characterisation, and thus risk assessment, but commonly suffer from inadequate landslide detection and interpretation. Bare-earth LiDAR models offer excellent opportunities to identify and understand diverse slope failures from their landscape signatures. However, LiDAR's utility is rarely fully leveraged because of unfamiliarity with its datasets and underappreciation of the geomorphic subtleties they record. We illustrate challenges – and some solutions – to interpreting and documenting landslide features with wide-ranging geomorphic distinctiveness using LiDAR through the worked example of a hilly 2.8-km^2 site in Tasmania. Its size and undulating slopes are representative of typical residential subdivisions and development-pressured land fringing many Australian cities. Previous high-level, reconnaissance mapping did not identify any landslides at this site. However, iterative, site-focused landform mapping using publicly available LiDAR data and complementary open-access datasets reveal diverse slope movements. They range from fresh-looking, indisputable landslides to very subdued features suggesting much older movements, all of which should be further considered during site visits. Improved landslide hazard characterisation in this example highlights key factors influencing landslide inventorying: LiDAR's utility in conveying diverse geomorphic indicators; complementarity of geospatial techniques for interrogating elevation data; contributions from supplemental information sources; inverse proportionality between land extent and mapping detail; value of mappers' previous experience; and benefits of discussion-based landscape interpretation. Expanding site inventories into adjacent terrain and to consider evidence of additional geohazards enhances both identification and likelihood-consequence estimation of hazard scenarios. Robust landslide inventories such as this improve the entire risk assessment process and enable better risk management.

1 INTRODUCTION

Geomorphic interpretation is critical to landslide inventories, which in turn are the foundation to all other aspects of landslide mapping, spanning from susceptibility mapping, through probabilistic hazard mapping, to risk mapping. Inventories also play a key role in local-scale landslide risk assessment by helping identify conceivable hazard scenarios as well as guiding the location and form of detailed site investigations. Robust inventories necessitate not only capturing of conspicuous landslide evidence but also identifying and interpreting muted and subtle features that indicate, or even only hint at, the occurrence and behaviour of much older slope movements. Bare-earth LiDAR models (Dong & Chen, 2017) have become critical tools in developing landslide inventories (e.g. Mazengarb & Stevenson, 2010; Miner et al., 2010) including detailed characterisation of specific landslides (e.g. Cook et al., 2022; Choi et al., 2024) and, where it is available, should be heavily used in those activities. Beyond providing exceptional detail on the location, extent, type, and behaviour of landslides, geomorphic subtleties conveyed by bare-earth LiDAR models can provide insights into landslide failure depth, relative age, and contributing factors (cf. Griffiths & Whitworth, 2012). However, the power of such data is commonly underutilised. This shortfall, which hinders hazard characterisation and ultimately landslide risk management, reflects the relatively limited attention to landslide geomorphology (cf. Crozier, 2010) and all-too-common unfamiliarity with LiDAR's range of capabilities. This is not surprising given that geomorphology – a key field in leveraging the utility of LiDAR – is limited in engineering training in Australia, even in many geoscience programs.

We illustrate the challenges faced in interpreting and documenting landslide features with varying degrees of geomorphic distinctiveness through a worked example. The landslide inventory presented herein is for a 2.8-km^2 site in Tasmania covered by publicly available State LiDAR datasets. It demonstrates LiDAR's capabilities in conveying even very subtle geomorphology as well as the importance of those landforms in driving landslide investigations that support appropriate landslide risk management. Our specific objectives are threefold: 1) highlight information that can be gleaned from bare-earth LiDAR elevation models; 2) provide pointers on maximising usefulness of LiDAR datasets, including integrating complementary information sources; and 3) demonstrate an appropriate level of detail for site-scale landslide inventory. Careful geomorphic mapping, as demonstrated here, greatly improves landslide characterisation and the consequent insights that can inform landslide risk assessment and management.

2 BACKGROUND

2.1 RISK ASSESSMENT PROCESS

Risk assessment and risk management enable some aspects of society to successfully coexist with hazardous processes. In Australia, the approach for slope failures follows the nationally recognised Australian Geomechanics Society (AGS) Guidelines for Landslide Risk Management (AGS, 2007a,b,c,d,e). A revision of the guidelines – for Australia and New Zealand – will be released in 2026.

Risk assessment can be summarised in five fundamental questions: 1. what might happen? (i.e. hazard characterisation); 2. how likely is it? (i.e. frequency analysis); 3. what would be the impact? (i.e. consequence analysis); 4. how important is it? (i.e. risk estimation and evaluation); and 5. what can be done? (i.e. risk management). This paper demonstrates the criticality of geomorphic interpretation to the first question and provides insights into how such interpretations can help address the second question. It aligns with initial components of Baynes and Perry's (2022) workflow for engineering geological models as well as the 'landslide characterisation' component of hazard analysis in AGS (2007a) (Figure 1).

2.2 GEOMORPHIC INTERPRETATION IN LANDSLIDE MAPPING

Geomorphic interpretation is key to identifying and describing past landslides and provides a basis for constraining where future landslides may occur (Griffiths and Whitworth, 2012). Information derived at this stage of investigation supports all aspects of landslide mapping as well as site-specific landslide risk assessment (cf. Figure 1a). Unfortunately, landslide geomorphology has historically received much less attention than other Earth-surface processes (Crozier, 2010).

LiDAR offers one of the best opportunities for landslide characterisation (Miner et al., 2010; Griffiths and Whitworth, 2012), regardless of project scale and scope. Beyond providing greater landform detail than most other remotely sensed datasets, bare-earth elevation models derived from LiDAR data reveal geomorphic indicators that are otherwise too subtle to recognise or entirely obscured by vegetation. Other datasets need to be considered in conjunction with LiDAR, including geologic mapping, historical aerial photographs, archival information, and local knowledge. Additionally, other modern remote sensing technics can provide important, complementary insights into landslides (e.g. Roberts et al., 2019; Cook et al., 2022; Choi et al., 2024). However, LiDAR datasets should be central to landslide mapping when available.

2.3 DATASETS AVAILABILITY

In Australia, Tasmania has some of the best coverage of open-access data for landslide characterisation. Much of it is available through online map viewers and associated GIS web services. All parts of the state are covered by multiple eras of aerial photography since 1930, with most now searchable and freely downloadable. LiDAR datasets are publicly accessible for ~75% of the state and are expanded annually; hillshades and contour lines are available from LIST Map (https://maps.thelist.tas.gov.au) whereas point clouds and gridded digital elevation models (DEMs) are available from ELVIS (https://elevation.fsdf.org.au). Geologic mapping varies across several scales down to 1: 25 000 although surficial units are commonly underrepresented in favour of underlying bedrock. Open-access drilling records comprise drill holes, auger holes, and test pits, with archived drill core available for viewing. Tasmania has an extensive landslide mapping program, although its ~10,000 identified and possible landslides largely reflect moderate-scale reconnaissance mapping.

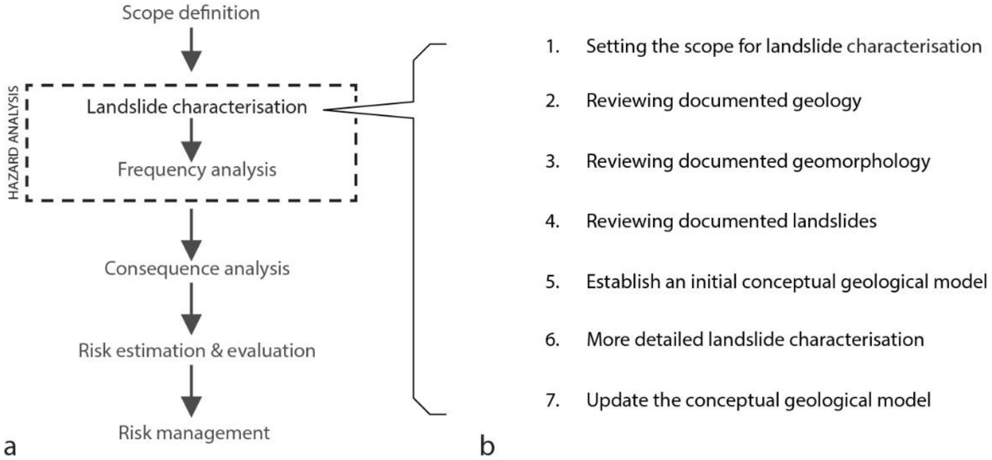

Figure 1: Context of hazards characterisation as a) a component of the landslide risk assessment process (simplified from AGS 2007a) and b) comprising the seven key steps formalised herein.

Dataset availability is highly variable elsewhere in Australia. LiDAR coverage is sporadic and only sometimes freely accessible (cf. ELVIS). Landslide mapping is particularly limited in most areas and, where it exists, is typically difficult to access. Geoscience Australia's listing of landslides and landslide-triggering events (GA 2012; Leiba 2013) provides some helpful details but is highly irregular in spatial-temporal coverage with spatial referencing limited to estimated point coordinates.

3 LANDSLIDE CHARACTERISATION PROCESS

Landslide characterisation forms the foundation of risk assessment (Figure 1a). We formalise landslide characterisation into seven steps (Figure 1b), elaborated below. This paper focuses specifically on LiDAR dataset usage in the recognition and understanding of landslide features to support three tasks: identifying processes and consequent hazards; interpreting the behaviour and timing of past movements; and estimating the character and likelihood of future movements.

3.1 SETTING THE SCOPE FOR LANDSLIDE CHARACTERISATION

Spatial extent and intended land use together dictate the scope and resolution of landslide characterisation. Necessary site background includes determining clearance and land-use history, aided by insights from historic imagery and topographic maps. Geographic bounds determine the nature and diversity of ground conditions that will be encountered, including slope geometries, materials, and processes. The types and density of land use determine exposure to hazards. They additionally may aggravate existing hazards and produce new hazards. Critically, hazard characterisation, and thus inventory area, should extend beyond just the spatial extent of the project area; insights from adjacent, analogous landscapes provide key opportunities for identifying and understanding existing and potential hazards.

3.2 REVIEWING DOCUMENTED GEOLOGY

Existing geologic information is a fundamental starting point for understanding hazards because of its insights into material properties and their spatial and stratigraphic variability. Both mapping and subsurface information should be considered, although their availability will depend on the scale, purpose, and quality of past work. Beyond geologic maps and drilling, any available soil maps and geophysical surveys should be considered. Rock and soil units determine geomechanical and hydrological properties. Additionally, they provide a starting point for geomorphic interpretation by indicating emplacement processes.

3.3 REVIEWING DOCUMENTED GEOMORPHOLOGY

Geomorphology provides complementary information to geology. Tell-tale landforms left by geologically recent processes remain coupled to their geologic records, enhancing understanding of those processes operating in and responsible for the landscape. In many cases, those processes also represent hazards. Regrettably, geomorphology is not commonly mapped in Australia. However, topographic and geologic mapping provide some insights into, respectively, landscape form and material properties. In the rare instances where geomorphology is mapped, it is typically either very localised or limited in detail. This partially reflects Australia's commonly mature landscapes and relatively slow process rates (cf. Taylor, 1994), which complicate geomorphic interpretation because constituent landforms are generally subdued.

3.4 REVIEWING DOCUMENTED LANDSLIDES

Existing landslide inventories and mapping provide a starting point for identifying and understanding past mass movement types, magnitudes, drivers, and frequencies. These resources are key sources of previous assessors' interpretations of the landscape. They typically include information from a variety of sources, some of which may be challenging to obtain (e.g. local knowledge) or altogether unavailable (e.g. confidential reports). Critically, if mapping is out of date, existing inventories may not represent current conditions or, possibly, even the most recent state of understanding. This is most likely to be the case as most mapping is only periodically refreshed. Furthermore, the information provided can range from limited to excessive (Mazengarb et al., 2010).

Unfortunately, landslide inventories and maps will not already exist in most cases, leaving the responsibility of identifying and interpreting landslides wholly to the current investigator. Even where landslide maps exist, they are commonly difficult to access because they are held by local authorities or commercial consultants; such mapping may be privileged information and thus not publicly available. A key exception is Tasmania's statewide, publicly available landslide inventory (Mazengarb and Stevenson, 2010). As the coverage, recency, and detail of the inventory is highly variable, it should be viewed as a reconnaissance-level depiction of mass movements.

Ancillary sources (e.g. aerial and orbital imagery, archival newspapers) should be considered. They provide complementary information including soil moisture, vegetation type, land use, and above-ground features removed from bare-earth LiDAR models. Additionally, information from different eras can constrain the timing of past landscape change.

3.5 ESTABLISHING AN INITIAL CONCEPTUAL GEOLOGICAL MODEL

Initial conceptual geological models formulate what landscape conditions and processes exist as well as how they influence hillslope evolution (cf. Baynes and Perry, 2022). They are the first call for understanding context and implications of landslide mechanisms. Formation of the conceptual model is directly influenced by the quality, extent, and scale of previous datasets and their interpretation. All existing information should be considered, including landslide mapping, geologic mapping, geomorphic mapping, and subsurface investigations (detailed logs, driller's logs, and even information from groundwater wells). The mapping scale and detail of previous inventories thus directly impacts model development. To a degree, previous assessors' conceptual model will be reflected in their landslide inventories, as these are heavily influenced by their interpretations.

3.6 UNDERTAKING MORE DETAILED LANDSLIDE CHARACTERISATION

This is the start of the new contributions of the current assessor. It may also be the only landslide mapping for the area. Even if not, previous work will likely have been at a smaller scale (i.e. less detailed), using poorer data (e.g. high-altitude aerial photography). Any features already captured are likely the most obvious ones. Mapping should consider multiple representations of the landscape at hand. However, those representations will depend heavily on available datasets.

New LiDAR-based mapping will be limited to superficial features. Geomorphology provides great insight into surface conditions and processes, but also reflects conditions below surface (e.g. estimates of failure depth based on landslide type and extent). However, subsurface conditions cannot be adequately understood from geomorphology alone.

3.7 UPDATING THE CONCEPTUAL GEOLOGICAL MODEL

The initial conceptual model is updated by considering previous work and adding new landslide interpretations. In some cases, particularly where little new information is available, that model may only slightly change. Alternatively, the model will change drastically where the new assessors' interpretations differ from those previous and, especially, where new insights are available. This is particularly relevant where previous work did not have the benefit of geomorphic insights provided by bare-earth LiDAR elevation data.

4 CASE STUDY

The following case study uses a real landscape in a hypothetical scenario to demonstrate the above seven-step landslide characterisation process. It emphasises the importance of geomorphic interpretation for site-specific landslide mapping (section 3.6) and ensuing conceptual geological model revision (section 3.7). All datasets presented are publicly available through online sources (detailed in section 2.3). The specific locality is unimportant and, thus, not indicated.

4.1 SCOPE

The project area is a rural agricultural site with mixed vegetation cover (Figure 2a) bordering the suburban fringe of an urban area. The fictitious scenario proposes subdivision of a parcel for moderate-density, detached or semi-detached, residential housing. We have extended the study area to be considered in mapping and conceptual model development beyond the dimension of the project area to ensure adequate context for thorough hazard characterisation.

4.2 GEOLOGIC MAPPING

Site geology, as depicted in Tasmania's 1:25 000 geologic map series (Figure 2b), spans just a few material types (cf. Corbett et al., 2014): Jurassic (ca. 170 Ma) Tasmanian Dolerite, which is locally deeply weathered; Cenozoic alluvium spanning gravelly Quaternary (< ca. 2.6 Ma) and predominantly fine-grained Palaeogene-Neogene (ca. 66-2.6 Ma) sediments; and Cenozoic ferricrete formed within colluvial cover and the older alluvial sediments.

No subsurface information is available within the study area, although nearby boreholes provide general context. Core logs through pre-Quaternary alluvium ~1 km away record weathered, very weak sedimentary rock to at least 10 m depth. Logs through dolerite ~3-4 km away indicate <1 m of residual soil over slightly weathered dolerite near ridgelines in contrast to ~1-1.5 m residual soil overlying at least 10-15 m of very deeply weathered dolerite lower on slopes.

4.3 GEOMORPHIC MAPPING

No geomorphic mapping has yet been published for this area. However, topographic and geologic information (Figure 2b) provide some helpful insights. General slope profiles, the substantial age of most geologic units, and the formation of ferricrete all suggest development of a thick colluvial apron. Mapped alluvium of wide-ranging ages indicates long-lasting fluvial influences as well as minimal modification of pre-Quaternary sediments. *In situ* weathering necessary to produce the ferricrete further reflects mature, relatively stable landscapes.

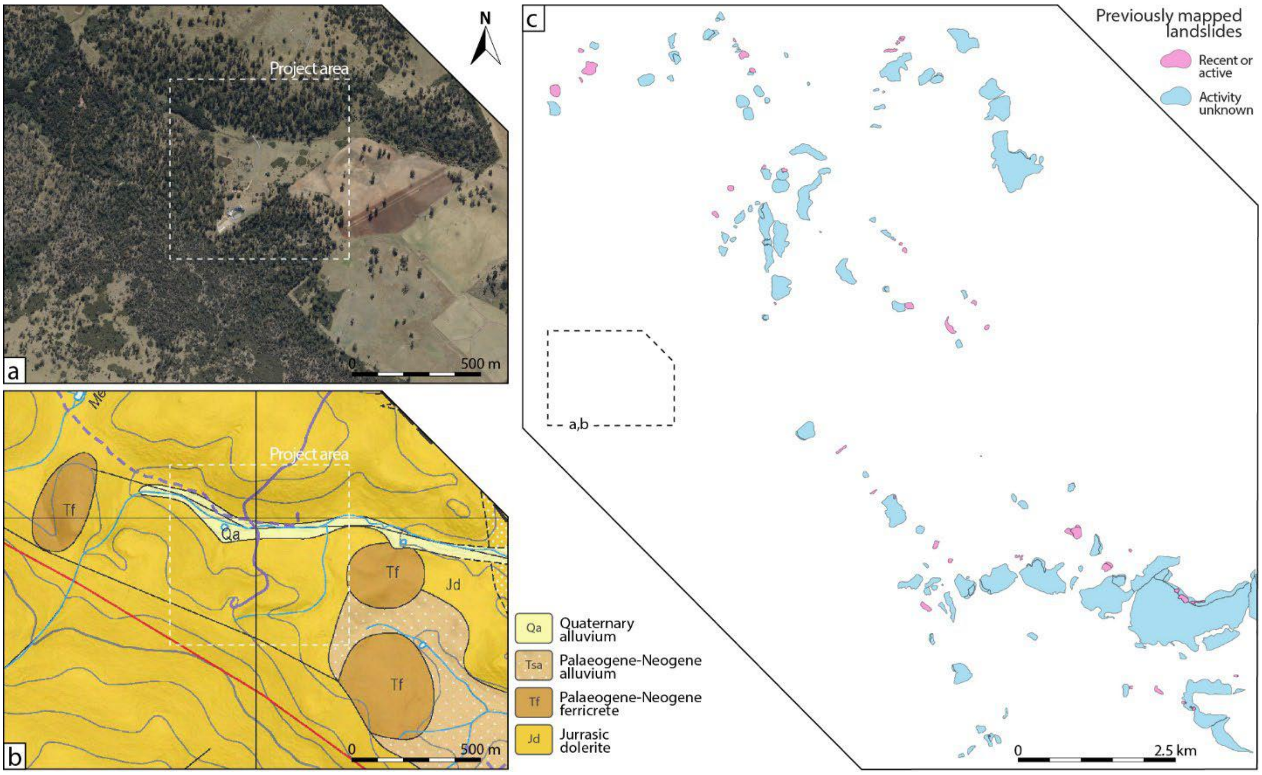

Figure 2: Available background information for the study area: a) recent aerial photograph; b) 1: 25 000 geologic mapping; and c) regional landslide mapping. All datasets are viewable in LIST Map.

4.4 LANDSLIDE MAPPING

Despite the study area's reasonably landslide-prone terrain and coverage by various information sources, no slope failures have been previously documented. No landslides are indicated in MRT's statewide landslide database (Figure 2c) or the most detailed published geologic mapping (Figure 2b). No landslide impacts are indicated in MRT's landslide damage dataset or could be found through searches of archival newspapers in the National Library of Australia's Trove repository.

4.5 INITIAL CONCEPTUAL GEOLOGICAL MODEL

Topographic and geologic information enable formation of a basic conceptual geological model focusing on the main, southwest slopes (Figure 3). Fresh dolerite occurs near surface in uppermost slopes with depths of deeply weathered dolerite and thinner overlying residual doleritic soils increasing down slope; soil-strength materials derived from dolerite exceed 15 m near slope toes, and residual soils are expected to become finer. Valley bottoms are covered by older (probably pre-Quaternary) alluvium with incised, narrow corridors of younger (Quaternary) alluvium along channels.

Insufficient landslide information hinders the demonstration of past failure mechanisms as well as the anticipation of future failure types, locations, and magnitudes. However, based on the simple conceptual model, debris slides are most likely to

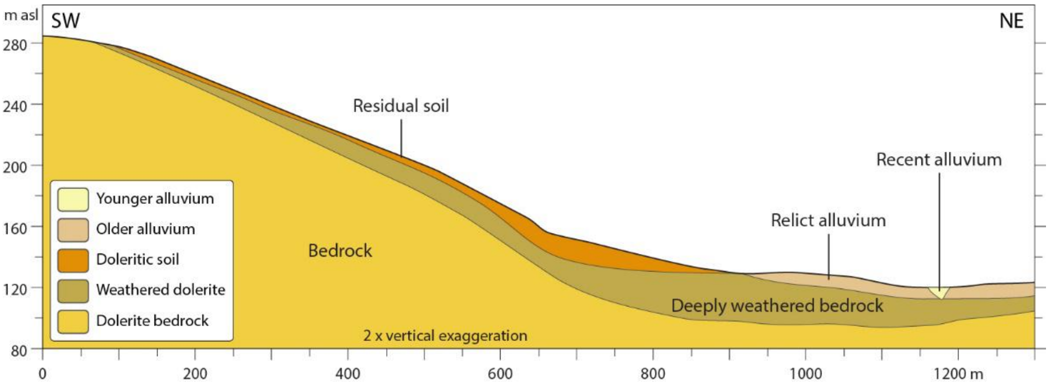

Figure 3: Initial conceptual geological model.

occur in coarse-grained mid-slopes and earth slides in fine-grained lower slopes. Small rotational or compound landslides (i.e. riverbank slumps) are likely to be concentrated along modern river channels, particularly near sharp cutbanks.

4.6 LANDSLIDE INVENTORY PRODUCTION

The authors mapped together while discussing interpretations, enabling efficient identification, description, and basic evaluation of features. The most obvious features were mapped first. Each subsequent mapping pass identified progressively more subtle features aided by insights from more obvious analogues already detected and by the interpreters' growing familiarity with the landscape. The landslide inventory was thus iteratively expanded with each pass identifying additional landslide features, albeit of progressively lower confidence. Notably, mapping leveraged complimentary ways of viewing the LiDAR models and their derivative representations (Figure 4) as well as ancillary datasets (e.g. Figure 2a,b).

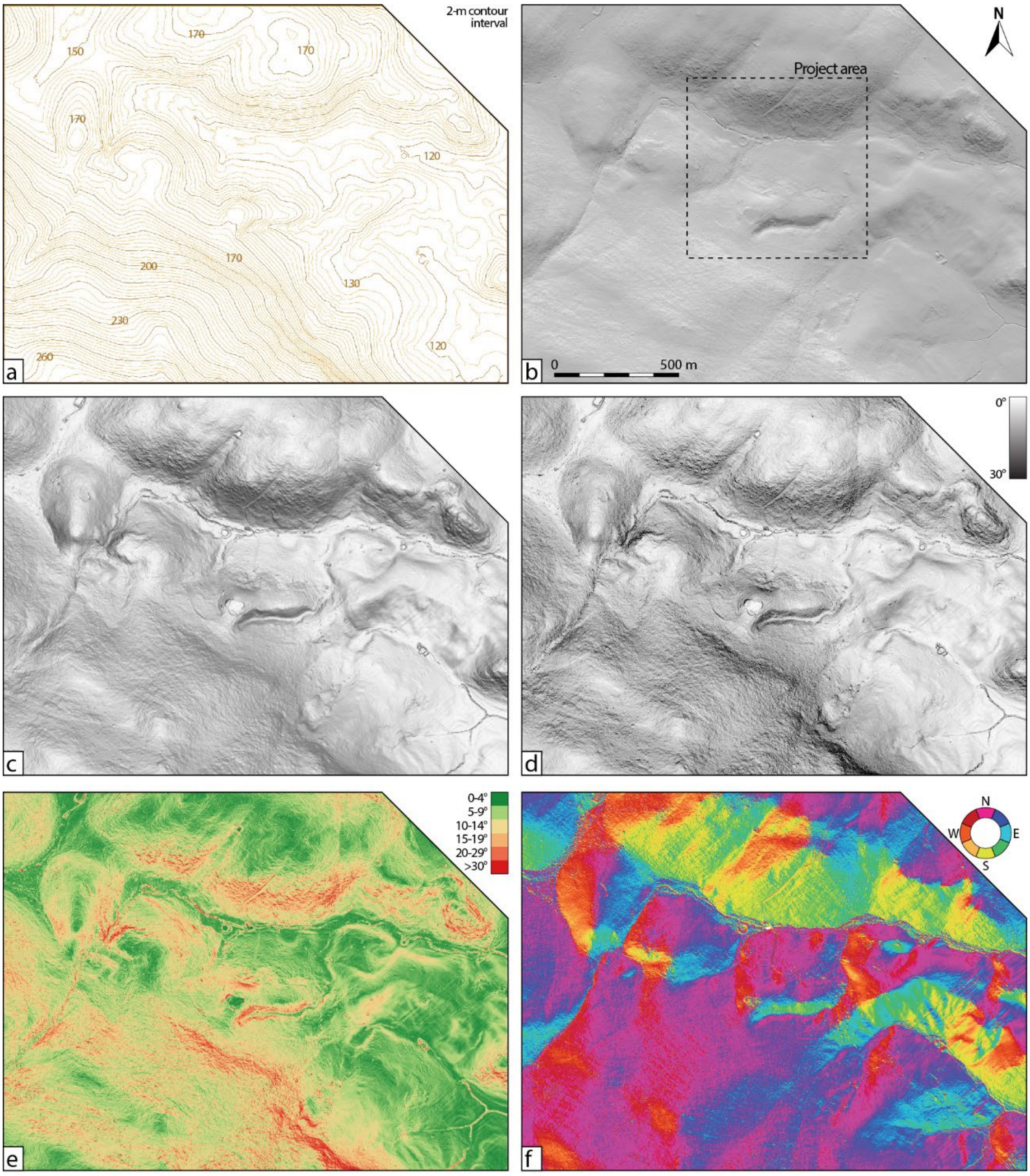

Figure 4: Diverse topographic representations of the same bare-earth LiDAR dataset: a) QGIS-generated contour lines; b) QGIS-generated hillshade; c) LIST Map hillshade; d) GlobalMapper slopeshade: e) QGIS-generated slope map; and f) QGIS-generated aspect map. Each is influenced by user-selected preferences, with some similar products appearing different ('b' vs 'c') and some different products appearing similar ('c' vs 'd').

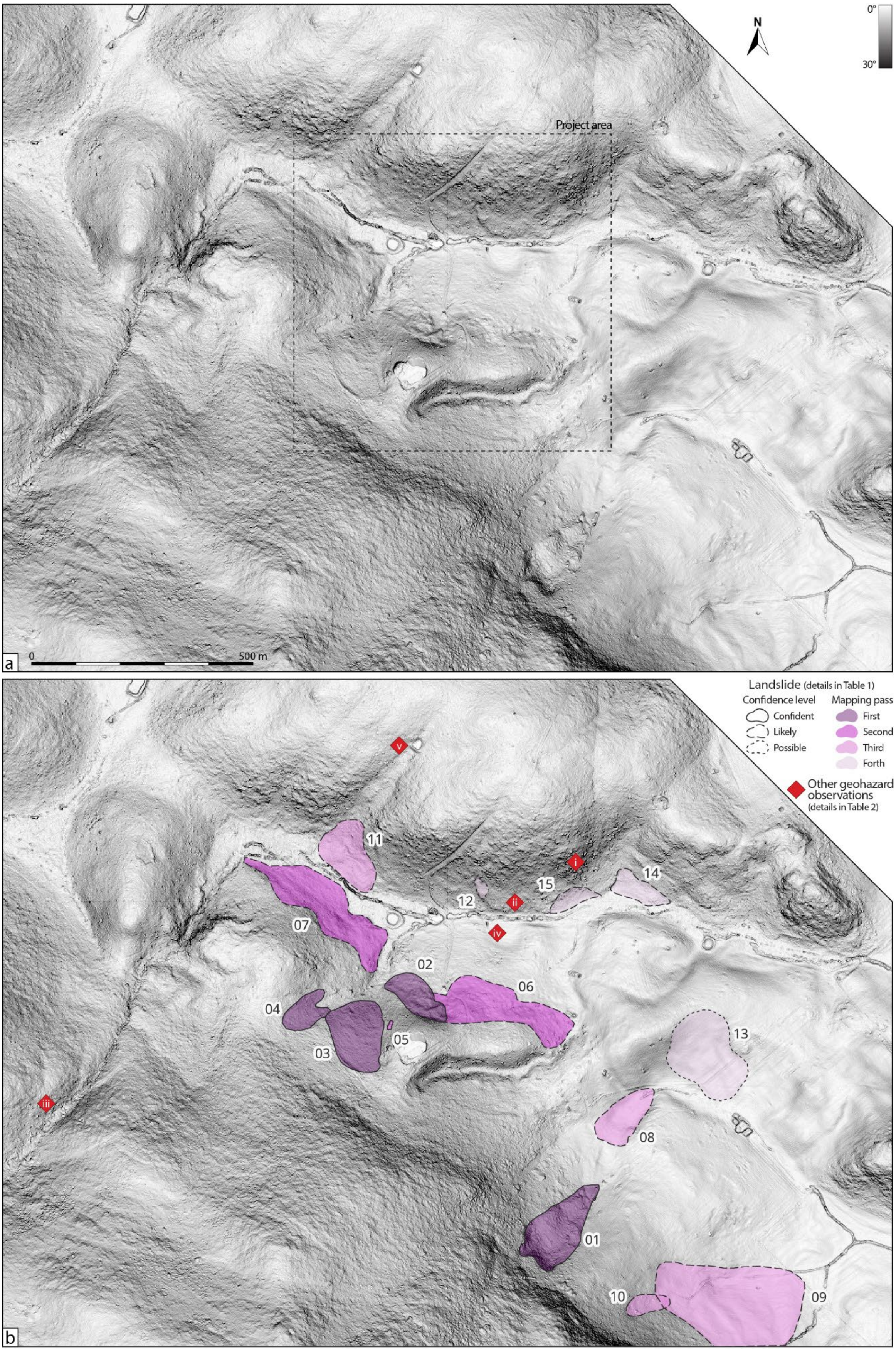

Figure 5: Iterative mapping with slope shader (Figure 4d) as base map. Identified features comprise landslides (polygons: details in Table 1) and other observations related to geohazards (diamonds: details in Table 2).

Table 1: Basic details of mapped landslides.

Feature	Pass	Type	Confidence	Rating[*]	Comment
01	1	Earth slide	Confident	1	Most obvious feature; pronounced headscarp, toe, & internal lobes
02	1	Debris slide	Confident	2	Conspicuous lobes becoming more muted toward western margin
03	1	Debris slide	Confident	3	Subtle, suggesting either greater age, shallower depth, or both
04	1	Debris slide	Confident	3	Subtle, suggesting either greater age, shallower depth, or both
05	2	Earth slide	Confident	2	Sharp boundaries, but very small; visible easily at very large scale
06	2	Debris slide	Likely	3	Similar to adjacent feature 02 but more degraded appearance
07	2	Debris slide	Likely	3	Similar to adjacent feature 02 but more degraded appearance
08	3	Earth slide	Likely	4	Muted but confidence increased by analogous feature upslope
09	3	Earth slide	Likely	2	Muted boundaries but distinct internal structure; confidence increased by likely analogous features (08 & particularly 01)
10	3	Earth slide	Likely	3	Very subtle, degraded morphology; limits visible in 3D perspective
11	3	Debris slide	Likely	4	Toe displaces stream but other limits unclear; mechanism uncertain
12	4	Debris slide	Possible	5	Lobate feature probably in soil with coarse rockfall; possibly evidence of how this colluvial apron evolves
13	4	Earth slide	Possible	5	Very muted downslope-trending ridges ending in lobes
14	4	Debris slide	Likely	4	Noted when examining LIST Map hillshade
15	4	Debris slide	Likely	4	Noted when examining LIST Map hillshade

* Qualitative rating of feature clarity:
1 - Landslide of identifiable type with sharp geomorphic features
2 - Landslide of identifiable type with subtle/degraded geomorphic features
3 - Landslide of identifiable type with subtle/degraded geomorphic features, limits difficult to determine
4 - Likely landslide, type and/or limits uncertain
5 - Speculative at best

We identified 15 landslide features within and adjacent to the project area through five iterative passes (Figure 5; Table 1). The slope-shaded DEM (Figures 4d, 5) was the main source of interpretation. However, differing visualisations benefited feature identification and characterisation by providing additional insights into landforms and the processes they reflect. For instance, some subtle landslide features (nos. 14 and 15) were not readily apparent in the slope-shaded DEM but were clearly evident in the LIST Map hillshade (Figure 4c vs 4d). Topographic profiles and 3D perspective views assisted in recognising and interpreting many features. Landslide features were primarily identified from LiDAR datasets, although ancillary datasets provided useful insights and context.

The main identified landslide mechanisms are earth slides and debris slides. Subtle features indicate that rock fall and debris flow could occur locally. Mapping identified several various geomorphic features of interest related to additional geohazard scenarios at the site (Figure 5b; Table 2): hints of dolerite outcrops producing rock fall (i) that may form colluvial aprons along some slope toes (ii); a likely bedrock channel that could carry debris flows (iii); tunnel gullying (iv); and a farm dam that could produce a channelised outburst flow (v). Attribution at minimum should include the fields in Table 1. Free-form comments or notes provide a critical summary that helps map users understand the rationale behind the identification of a given feature.

Table 2: Basic details of other geohazard observations.

Feature	Pass	Type	Confidence	Comment
i	3	Rockfall	Likely	Scabby texture indicates heavily jointed bedrock at or near surface
ii	4	Colluvial apron	Possible	Lobate aprons suggest debris accumulation from suspected rockfall sources
iii	4	Bedrock channel	Likely	Shallow bedrock forms a channel that could carry saturate debris
iv	2	Tunnel gullying	Confident	Deep, narrow, locally covered channel suggesting subsurface erosion
V	3	Farm dam flood source	Possible	Earthen dam impounding a small reservoir, if it failed, could release a small but extremely rapid flood down the channel below

4.7 REFINED CONCEPTUAL GEOLOGICAL MODEL

Geomorphology recognised using bare-earth LiDAR data helped to confirm and refine the initial conceptual geological model, including expansion to the area's northern slopes (Figure 6). Notably, the detailed hillslope characteristics determined using DEM representations, profiles, and 3D perspectives provide key additional insights into material properties and formative processes. Steepness, morphology, and texture were particularly useful. Rough patterns on steeper slopes in the study area's north indicate the main departure from the initial conceptual model: dolerite bedrock is near and locally at surfaces in middle to upper slopes whereas debris, possibly from rock fall, mantles slope toes.

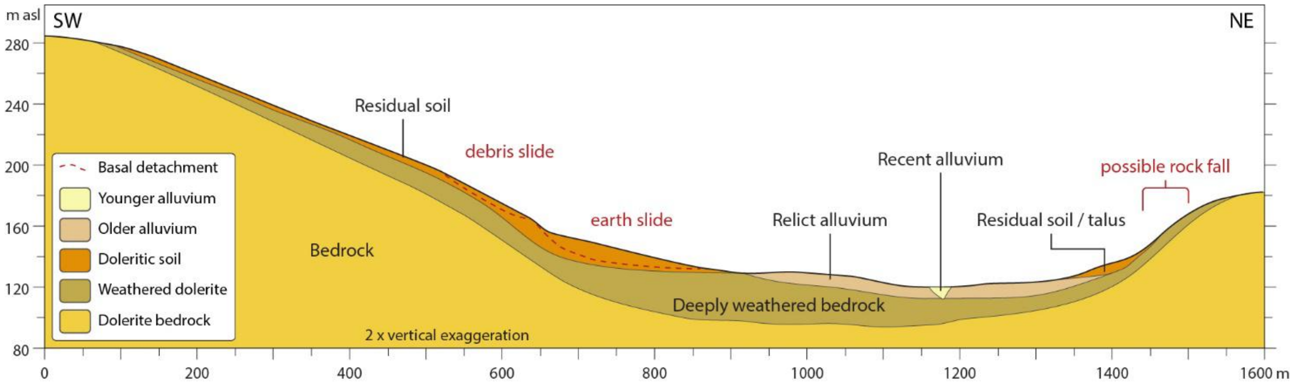

Figure 6: Revised and expanded conceptual geological model.

The initial conceptual model reasonably explains moderate-to-gentle slopes elsewhere in the study area. Surface textures along slope toes support the previous expectation of substantial, downslope-fining colluvial deposits on most slopes. Spatial distributions of landside mechanisms, as interpreted from geomorphic expression, further support the previously expected extents and relative depths of weathered and sedimentary units. Thus, the revised conceptual geological model is similar to the initial one but adds recognition that locations of the most common landslide types are determined by the thickness and fineness of dolerite-derived slope deposits.

5 DISCUSSION

A structured approach to landslide mapping helps achieve better consistency and overall quality. The worked example herein helps demonstrate various factors and considerations in landslide mapping, particularly when using bare-earth LiDAR DEMs. Their careful interpretation will help improve landslide inventories of any scale.

5.1 CASE STUDY FINDINGS

The above case study illustrates subtleties and capabilities of bare-earth LiDAR DEMs for landside mapping. It also demonstrates the vast improvement in site-specific landslide characterisation that LiDAR datasets enable when thoroughly investigated. No landslides were identified at the site during previous geologic or regional landslide mapping. By contrast, careful LiDAR DEM interpretation identified numerous relevant features: five landslides; ten suspected landslides; and additional geohazard scenarios including tunnel gullying and channelised outburst from a small farm dam reservoir. Each of these features and processes could negatively impact current and future site uses. Each must be carefully considered throughout the risk assessment process to determine whether proposed future development is appropriate and if landslide risk management is necessary to achieve tolerable risk levels.

Subtleties in bear-earth LiDAR datasets indicate significant potential geohazards at the site and many more past landslides than most practitioners or land managers would likely have expected. Landslide potential elsewhere in Australia is probably similarly underappreciated. The case study site is representative of landscape conditions and development pressures in the periphery of urban areas across Australia’s Eastern Uplands (cf. Pain et al., 2011). It is thus relevant to development-pressured regions not only in Tasmania but in landslide-affected parts of mainland Australia.

5.2 INSIGHTS INTO LIDAR-BASED LANDSLIDE MAPPING

There is no single way to best utilise LiDAR datasets. The general process and specific activities herein provide some guidance on its effective use for landslide mapping. Project area, resourcing, and purpose together determine mapping scale, thresholds for what is or is not considered, the degree to which features are split or amalgamated, and the level of detail in attribution.

5.2.1 Specifics of the mapping process

Some best practices within the mapping process, as demonstrated in the case study, are strongly recommended. Mapping should extend beyond the designated project area. How far, however, depends on consistency of physiography, geology, and geomorphology. The aim is to consider representative conditions that will help inform processes and possible hazards at the project site. Nearby areas may have better information or more informative features, thus providing clearer demonstration of processes and hazards at play. Conversely, looking too far away may add too much complexity or variation in preparatory conditions, landslide mechanisms, and failure triggers.

Best practice uses multiple, complimentary information sources. Beyond being the best available datasets, these should provide differing information types (e.g. ground cover, elevation, and reported observations) and, where possible, represent different eras to help inform rates of landscape changes (e.g. multitemporal aerial photography and satellite imagery). In the case of LiDAR, using multiple representations of bare-earth elevations is especially important to provide different perceptions and perspectives that support robust interpretations (cf. Figure 4). Where LiDAR datasets are unavailable or of poor quality, new LiDAR collections may be critical to project success.

Making multiple passes allows mapping to systematically progress from the most obvious to the least distinct features. This helps to calibrate the assessor in recognising the range of morphology types and their gradual degradation in a given landscape. Beyond leveraging obvious features to assist in interpreting more muted analogues, this approach helps inform the relative antiquity and activity of previously mapped landslides.

Many details can be interpreted remotely from LiDAR datasets. However, the range and confidence of information remain limited without field confirmation and detailed investigation. Given the numerous attributes that could be included in a landslide inventory (cf. Mazengarb et al., 2010), careful consideration is necessary to avoid superfluous data while ensuring that sufficient information is provided, not only for present needs but for anticipated future inventory uses. Inventories should also convey the level of interpretation confidence, which commonly reflects the degree of geomorphic clarity.

5.2.2 Scale and detail

Mapping scale and detail will depend on four factors: extent of area, complexity of area, purpose of work, and resources available. Notably, workload increases geometrically, not arithmetically, with project scale. For instance, by necessity of its areal extent, Tasmania's extensive statewide landslide inventory – considered to be one of the best in Australia – does not capture all obvious or potential landslide features and commonly groups contiguous landslides into landslide areas or landslide complexes. Additionally, the detail of Tasmania's statewide mapping differs from location to location based on mapping date, available base datasets, risk profile, relevance to past projects, and who specifically did the work. Mapping at larger scale for more targeted projects – such as specific subdivisions, lots, or infrastructure corridors – should greatly expand upon available regional-scale mapping.

5.3 IMPORTANCE OF EXPANDING BEYOND EXISTING MAPPING

Absence of previously mapped landslides is no guarantee that landslide evidence is lacking in the landscape. This is particularly the case where LiDAR now provides new opportunities for detailed geomorphic mapping that was far more challenging and potentially impossible with earlier datasets and information, such as aerial photograph interpretation and on-site inspections. Simply stating "no mapped landslides" is insufficient for landslide characterisation; site assessors must evaluate the study site at an appropriate scale and explain what they have done.

Any existing mapping should be considered a starting point for site-specific inventories. Site investigators must consider not only what is already known about a site, but what might have been missed in previous mapping due to scale, data availability, or purpose. The small area of site-scale investigations enables far more detailed interpretation and mapping. Do not assume that previously mapped landslides are the only features present or accurate representations of current slopes. Any mapping captures a landscape at a point in time. New landslides will eventually occur, and existing ones can change in extent, mechanism, or obviousness. Additionally, other natural and anthropogenic processes will modify slopes.

6 CONCLUSIONS

We developed a seven-step landslide characterisation process that leverages the geomorphic utility of LiDAR datasets. Detailed geomorphology conveyed in bare-earth LiDAR models is largely independent of vegetation cover and provides critical insights on the location, extent, and mechanisms of past landslides. It also provides evidence that helps approximate landslide age. A worked case study demonstrates the proposed steps. Additionally, it highlights the importance of thorough geomorphic interpretation in landslide mapping, with impacts on the entire landslide risk management process.

LiDAR is one of the most effective tools available for producing robust, appropriately detailed landslide inventories. It is especially powerful for understanding Australia's relatively old landscapes and generally slow processes, where subtle geomorphology complicates the identification and interpretation of landslide features. Our landslide characterisation process and case study illustrate several additional key points. Landslide mapping requires multiple passes to maximise LiDAR's benefits. More detail must be considered at site-scale than small-scale mapping exercises, with the former highly likely to identify additional features. Expanding landslide inventories spatially beyond the study site and to include related geohazards enhances the identification and subsequent likelihood-consequence estimation of hazard scenarios. Landscape interpretation involving discussion amongst assessors, combined with their previous mapping experience enhances comprehensive recognition and understanding of landslide features. Robust landslide inventories directly improve subsequent risk assessment steps and enable better risk management.

Critically, data sources and past interpretations are not infallible. They represent a point in time within ever-changing landscapes. Features in addition to previous mapping very likely exist, having either gone unrecognised or occurred since.

We make the following key recommendations:

- When available, LiDAR data should feature extensively in desktop mapping and guide on-site investigation.
- Complementary geospatial techniques and visualisations should be employed when interrogating elevation data.
- LiDAR data need to be used in combination with supplemental information sources such as other modern technologies, historical imagery, archival records, and local knowledge.
- Mapping requires field verification, acknowledging that subtle features may be most apparent in LiDAR datasets.
- Because of the dynamic nature of landscapes, landslide mapping should be periodically updated.

Having completed a robust landslide characterisation, the rest of the risk assessment process can then more effectively proceed beginning with frequency analysis, which can itself be guided by LiDAR-based geomorphic interpretation.

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