

Dataset of Deep-Seated Gravitational Slope Deformations and Their Associated Landforms in Friuli Venezia Giulia Region (Italy)

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Abstract

Deep-seated gravitational slope deformations (DGSDs) are large, slow-moving landslides that strongly influence mountain landscape evolution and slope stability. Despite their geomorphological importance, no standardized regional geospatial dataset describing DGSDs and their associated gravity-induced landforms has been available for the Friuli Venezia Giulia Region (NE Italy). In this study, a dataset including DGSDs and their gravity-induced landforms that affect the mountainous sector of the above-mentioned region is presented. The dataset was produced through the integrated interpretation of high-resolution LiDAR-derived digital elevation models, orthophotos, European Ground Motion Service (EGMS) InSAR data, landslide inventories, and uncrewed aerial vehicle (UAV)-assisted field surveys. It is distributed as a GeoPackage containing DGSD boundaries together with point, line, and polygon layers representing gravity-induced landforms, as well as an attribute table describing the geometry, morphometry, geology, auxiliary data, metadata, and associated landforms of each mapped DGSD. Its standardized and interoperable structure facilitates visualization, querying, comparison, and integration with other geospatial datasets, providing a reproducible resource for future geomorphological investigations and database updates.

Dataset: <https://doi.org/10.6084/m9.figshare.33112016>.

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Keywords: large landslide; DGSD; landslide inventory; geohazard; geomorphological mapping; Southern Alps



Academic Editor: Vladimir Sreckovic

Received: 29 July 2026

Revised: 28 August 2026

Accepted: 29 August 2026

Published: 31 August 2026

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1. Summary

Deep-seated gravitational slope deformations (DGSDs) are large landslides that are common in the Alps and other European mountain ranges [1–3]. They are typically characterized by very slow movement rates and evolve over very long timescales, ranging from 10^4 to 10^5 years [4,5]. DGSDs exert considerable influence on landscape evolution, slope stability, and groundwater circulation. They often favor the occurrence of collateral landslides, including rockfalls, rotational and/or translational landslides, and debris flows [6–9]. Accurately identifying and classifying DGSDs are therefore essential for effective landslide mapping and hazard assessment [10,11]. However, recognizing and mapping

DGSDs remain challenging because of their large size, indistinct boundaries, and the presence of vegetation and shallow landslides that mask diagnostic DGSD-induced landforms (Figure 1) [12–15].



Figure 1. The Cima Val di Puartis DGSD. Some of the most representative gravity-induced landforms are highlighted, including (A) an uphill-facing scarp, (B) a trench, and (C) a ridge top depression. Their gravity-induced origin is supported by their spatial association with other diagnostic deformation features along the entire slope and their greater abundance within the instability zone than in the adjacent areas.

The study area encompasses the mountainous sector of the Friuli Venezia Giulia (FVG) Region (NE Italy). It represents the southeastern termination of the Alpine range and is characterized by a complex geological setting, spanning in age from the Paleozoic era to the Quaternary period. It is dominated by carbonate and siliciclastic rocks, as well as flysch successions, with minor volcanic and low-grade metamorphic rocks [16]. FVG lies within the Alpine–Dinaric transition zone and is affected by active compressional tectonics [17], with major thrust systems and regional faults exerting structural control on the landscape. Its high-relief topography, characterized by steep slopes and deeply incised valleys, reflects the combined effects of long-term tectonic evolution and Quaternary glacial and fluvial erosion [18]. Overall, these characteristics, together with significant seismic activity [17], and abundant precipitation [19], favor the occurrence of DGSDs.

Nevertheless, until recently only a limited number of DGSDs were reported in the Alpine sector of FVG [5,6,20,21].

To address this gap, a regional geomorphological investigation was carried out through a systematic analysis of high resolution (HR) LiDAR-derived digital elevation models (DEMs), orthophotos, existing landslide inventories, and satellite-derived ground deformation products (European Ground Motion Service, EGMS). The most spectacular DGSDs were validated through field-visit observations.

We identified 21 DGSDs, representing the first homogeneous regional dataset of these large landslides in the mountainous sector of FVG (Figure 2).

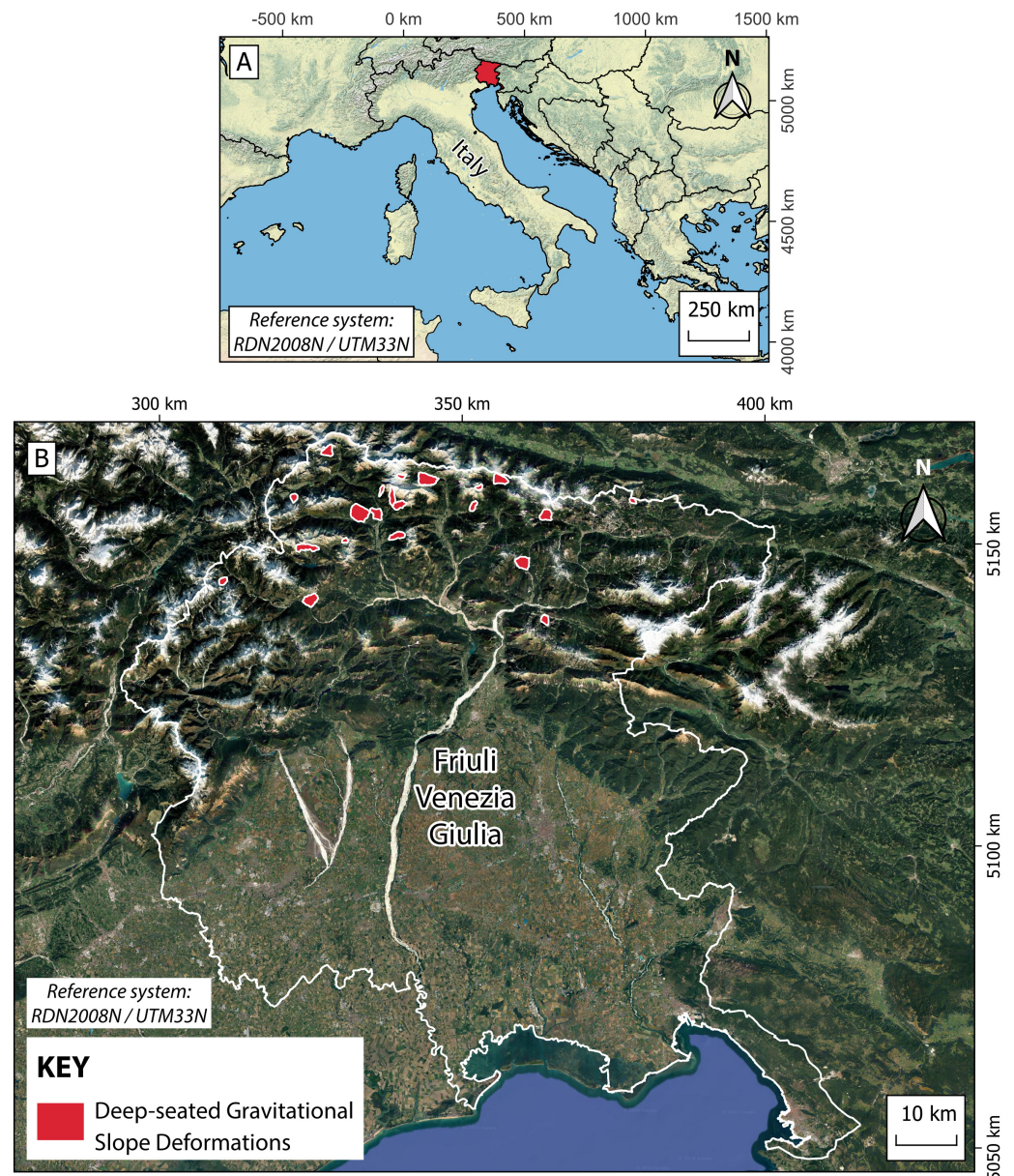


Figure 2. (A) Location of FVG region; (B) location of 21 DGSDs that affect northern part of FVG region.

This study presents a complete geospatial database produced during the investigation. This product is available as an open GeoPackage (GPKG) that includes layers detailing the spatial extent and morphometric characteristics of each mapped DGSD, as well as vector layers representing the different types of DGSD-induced landforms. Each mapped DGSD is accompanied by a standardized attribute table including identification, geometric, morphometric, geological, auxiliary, and metadata information, as well as the occurrence of gravity-induced landforms, providing a comprehensive description of each phenomenon.

The database supports a wide range of applications, including regional geomorphological mapping, landslide hazard assessment, engineering geological investigations, landscape evolution studies, and future inventories of DGSDs. The adoption of an open, GeoPackage format enables easy integration with geographic information systems (GIS) and allows for straightforward reuse and updating. Furthermore, the database provides a reproducible framework to facilitate future investigations of deep-seated landslides in

Alpine environments and enables comparison with other large-landslide studies from other Italian regions [3,22,23].

2. Data Description

The DGSDs and their associated landforms are stored in a GPKG titled DGSD_FVG_dataset.gpkg. This format adheres to the Open Geospatial Consortium (OGC) standard format and can be directly imported into widely used GIS software. The GPKG includes four vector layers, as described in Table 1, together with their geometries and a short description.

Table 1. List of layers that populate the GPKG named DGSD_FVG_dataset.

Layer	Geometry	Description
dgds_areas	polygon	DGSD location and associated attributes
dgds_points	point	punctual gravity-induced landforms
dgds_lines	line	linear gravity-induced landforms
dgds_polygons	polygon	polygonal gravity-induced landforms

The dgds_areas layer contains one polygon for each mapped DGSD together with a standardized attribute table organized into seven thematic groups. Table 2 lists the groups and attributes.

Table 2. List of groups and attributes of dgds_areas layer.

Thematic Group	Attribute	Type
Identification	Id	String
	name	String
	municipality	String
Geometry	size (km ²)	Real
	size class	String
	size descriptor	String
	length (m)	Integer
	width (m)	Integer
	width/length	Real
Morphometry	minimum elevation (m a.s.l.)	Integer
	maximum elevation (m a.s.l.)	Integer
	elevation difference (m)	Integer
	mean slope (°)	Integer
	slope aspect	String
	affected slope height (m)	Integer
Geology	predominant lithology	String
	outcropping lithologies	String
	bedding vs. slope	String
	fault crossing	Boolean
	main structural trend	String
	geomorphological context	String
Auxiliary Data	EGMS points	Integer
	EGMS density (points/km ²)	Real
	mean annual precipitation (mm/year)	Integer
Metadata	source	String
	method of investigation	String
	mapping confidence	String

Table 2. *Cont.*

Thematic Group	Attribute	Type
Gravity-induced Landforms	ridge top depressions	Boolean
	gravity-induced grabens	Boolean
	trenches	Boolean
	uphill-facing scarps	Boolean
	collateral landslide scars	Boolean
	collateral landslide deposits	Boolean
	toe bulge	Boolean
	toe bulge fractures	Boolean
	unloading valleys	Boolean
	sinkholes	Boolean

These attributes capture the geometric, morphometric, geological, and remote sensing characteristics of DGSDs, along with metadata. Attributes named size class and size descriptor follow the landslide classification of McColl and Cook [24]. The classification assigns landslides to discrete size classes based on their mapped area (or volume, where available). All mapped DGSDs belong to Classes 6 and 7, corresponding to landslide areas ranging from 0.5 to 10 km², and are classified as large landslides. The Auxiliary Data group reports the number and density of interferometric synthetic aperture radar (InSAR) measurement points provided from the EGMS within each DGSD, as well as the mean annual precipitation. The Metadata group documents the original source for each DGSD, together with the investigation method and the consequent mapping confidence. The Gravity-induced Landform group uses Boolean presence or absence fields to identify different gravity-induced landforms within each phenomenon.

The three layers describing gravity-induced landforms each contain a type attribute identifying the following gravity-induced landforms: (i) ridge top depressions, (ii) gravity-induced grabens, (iii) trenches, (iv) uphill-facing scarps, (v) collateral landslide scars and deposits, (vi) toe bulges and associated fractures, (vii) unloading valleys, and (viii) sinkholes. Whenever applicable, additional geometric attributes are provided.

To facilitate comparisons with other inventories, Appendix A provides a brief statistical summary of the main characteristics of the dataset.

3. Methods

The dataset was produced by systematically interpreting publicly available HR LiDAR-derived DEMs (0.5 and 1 m), orthophotos (0.1 and 0.2 m), multi-temporal Google Earth imagery, EGMS InSAR measurements, and existing landslide inventory. The study area was subdivided into a regular grid of approximately 3 × 3 km to ensure homogeneous spatial coverage and reduce interpretation bias when identifying DGSDs and their associated gravity-induced landforms.

DGSDs were detected based on their mountain-scale size, the presence of diagnostic assemblages of gravity-induced landforms and collateral landslides (Figure 3), and their spatial association within the instability zone, following the approach adopted by previous authors [15,21]. Additional diagnostic criteria included poorly defined lateral and basal boundaries, structural control, and increased displacement and morphological expression relative to equivalent structures outside the instability zone. The gravity-induced landforms and landslide deposits were distinguished and classified according to their characteristic morphology, geometry, spatial relationships, and topographic expression. The boundaries of each DGSD were digitized in a GIS environment, and a comprehensive set of attributes (Table 2) was subsequently compiled.

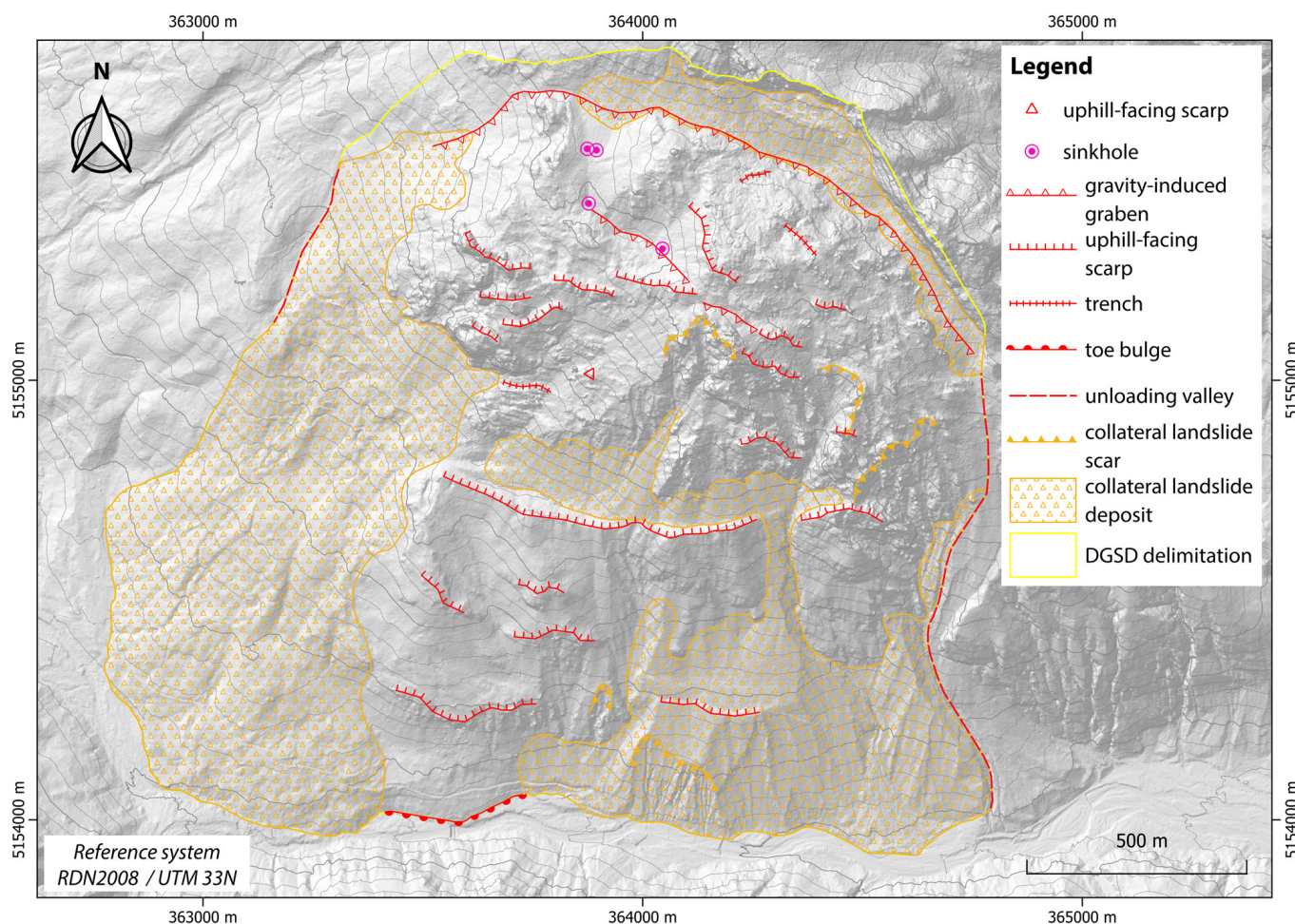


Figure 3. Map of Treghet DGSD and its landforms.

Four DGSDs were therefore validated through UAV-assisted field surveys. The UAV imagery was processed using the structure-from-motion/multi-view stereo workflow [25,26] to produce centimeter-scale DEMs, orthomosaics, and 3D models. These UAV-digital photogrammetry products assisted detailed geomorphological mapping and verification of the gravity-induced landforms.

The dataset was subjected to quality control through repeated visual inspection of mapped geometries and cross-validation among the different remote sensing datasets. Although using HR topographic data considerably improves the recognition of DGSDs, the interpretation of geomorphological boundaries and landforms retains an unavoidable degree of subjectivity, particularly where landforms are partially masked by erosion-depositional processes or collateral landslides. Consequently, the database should be regarded as an expert-based geomorphological interpretation of the current state of knowledge.

The database is intended for ongoing updates as new DGSDs are identified or as further field investigations are conducted. Its spatial distribution and standardized attributes provide a basis for regional landslide susceptibility analyses and can contribute to landslide hazard and risk assessment, with its potential increasing as the database is further expanded.

Author Contributions: Conceptualization, C.L., C.C., S.D., and L.Z.; methodology, C.L.; software, C.L.; validation, C.L., C.C., and S.D.; formal analysis, C.L.; investigation, C.L.; resources, L.Z.; data curation, C.L.; writing—original draft preparation, C.L.; writing—review and editing, S.D., C.C., and L.Z.; visualization, C.L. and S.D.; supervision, C.C., S.D., and L.Z.; project administration L.Z.; funding acquisition, L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Regione Autonoma Friuli Venezia Giulia, grant number J95F21002770002, J92C21002560002, and J97G25000300002. Scientific coordinator: Prof. Luca Zini.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are openly available in [FigShare] at [<https://doi.org/10.6084/m9.figshare.33112016>].

Acknowledgments: During the preparation of this manuscript, the authors used Chat GPT 5.5 for the purposes of language revision. The authors have reviewed and edited the output and take full responsibility for the content of this publication. All scientific contents are entirely the authors' original work.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DGSD	Deep-seated Gravitational Slope Deformation
EGMS	European Ground Motion Service
UAV	Uncrewed Aerial Vehicle
FVG	Friuli Venezia Giulia
HR	High Resolution
DEM	Digital Elevation Model
GPKG	GeoPackage
GIS	Geographic Information System
InSAR	Interferometric Synthetic Aperture Radar
OGC	Open Geospatial Consortium

Appendix A

Figure A1 summarizes the main characteristics of the mapped DGSDs and the associated gravity-induced landforms. Most DGSDs belong to landslide size class 7 (76%), whereas the remaining features are classified as size class 6 (24%). Siliciclastic successions represent the dominant lithological setting (48%), followed by mixed carbonate–siliciclastic (33%) and carbonate successions (19%). More than half of the mapped DGSDs occur along major glacial valleys (52%), while tributary valleys and tributary glacial valleys account for 29% and 19%, respectively. Uphill-facing scarps and trenches are the most frequently mapped gravity-induced landforms, and the prevailing slope aspects and fault strike directions are predominantly south-facing and east–west oriented, respectively.

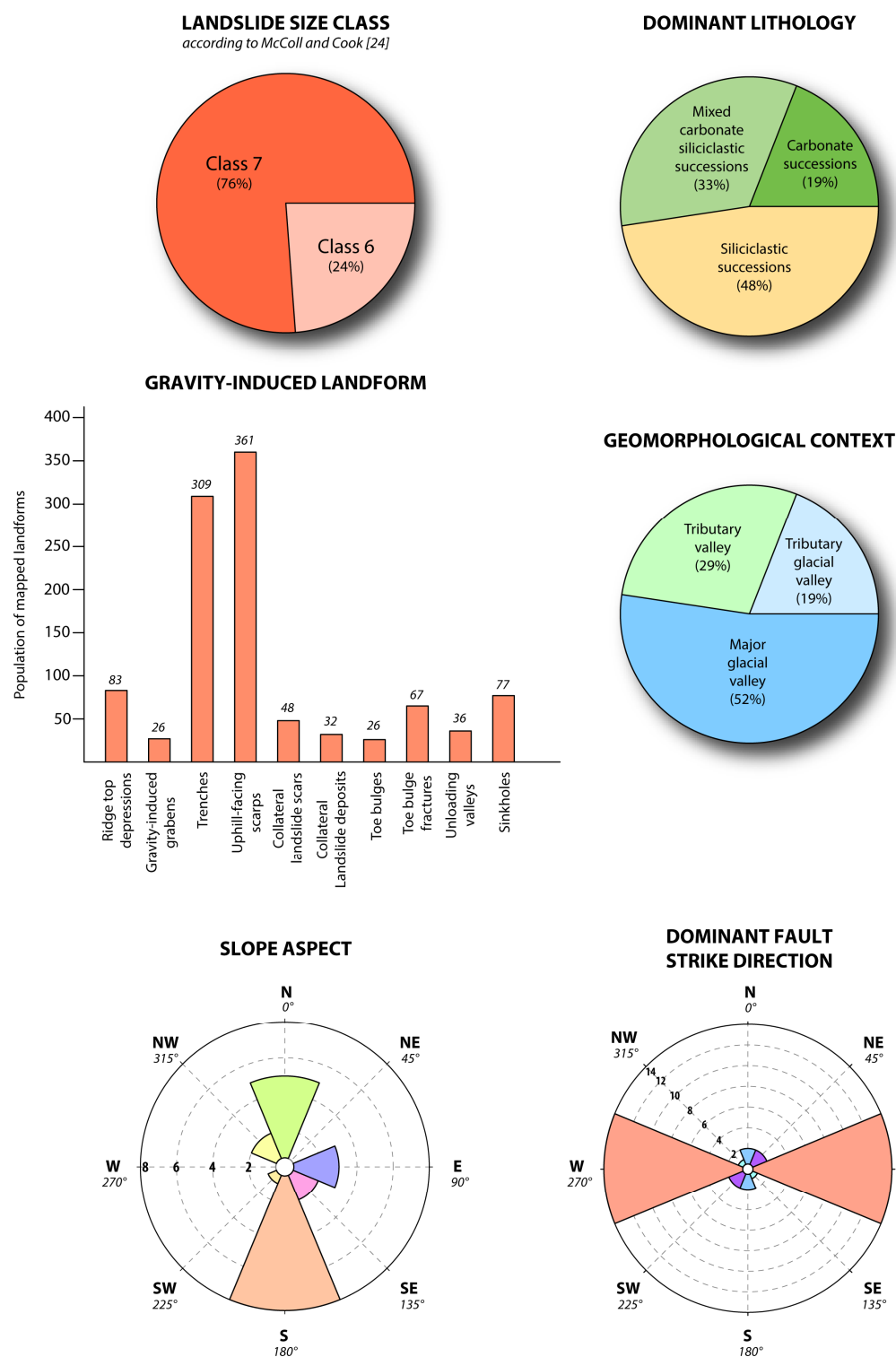


Figure A1. Main characteristics of the mapped DGSDs and the slopes affected by them.

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