Deep-Seated Gravitational Slope Deformations

→ giant, non-catastrophic, long-lasting landslides
→ relatively low displacement rates (→ tens mm/a) - large cumulative displacements
→ involve entire high-relief alpine slopes (toe to ridge)

→ morpho-structural evidence (middle-upper sectors)
→ toe bulging / enhanced rock fracturing (middle-lower sectors)
→ secondary, often catastrophic landslides (middle-lower sectors)
Types of DSGSD

Sackung  (Zischinsky, 1966; Sagging, Hutchinson, 1988; Rock flow, Varnes, 1978)

→ morpho-structural evidence (upper slopes)
→ toe bulging («talzuschub»)
→ «creep» in rock mass or along structures
→ strain localization in a basal shear zone («gleitung»)

Lateral spread  (Varnes, 1978; Hutchinson, 1988)

→ Lateral movements: rigid slabs over ductile rocks (liquefaction, softening)
→ Type A: no strain localization
→ Type B: spread over a localized shear zone

Litho-stratigraphic control

Lithology and stratigraphy s.l.:

→ rock mass strength
→ sharp changes in “rheology” s.l.
→ geometry of weak layers
→ volume and degree of freedom of potentially unstable slopes

Typical situations:

Foliated metamorphics or thinly bedded sedimentary
→ sackung (Alps, Apennines)

Fractured granitoids
→ sackung (Alpi)

Thickly bedded sequence of rock with strong rheological contrasts
→ lateral spread (Apennines)
**Engineering significance**

→ progressive vs. regressive evolution  
→ possible, partial catastrophic evolution

![Dynamic stability diagram](attachment:image.png)  

Broadbent e Zavodni (1982)

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**Engineering significance (2)**

→ damage to engineering structures (surface and underground)  
→ rock mass strength degradation

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Gepatsch dam (Tirol)  
Zangerl et al., 2010

M. Piazzo tunnel (LC)  
(SS36 – FFSS Lecco-Colico)

Ambrosi e Crosta (2006)

Mt. Varadega (SO)
DSGSD occurrence: topographic settings

Long ridges

Concave or laterally-confined slopes
DSGSD occurrence: topographic settings

Slopes bounded by tributary valleys

Convex slopes
**DSGSD occurrence: topographic settings**

Slopes crossing multiple catchments

**Gravitational morpho-structures**

morphological expressions of gravitational structures

- local evidence of global DSGSD kinematics
- individuals vs. associations

Mt. Watles (Val Venosta)
**Gravitational vs. tectonic**

Morphological convergence (rock strength, maturity...)

- less persistent / more scattered
- swarms of multiple features, larger individual offsets
- less continuous across ridges / drainage
- usually limited to specific slope sectors
- associated / fading to catastrophic slope instability

\[ \text{Upper Valtellina} \]

**Morpho-structures: characterization**

- field mapping – **kinematic interpretation**
- trenching (stratigraphy, sedimentology, structural analysis, dating)

Alpine rock slope failures: mechanisms, controls, characterization  
F. Agliardi – Matrei, 19 June 2012
Structures induced by DSGSD

Chigira, 1992

- shear zones: asymmetric, fabric-dependent
- folds: flexural slip, intense fracturing in axial zones

Evidence of basal shear zones (Desio, 1962)

Evidence from deep site investigation data
Mechanisms

No unique mechanisms!

Wide range of:
- geo-settings
- morpho-settings
- geometry
- kinematics
- maturity/activity

Relationships with:
- stratigraphy
- structural patterns
- individual structures

Dramatic variability – LARGE DATASETS NEEDED !!!

Orogen-scale DSGSD inventory: Alps

904 individual DSGSD

Not rare phenomena!

“blind” GoogleEarth mapping, single expert
- mapped area: 103,000 km² (I, F, CH, A)
- DSGSD: 5472 km² (about 5%)
- individual areas: 0.2 → 108 km²
- different settings / units
DSGSD settings

**Spatial scales of DSGSD**

- Frequency density
- Power-law exponent (-b):
  - 904 **DSGSD**: 2.48
  - 791 **large landslides**: 2.49
  - Joint dataset: 2.49

→ smooth transition from mapped “large landslide” to DSGSD

→ definition depends on morpho-structural expression (“typical” DSGSD → A > 10 km²)

DSGSD: maximum involvement of geological structure
Geological structure and DSGSD

→ Rock type

→ Structural controls

local scale: fabric, fractures, master features

regional scale: major structures, nappe boundaries

(passen, active)

Rock-type control

Geological map 1:500,000

Homogeneous dataset over a large area: about 82,500 km², 725 DSGSD

→ high DSGSD density: metapelites (13%), orthogneisses (6.5%), flysch s.l. (4%)

→ carbonates and granitoids poorly affected

anisotropic, moderately strong rocks sustain high relief without failing catastrophically
**Slope-scale structural controls: steep fractures**

**Cima di Mandriole** (Trentino, Italian Central Alps)  
(Agliardi et al., 2012; in press)

Persistent steep fractures:
- **kinematic freedom**
- **occurrence and geometry of morpho-structures**
- **“barrier” effects**

**Slope-scale structural controls: low-angle faults**

**Mt. Watles** (Val Venosta, Italian Central-Eastern Alps)  
(Agliardi et al., 2009)

Regional, low-angle fault (**Schlinig Fault**)
- **Nappe boundaries, thrusts:**
  - stratigraphy, fault rocks
  - shear strain localisation
**Slope-scale structural controls: folds**

**Passo Vallaccia** (Vizze Valley, Eastern Alps)

(Massironi et al., 2010)

Folded multi-layer:
- stress-strain distributions
- rock mass strength degradation
- detachment layers

In-situ stress: topographic + tectonic + stress anisotropy
- extent / distribution of plastic strain (Savage & Varnes, 1987)
- topographic stress amplification (Miller & Dunne, 1996)

**Role of in situ stress**

\[ K = \frac{\sigma_H}{\sigma_V} \]

Brown and Hoek (1978)
McGarr and Gay (1978)

- K = 0.3 (pure gravity, extensional regime)
- K = 1.0 (compression, strike-slip)
- K = 2.0 (compression)

Ambrosi and Crosta (2011)
**Role of active tectonics**

In areas of moderate magnitude seismicity (e.g. Apennines)

→ seismic ground shaking (Radbruch-Hall, 1978; Dramis, 1983; Sorriso-Valvo, 1988)

→ co-seismic deformation observed by satellite Radar interferometry (DInSAR) for earthquakes with $M > 6$ (e.g. Umbria 1997; L’Aquila, 2009)

→ mainly re-activation of existing DSGSD

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In areas with low magnitude seismicity (e.g. Alps)

→ seismic ground shaking effects: difficult to demonstrate in alpine areas ($M < 5.5$; rare permanent ground deformations, rare sediments recording co-seismic effects, e.g. liquefaction; Keefer, 1996)

→ **Central Alps**: mechanical consistency between the kinematics of faults re-activated by DSGSD, EQ moment tensor solutions, and regional stress regime)

DSGSD clustered in areas with inferred active faults

Possible mechanisms:

→ contribution to in-situ stress
→ rock damage and rock mass strength degradation
Role of active tectonics (3)

Recent and present-day uplift

Area ~ 20.600 km² - 354 DGPV (1967 km²)
Rock uplift dataset: NRP20 (Kähle et al., 1997) - Swiss Alps and surroundings

- DSGSD: 71% in areas with recent uplift > 1 mm/yr
- Minimum local relief in DSGSD areas ~ 1000 m (often >1500-2000 m)
- Tectonically active areas: local relief large enough to induce stress concentrations large enough to activate DSGSD in moderately strong rock masses

Role of glaciation / deglaciation

- Glaciation: valley deepening / widening, steepening, valley cross-profile
- Deglaciation: debuttressing, tensile damage, joint opening, groundwater regime

Tensile damage: Finite Element modelling

Evoluzione del profilo

Harbor, 1995

DGPV triggering: Finite Difference model

Agliardi et al (2011)

Agliardi et al (2012)
Role of groundwater changes (2)

Changes in reservoir water level
→ reservoir filling stages
→ seasonal low-stand levels: rapid drawdown, seepage

Example: Hochmais-Atemkopf (A)
→ DSGSD partial re-activation in the initial reservoir filling stage
→ later: highest displacement rates (surface monitoring) correlate with seasonal reservoir level minima

Regional scale: Upper Valtellina

Campo-Ortler nappe (Austroalpine)
→ Ortler sedimentary rocks (limestones, dolomites)
----- Zebrù Line -----
→ Campo metamorphics (metapelite, gneiss, gabbro, metabasites, marble)

→ complex tectono-metamorphic evolution
→ isoclinally-folded, transposed foliation + alpine overprint (D3)
→ major tectonic features: Zebrù Line, overthrusts
→ recent regional fracturing – complex fault associations
**Active tectonics**

- Seismic record (ECOS)
- MT solutions (ETHZ, Harvard CMT)
- Uplift data (Kahle et al., 1997)
- Permanent GPS (Tesauro et al., 2005)

→ active tectonic processes

- Shallow earthquakes (< 15 km)
- Maximum recorded Mw: 4.9 (1999, N of Bormio)
- Uplift rate up to 1.4 mm/yr
- High topographic relief (> 1500-2000 m)
- N-S compression regime

**Recent faults in the Central Alps**

(Agliardi et al., 2009)

- Striated fault planes at 43 location in Central Alps
- Slickenside geometry and relative chronology
- Stress inversion by iterative and direct methods (Angelier, 1984, 1990)

1) NW-SE compression: E-W dx + N-S / NNE-SSW sx
strike-slip faults + reverse NE-SW

2) N-S compression: NNW-SSE dx + NNE-SSW sx
strike-slip faults + N-S dip-slip

→ Stage 2 consistent with present day seismicity
**Lineament mapping**

Aerial photos + fieldwork

Criteria:
- morpho-structural evidence
- relationships with topography
- relationships with drainage

**Tectonic lineaments** (3574)
- faults, master joints

**Gravitational features** (697)
- scarps, counterscarps, trenches

**Tectonic vs. gravitational morpho-structures**

Statistical analysis of lineament trend frequency (absolute + length-weighted)

**Tectonic lineaments**:
- 2 main sets: NW-SE, NE-SW
- consistent with recent faults and present-day regional stress

**DSGSD features**:
- clearly re-activate tectonic features
- NW-SE dominant
- larger dispersion

→ control by recent tectonic features on gravitational morpho-structures
→ topographic control
DSGSD: large-scale mapping

Gravitational morpho-structures → associated to DSGSD or large landslides

28 DSGSD areas:
- Valfurva → NW-SE trend
- Valtellina → N-S trend
- Val Viola → NE-SW

Over 30 large landslides:
- locally active (e.g. Ruinon)
- frequently inside DSGSD
- higher degree of evolution
  (clear boundaries, developed shear surfaces, etc.)

→ DSGSD along major recent structures (large scale structural control)
→ DSGSD control on rock slide/avalanche phenomena

The Bosco del Conte DSGSD

Main features:
- metapelites (Bormio phyllite)
- close to a regional overthrust
- poorly-defined boundaries
- NE-SW morpho-structures

→ lithological and structural controls

- displaced glacial erosion features → post-LGM activation
- SAR evidences → present-day activity
DSGSD vs. glacial history

- LGM surface elevation > 2500m a.s.l.
- deeply incised glacial valleys

numerical models
- DSGSD triggering by deglaciation

Possible mechanisms of glacial actions:
- post-glacial rebound
- valley erosion / slope debuttressing

2D continuum modelling of the Bosco del Conte area (FLAC)