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## Deep-seated gravitational slope deformation involving glacial evidence in the Rodoretto Valley (NW Alps)

M. Gabriella Forno <sup>a</sup>, Marco Gattiglio <sup>a</sup>, Stefano Ghignone <sup>a</sup> and Glenda Taddia <sup>b</sup>

<sup>a</sup>Dipartimento di Scienze della Terra, Università degli Studi di Torino, Torino, Italy; <sup>b</sup>Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture, Politecnico di Torino, Torino, Italy

### ABSTRACT

The Rodoretto Valley (about 25 km<sup>2</sup>) (Western Alps, NW Italy) shaped in the metamorphic bedrock, covered by Quaternary sediments, is involved in significant deep-seated gravitational slope deformation (DSGSD). A detailed field survey revealed several morpho-structures typically related to DSGSD phenomena (open fractures, doubled ridges, scarps, trenches, counterscarps and bulging reliefs) and other significant gravitational morphologies, here defined as gravitational valleys, not previously reported in geological literature. Fieldwork also allowed us to distinguish various types of glacial sediments, reconstructing the supply basins, relatively dating glacialism to LGM and Late Glacial-Holocene and evaluating their gravitational dislocation. The wide extension of the area characterized by DSGSD and incredibly big dimension of single morpho-structures are the most important recognized features. In particular, we observed that entire sectors of the study area were gravitationally conditioned not only by local slid along the Rodoretto slopes but also by movement towards the nearby and deeper Germanasca Valley.

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Deep seated gravitational slope deformation; glacial shaping; Quaternary; Alpine geomorphology; Germanasca Valley

### 1. Introduction

The study area comprises the entire Rodoretto Valley, which is a left lateral tributary of the Germanasca Valley, located in the Western Alps (NW Italy) between 1200 and 2900 m a.s.l. The upper valley is mainly N–S oriented, while the middle and lower valley is N70° oriented. The whole valley is shaped in the alpine metamorphic bedrock covered by Quaternary deposits, as already partly reported by Italian official geological map (Mattiolo et al., 1913). Some information on the presence of DSGSD morpho-structures in the study area are already known, essentially developed along fracture systems (Forno et al., 2012; Forno, Lingua, et al., 2013a), and also studied by innovative tools for the acquisition of field data (Forno et al., 2011; Piras et al., 2017; Taddia et al., 2015). The features of the Rodoretto DSGSD partly show common elements with other gravitational deformations recognized in the Western Alps, wherein metamorphic rocks are deeply involved in such deformation. Gravitational morpho-structures also emerged in the fieldwork, not yet recognized as related to DSGSD.

The aim of this work is to (i) update fieldwork data finalized to a detailed geomorphological mapping of the entire Rodoretto Valley, (ii) reconstruct the gravitational evolution during the Quaternary, also through the involving and dislocation of glacial elements.

This map is part of a larger project that aims to study meaningful sectors of the Western Alps characterized by DSGSDs, as an expression of neo-tectonic movement related to the Quaternary gravitative collapse of the Western Alps.

### 2. Methods

The geological and geomorphological data were collected during detailed geological surveys (at the 1:5000 scale), aiming to reconstruct the Quaternary succession and the gravitational evolution. The bedrock lithologies (not represented in this map) were also used to recognize the supply area of the glacial deposits. The collected geomorphological data were stored in a GIS database and represented on a topographic map compiled from the Carta Tecnica Regionale Vettoriale of the Regione Piemonte (vector\_10 series, Edition 1991–2005). The poor quality of topographic map, in which the morphological surface is often inadequately represented, required a strong commitment to realize a good detailed geological map.

Field data were generalized at a 1:10,000 scale on the geomorphological map (Main Map), which covers an area of approximately 25 km<sup>2</sup>. Particular attention was paid to mapping and describing glacial sediments according to facies, relative age and source basin, and

**CONTACT** Stefano Ghignone s.ghignone@unito.it Dipartimento di Scienze della Terra, Università degli Studi di Torino, Via Valperga Caluso 35, 10125 Torino, Italy

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the partly unknown gravitational morpho-structures. Glacial features and gravitational morpho-structures were also represented in dedicated sketch maps (see Figure 1(a,b)). Cross-sections were drawn integrating the topographic map with field observation (inset A, in the Main Map).

### 3. Bedrock affected by DSGSD

The Rodoretto Valley is located in the axial sector of the Western Alps, where the bedrock is constituted by alpine metamorphic rocks belonging to the Piedmont Zone (PZ, Jurassic-Cretaceous) and the Dora Maira Unit (DM, Paleozoic-Triassic).

Along the Western Alpine belt, the ocean-related PZ is divided into Internal and External zones, based on lithostratigraphic features (Dal Piaz et al., 2003; Deville et al., 1992 and references therein) and metamorphic peak conditions (eclogite-facies and blueschist-facies conditions, respectively; Agard et al., 2001; Ghignone et al., 2021). The continent-related DM tectonically lies below the PZ and is characterized by eclogite-facies conditions (Cadoppi et al., 2016; Gasco et al., 2011). In the study area, the tectonic contact separating the two tectono-metamorphic units is represented by the southern continuation of the Susa Shear Zone located in the Susa Valley (Ghignone, Gattiglio, et al., 2020a; Ghignone, Balestro, et al., 2020b).

Our geological survey highlighted that the Rodoretto Valley is mainly developed in the External PZ (the Internal zone is not present in the study area), which consists of a thick calcschist succession with few interbedded meta-ophiolite bodies. The calcschist shows different compositions from carbonate-rich to pelite-rich terms, often alternating each other at cm- to m-sized scales. Meta-ophiolite, discontinuously outcropping at various structural levels, consists of metric to decametric *boudins* of prevailing metabasic rocks with minor serpentinite, iso-oriented according to the main foliation. These lithotypes locally present a preserved typical oceanic metasedimentary cover (basaltic metabreccia, quartzite and grey marble layers). The DM crops out only in the eastern sector of the Rodoretto Valley (at the confluence with the Germanasca Valley) and consists of a polymetamorphic basement (micaschist), covered by paragneiss and a thin Mesozoic carbonate metasedimentary succession, mainly constituted by dolomitic marble.

Fieldwork evidenced that the entire bedrock succession shows a pervasive metamorphic foliation that is constantly dipping towards the W-WSW with low to medium dip angles, which represents the axial plane of the most pervasive folds. The tectonic contact between the PZ and DM is defined by hundreds-metres-thick shear zone, characterized by mylonitic foliation resulted from reworked calcschist and micaschist belonging to the two juxtaposed tectono-

metamorphic units. Various-sized bodies of quartzite, dolomitic marble, gneiss, micaschist, metagabbro and other metabasic rocks are wrapped by mylonites.

Our investigations highlighted also three main tectonic fracture systems with N-S, N50°, N140° strikes, and minor E-W oriented elements, responsible for the bad geomechanical conditions of the bedrock and the complex morphological setting of the entire Rodoretto Valley.

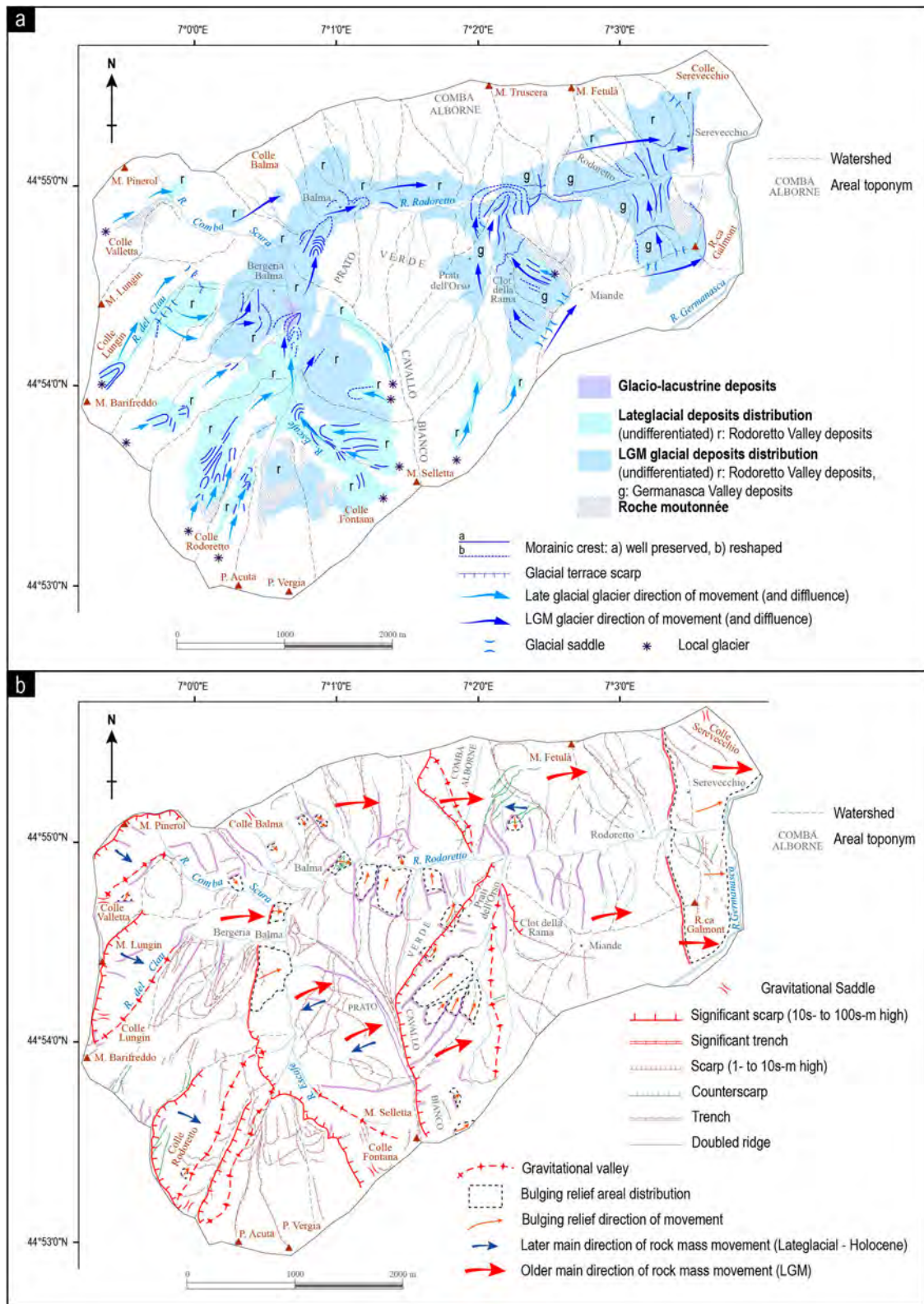
### 4. The Quaternary sediments and landforms involved in gravitational movements

The geological survey of the Rodoretto Valley showed that some relatively continuous covers of subglacial sediments are preserved in wide sectors forming grassy slopes with typical uniform inclinations and wide glacial terraces (Figure 2(a-c)). These sediments consist of centimetric to decimetric angular and sub-angular clasts, with few subrounded boulders, mixed in a subordinate (10–20%) overconsolidated sandy-silty matrix, grey in colour (Figure 2(d,f)). The clasts show a preferential orientation (30–35° dip) subparallel to the slope of the glacial valley (Figure 2(d)). Subglacial sediments, which are usually fine-grained and formed by rounded elements, in such sectors appear as coarse-grained sediments, with angular fragments as a result of the strongly fractured rocks in the DSGSD context (Figure 2(e)) (Forno et al., 2020).

The high and middle Rodoretto Valley (upstream of Coste) and its tributaries show sediments essentially belonging to the PZ (calcschist fragments, with rare metabasic rocks). The monotonous petrographic composition of the clasts is consistent with the exclusive supply from the Rodoretto Glacier (entirely emplaced in the PZ).

Conversely, subglacial sediments outcropping in the low Rodoretto Valley (downstream of Coste), in the Clot della Rama Valley and in the wide Serrevecchio, Bonous and Rocca Galmont glacial terraces are constituted by rocks belonging to the DM (gneiss, quartz-micaschist and dolomitic marble) besides those coming from the PZ (calcschist fragments, boulder of metagabbro, other metabasic rocks, with rare serpentinite, chlorite schist and eclogite). Such mixed composition of the clasts suggests a contribution by the Germanasca Glacier (Figure 2(f)). This various composition testifies that diffuence phenomena from the Germanasca Glacier occurred into the Rodoretto Glacier. The distribution of sediments connected to these diffuences in the Rodoretto Valley floor suggests that the Germanasca glacial lobe subsequently survived to the partial retreat of the Rodoretto Glacier.

Ice-marginal sediments are present in the entire valley bottom, forming moraines with various degrees of preservation (Figure 3(a-c)). These sediments



**Figure 1.** (a) Schematic map regarding the glacial sediments and landforms in the Rodoretto Valley. (b) Distribution of gravitational morpho-structures in the Rodoretto Valley with evidenced the main movement directions of rock masses. The main glacial evidence consisting of glacial sediments, glacial terraces, moraines, glacial saddles and diffuence phenomena was mapped in a special sketch map (a). The most significant gravitational morpho-structures were also mapped in another special sketch map (b).

consist of decimetric to metric subangular clasts (Figure 3(e)), with few subrounded boulders (Figure 3(d)), mixed in a subordinate, normally consolidated, sandy-silty matrix that is slightly carbonate cemented (Forno et al., 2020). The clasts show a preferential

arrangement according to the external flanks of the moraines (Figure 3(e)). The wider frontal moraines (which are hundreds of metres long, tens of metres high and curved) are preserved between Rodoretto and Balma (Figure 3(a)) and are composed of



**Figure 2.** (a) Regular slope forming the LGM glacial mountainside (gm) (NE of Balma). (b,c) Serrevecchio and SW slope of the Escafe Valley glacial terraces (gt) corresponding to relicts of the LGM glacial valley floor. (d,e) Subglacial sediments outcropping NE of Balma, characterized by a coarse-grained texture, scarcity of matrix and subangular clasts with arrangement according to the glacial slope. (f) Subangular to subrounded boulders and cobbles and coarse-grained matrix forming the subglacial sediments in the Serrevecchio terrace. The glacial shaping of the Rodoretto Valley left grassy slightly inclined slopes (a–c) and grey sediments (d–f), formed by subangular to subrounded clasts and poor matrix.

calcschist, metagabbro and other metabasic rocks (essentially ‘*prasinite*’ *Auct.*), gneiss, quartz-micaschist clasts, with rare serpentinite and dolomitic marble. This various composition of the sediments, the large dimensions of moraines (which are particularly wide around Arnaud where a large frontal moraine system developed) and their location in the lower Rodoretto Valley, suggest the occurrence of other diffuence phenomena of the Germanasca Glacier. In this case, the diffuences occurred along the watershed with the Rodoretto Valley, through the Clot della Rama glacial saddles (see Figures 7(d) and 8(a)). Several small concentric frontals (Figure 3(c)) and lateral moraines (which are tens of metres long and metres high) (Figure 3(b)), essentially formed by calcschist clasts, are also preserved in the upper and middle Rodoretto Valley and its tributaries. This monotonous composition, in addition to small

dimensions and locations in the upper Rodoretto Valley and its tributaries, indicates an exclusive contribution by the local glaciers.

The relative chronology of glacial sediments is instead indicated by the extension and the relationships between the different sedimentary bodies. We reconstructed that the relatively continuous subglacial cover in the lower valley and in the wide terraces of the upper valley, as well as the ice-marginal bodies forming the large moraines between Rodoretto and Balma and at the outlet of the Clot della Rama Valley were fed by the larger glaciers that developed during the Last Glacial Maximum (LGM). The reshaping of several of these moraines, now discontinuously preserved, is in agreement with this reading. Conversely, we infer that the subglacial cover is located in the upper and middle valley and ice-marginal sediments



**Figure 3.** (a) LGM frontal moraine south of Rodoretto, with a metabasite boulder on the summit. (b) LGM lateral moraine (m) northeast of Bergeria Balma, bordered by a glacial spillway (gs). (c) Holocene reshaped frontal moraine at the outlet of the Escafe Valley, evidenced by a curved arrangement of large calcschist boulders (dashed line). Ice-marginal sediments formed by (d) large from subangular to subrounded boulders (SW of C. Saras) and (e) decimetric subangular clasts showing preferential arrangement (SE of Bergeria Balma). (f) Landslide sediments forming a wide fan south of M. Pinerol. The Rodoretto glacial tongue, full of debris, also left an asymmetrical elongated ridge, several metres high, read as a moraine (a–c), constituted by subangular clasts (d,e). A wide landslide fan (f) was formed subsequently the glacial shaping, supplied by the high slope.

forming the small-sized moraines at the head of the main valley and its tributaries, which are everywhere well preserved, were instead deposited by the small local glaciers that occurred during the Late Glacial-Holocene.

Both subglacial and ice-marginal sedimentary bodies are displaced by gravitational structures, such as scarps, trenches and bulging reliefs (see chapter 5), losing their primary continuity (inset A in the Main Map).

Landslide accumulations are common in the investigated area, extensively covering the head of the Rodoretto Valley, the floor of Clot della Rama Valley and the right slope of the middle Rodoretto Valley (Figure 3(f)). The massive landslide sediments consist of centimetric to metric angular clasts, mainly constituted by calcschist, mixed in

abundant, slightly consolidated, silty-sandy matrix. These sediments consist of subangular and subrounded glacial clasts. The detachment niches locally correspond to gravitational scarps. Landslide accumulations are subsequent to glacial shaping and are essentially Holocene in age.

Avalanche sediments are exiguous in the Rodoretto Valley floor, essentially forming avalanche fans at the outlet of the lateral valleys (see a in Figure 5(e)). These sediments are constituted by centimetric to decimetric angular tabular rock clasts, mixed in a poor unsorted matrix. Torrential sediments form a wide strip in the Germanasca Valley and instead of a thin strip in the Rodoretto Valley floor. They consist of stratified centimetric to decimetric gravel, rounded to subrounded in shape, with a monotonous composition in the Rodoretto Valley (essentially calcschist) and with a



**Figure 4.** (a) Strongly fractured rocks N of Balma (f). (b) N140 directed open fracture on the SW slope of Escafe Valley. (c) Doubled ridges on the Cavallo Bianco western slope, evidenced by two elongated depressions (arrows) partly filled by subglacial sediments. (d) Significant scarp (s) that displaces the wide glacial terrace (gt) along the SW slope of Escafe Valley also characterized by strongly fractured rocks (f). (e,f) N-S scarps displacing the northern slope (s) and watershed (arrows) of Rodoretto Valley. The Rodoretto gravitational evolution created very fractured rocks (a) and morpho-structures on the slope as an open fracture (b), doubled ridges (c) and high scarps that displaced the mountainside (d,e) and watershed (f).

mixed composition in the Germanasca Valley. These sediments are deposited subsequent to the glacial shaping, during the Holocene.

Roche moutonnée locally occurs in the entire area, particularly at the head of the Rodoretto Valley and in the Clot della Rama Valley, indicating significant glacial erosion during the LGM. The trends of associated striae suggest the local glacier directions (Figure 1(a)).

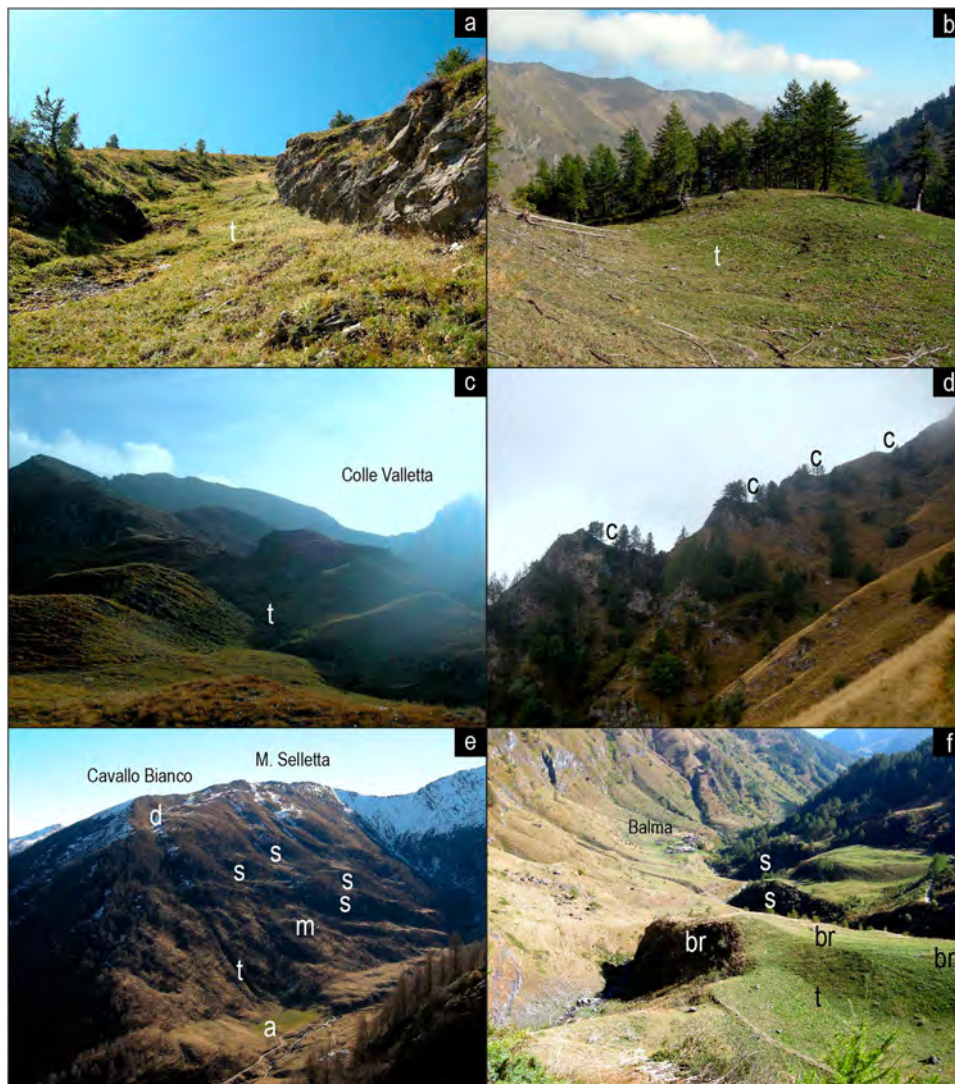
### 5. Gravitational morpho-structures

Fieldwork revealed the occurrence of several morpho-structures typically connected to DSGSDs in the entire Rodoretto Valley, essentially evolved along the three reported tectonic fracture systems (N-S, N50° and N140°) (Figure 1(b)). These fracture systems have highly variable spacing, from centimetric to

decametric, which defines rock masses with different degrees of fracturing. In detail, the intersection among such fracture systems with small spacing gives rise to sectors characterized by strongly fractured bedrock (f in Figure 4(a)). Here, centimetric portions of rock appear isolated from each other and consequently the rock mass loses cohesiveness, suffering severe erosion. These areas lack evident rock outcrops and are covered by thin colluvial sediments that simulate the presence of landslide accumulations, as visible W of the Comba Alborne (f in Figure 4(a)) and along the Colle Fontana (see f in Figure 8(b)).

Remarkable several tens of metres long and some metres high open fractures (Figure 4(b)) occur in the entire study area and are particularly significant in the slope upper sectors where they give rise to a notched profile of the watershed, also dislocating the





**Figure 5.** (a) Longitudinal trench (t) mainly connected to distancing of fracture sides (the two rocky walls, S of Prati dell’Orso). (b) Party filled transversal trench (t) along the bulging relief west of Bergeria Balma. (c) Transversal trench (t) south of M. Pinerol. (d) Counterscarps (c) evidenced by gravitational saddles N of Rimas. (e) Cavallo Bianco doubled ridge (d) continuing in a longitudinal trench (t) which supplies a wide avalanche fan (a) and location of scarps (s) and a tilted moraine (m). (f) Scarps (s), displacing moraines, and trench (t) involving a bulging relief (br) in the Rodoretto Valley floor SW of Balma. An elongated depression developed along a gravitational trench (a–c), while saddles on the watershed evidenced several counterscarps (d). Rocky walls and an elongated depression instead underlined gravitational scarps and trenches (e,f).

glacial evidence (e.g. watershed N of Arnaud) (arrows in Figure 4(f)).

Kilometre-long *doubled ridges* are also locally observed along the Cavallo Bianco western slope, wherein the watershed decreases in elevation by a few tens of metres, also by promoting the development of local glaciers (arrows in Figure 4(c)).

Several *scarps* strongly characterize the morphology of the whole Rodoretto Valley. Few of these morphostructures reach a length of over 4 km and a height of hundreds of metres, here defined as significant scarps (s in Figure 4(d)). Other scarps that are several hundreds of metres long and metres high, form stepped slopes (s in Figure 4(e)) of alternating rocky walls (see s in Figure 6(a)) and slightly sloping sectors hosting subglacial deposits forming the slope of the glacial valley (see gm in Figure 6(a)). These sets of scarps,

which represent the main evidence of the Rodoretto DSGSDs, displace glacial sediments and landforms as e.g. on the Cavallo Bianco western slope (s in Figure 5(e)), with a displacement of about 70 m, SW of Balma (s in Figure 5(f), with a displacement of about 50 m) and on the lower sector of Clot della Rama Valley, with a displacement of about 10 m, promoting waterfalls along the watercourses. Therefore, subglacial bodies lose their continuity, simulating glacial terraces, providing information on scarp displacement (Figure 5(e)). Scarps usually also give rise to a complex hydrographic network, that is mainly composed by linear stretches parallel, perpendicular or variously oriented respect to the contour lines (see Figure 6(b, d)). Furthermore, originally inclined downstream moraines deformed by scarps (Cavallo Bianco western slope), now occur counter to slope tilted, providing an



**Figure 6.** (a) Scarps forming steps (s) along the N50° fracture system dislocating the glacial mountainside (gm) (M. Barifreddo eastern slope). (b) NE of M. Barifreddo segmented valley developed along the fracture systems oriented N50° (a) and E–W (b); a wide N140° trench (t) occurs near Colle Valletta. (c) Snow accumulation (preserved after summer) in the Comba Scura gravitational valley. (d) Segmented trend of R. del Clau along the N50° (a) and E–W (b) fracture systems. Several scarps displaced the slope of glacial valley (a) and watercourses developed along the gravitational open fractures (b,d), that also favour the snow accumulation (c).

uncommon evidence of DSGSD evolution (m in Figure 5(e)). Locally, upstream plunging steps associated with scarps, are evidence of *counterscarps*, giving rise to gravitational saddles along the watersheds (e.g. N of Arnaud) (c in Figure 5(d)).

*Trenches* are also significant DSGSD-related elements, common in the investigated area, particularly upstream of bulging reliefs (see chapter 6). Their dimensions vary, with lengths between few metres to several hundreds of metres and widths mainly of several metres. We recognized transversal and longitudinal trenches that develop parallel and perpendicular to the contour lines, respectively (Forno et al., 2012) (not distinguished from each other in the Main Map). Transversal trenches were recognized in the lower Rodoretto Valley floor (Figure 5(b,c)). These trenches occur as various-sized horizontal or slightly inclined elongated troughs, forming wide close depressions locally partly filled by glacial sediments (Balma and NW of Bergeria Balma) (t in Figure 5(b,c)). Glacial deposits filling close depressions allowed to establish the LGM age of these morpho-structures. Longitudinal trenches instead result in abrupt elongated depressions mainly developed according to the maximum slope, cutting the glacial evidence and deepened by watercourses or avalanches (Cavallo Bianco western slope) (t in Figure 5(a)). Some particularly evident longitudinal trenches (M. Barifreddo and M. Pinerol eastern

slopes) separate significant unstable rocky masses (t in Figure 6(b)).

Finally, *composite morpho-structures* are common in the upper sectors of several slopes (Comba Scura southern slope and Cavallo Bianco western slope). These morpho-structures usually show scarps with sub-horizontal trend in the upper stretch and very steep longitudinal trenches in the lower stretch, therefore exhibiting an overall curving trend (in plant) that progressively isolates lower sectors of slope from the main one.

## 6. Other DSGSD evidence

Detailed geological fieldwork in the study area allows us to observe other gravitational evidence, although not typical of all DSGSDs. The most common are several *bulging reliefs*, which are described in the toe sector of some DSGSDs (Agliardi et al., 2001). They consist of isolated rocky reliefs, perched with respect to the main slope. The bulging reliefs recognized in the area present a trench in their upper sector, wherein subglacial sediments are usually preserved, while a subvertical rocky scarp occurs in the prominent frontal edge (Figure 7). These structures are likely connected to opening movement and/or sliding along surfaces that dislocate the bedrock and Quaternary cover, characterized by straight or concave trends. The displacement of



**Figure 7.** Different scales of bulging reliefs (br) characterized by a prominent rocky ridge partly covered by subglacial sediments (a: Comba Scura, b: W of Rimas, c: Balma, d: Rocca Galmont and Serrevecchio). (a) a metabasite body (mb) is displaced by bulging relief (br). (b,c) The bulging reliefs also cut the continuous subglacial cover (sc). (d) Rocca Galmont and Miande glacial saddles connected to diffluence phenomena of the Germanasca Glacier are also reported (arrows). Rocky reliefs hanging on the grassy glacial slope consist of significant gravitational morpho-structures (a–d) known as bulging reliefs

bulging reliefs can be directly evaluable where the bedrock comprises different lithologies involved in gravitational movements (e.g. Comba Scura, metabasic rocks versus calcschist displaced of about 50 m) (mb in Figure 7(a)) or where this displacement breaks glacial landforms and sediments.

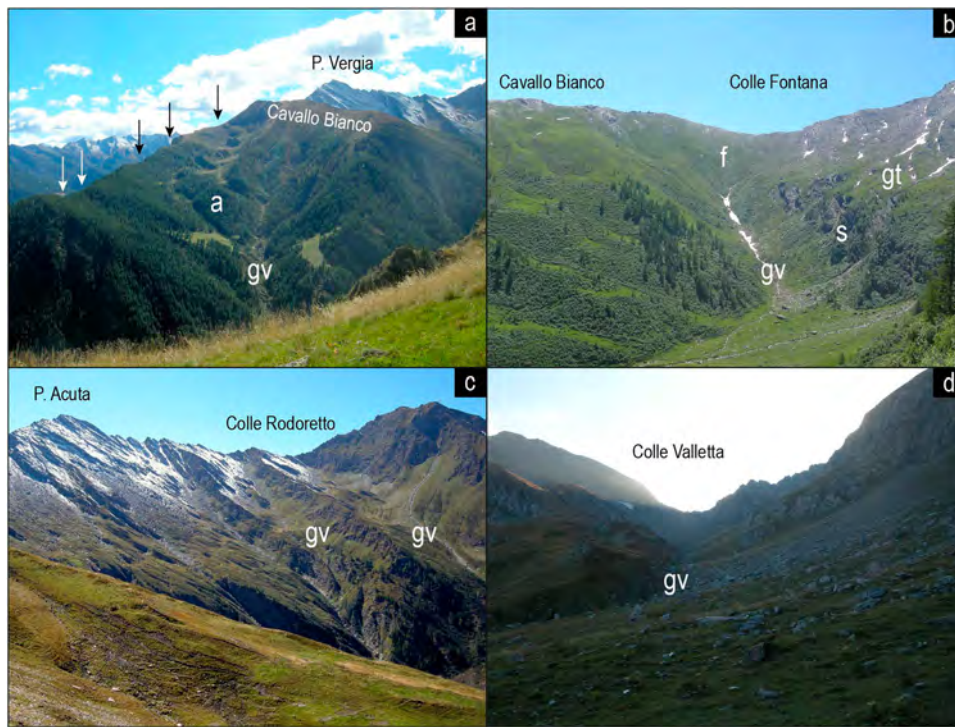
The more evident bulging relief occurs at Rocca Galmont and Serrevecchio (Figure 7(d)), where the Rodoretto-Germanasca watershed shifts eastward, progressively overrunning the deeper Germanasca Valley floor. Consequently, the narrowing of the valley promotes an abundant deposition of torrential sediments upstream. The evolution of this relief also favoured the shaping of two saddles along the watershed between the Rodoretto and Germanasca valleys and promoted the diffluence phenomena of the Germanasca Glacier.

Other remarkable bulging reliefs are also recognized in the Rodoretto Valley floor (Bergeria Balma and Balma) (Figure 7(c)), which promote strong erosion by the main river in the prominent frontal sectors (over-steepened watercourse in the Main Map). These prominent sectors interrupt the continuity of the subglacial cover, forming the slope of glacial valley, as visible in the relief of Rimas and Balma, confirming the DSGSD post-glacial evolution (sc in Figures 7(b,c)).

In addition, fieldwork shows the presence of asymmetrical valleys characterized by two flanks and

watersheds with very different elevations (Figure 8). The outcropping rocks are less fractured in the higher slope and are instead strongly fractured and loosened in the lower slope. Several landslide accumulations also occur on their valley floor (a in Figure 8(a)). We interpreted such peculiar valleys as not connected to glacial or fluvial shaping but rather formed by opening and lowering of one slope, with a consequent minor elevation of the slipped mountainside. The hydrographic network (Figure 8(c)) or glacier (Figure 8(d)) only subsequently deepened the valley floor. These valleys, here defined as *gravitational valleys*, therefore developed along a sliding surface, which corresponds to the higher slope, and are likely due to emphasized evolution of significant scarps (s in Figure 8(b)) with associated trenches.

A clear example of this evidence is the N–S Clot della Rama Valley (gv in Figure 8(a)), progressively formed by eastward sliding of the Miande slope (left in Figure 8(a)). This valley shows an eastern watershed (arrows) located approximately 400 m lower than the opposite one (Cavallo Bianco). We can suppose that the partly preserved Cavallo Bianco eastern slope, which shows a regular N–S trend and a constant dip, is the driving sliding surface and that the movement along this surface causes the opening of the valley. Moreover, the rocks appear strongly fractured and loosened in the eastern slope, and the valley floor is widely covered by landslide accumulations (a in



**Figure 8.** Various examples of asymmetrical gravitational valleys (gv) characterized by different elevations in the two watersheds (a: Clot della Rama, b: Escafe, c: Colle di Rodoretto and Punta Acuta, d: S of M. Pinerol). (a) Rocca Galmont and Miande saddles (white arrows) and Clot della Rama saddles (black arrows) connected to diffluence phenomena of the Germanasca Glacier and landslide accumulations in the valley floor (a) are also reported. (b) Strongly fractured rocks along the Colle Fontana (f) and significant scarp (s) that displaces the glacial terrace (gt) on the southwestern slope of the Escafe Valley are also evident. (c) Gravitational valley (gv) subsequently deepened by the hydrographic network. (d) Gravitational valley (gv) reused by glacier. A very asymmetrical valley was linked to the gravitational evolution of the slope (a–d) and defined as gravitational valley, that also favours diffluence phenomena (a).

Figure 8(a)) supplied by the very steep western slope. The diffluences of the Germanasca Glacier along the Clot della Rama glacial saddles (black arrows in Figure 8(a)) are also due to the development of this valley.

Similarly, the N140°-oriented asymmetric Escafe Valley (gv in Figure 8(b)) has a northeastern flank (Cavallo Bianco) that is approximately 200 m lower than the opposite flank. The southwestern slope of the Escafe Valley comprises a remarkable subvertical rocky wall, that is approximately 100 m high, corresponding to a significant scarp (s in Figures 4(d) and 8(b)) shaped in slightly fractured rocks. Conversely, its northeastern slope slightly decreases towards the WSW and shows very fractured and loosened rocks (f in Figure 8(b)). This gravitational valley was likely progressively formed by the sliding towards the NE of its lower northeastern slope (Cavallo Bianco) on the Colle Fontana significant scarp, promoting the distancing of the two slopes. This scarp (s in Figures 4(d) and 8(b)) displaced the LGM glacial valley floor (gt in Figures 4(d) and 8(b)) making it higher in elevation than to the current lowered valley bottom of about 100 m. We interpreted that the opening of the Escafe Valley allowed the subsequent sliding of the Cavallo Bianco western slope towards the SW (Figure 5(e)).

Depressions connected with DSGSD-related morpho-structures at different scales increase the local

accumulation of snow (Figure 6(c)) and promote the development of local glaciers, especially on north-facing slopes, which further deepen the depressions. High altitudes (2200–2700 m a.s.l.) associated with this evidence suggest that the formation of local glaciers occurred during Holocene when the main glaciers were already absent in the valley floor. The finest examples of this evolution occur along the Escafe and Colle Rodoretto valleys, wherein the development of local glaciers is suggested by several lateral moraines and small local concentric frontal moraines exclusively supplied by local lithotypes. Evidence of local glaciers development was also recognized in the Monte Pinerol SE slope, which is characterized by a wide glacial cirque, and on the Cavallo Bianco southwestern slope, where close gravitational depressions connected to doubled ridges and scarps hosted small glaciers, forming subglacial sediments and well-preserved moraines.

## 7. Discussion and conclusion

This research provides an update of the Rodoretto geomorphological mapping that makes available significant information on the general features of DSGSDs. Detailed geological fieldwork allowed us to mapping the distribution of gravitational elements

and Quaternary sediments of the Rodoretto Valley, which are essentially connected to DSGSD phenomena and glacial shaping. The activity of these phenomena is suggested by strongly fractured and loosened rocks and several DSGSD morpho-structures (open fractures, scarps and trenches associated with counter-scarps and doubled ridges), that are oriented N–S, N50°, N140° and locally E–W. Bulging reliefs are also common gravitational morpho-structures connected to gravitational sliding of slope sectors. In detail, DSGSD morpho-structures with different prevailing trends characterize the various sectors of the Rodoretto Valley. The upper valley shows prevailing scarps with N140° and N50° trend, while the middle and lower valley is essentially characterized by structures N–S and N50° oriented.

The gravitational morpho-structures can be easily identified in most cases due to their typical morphologies as steps of scarps or depressions along the transversal trenches. The gravitational nature of most morpho-structures is especially inferred by the association of many congruent elements, indicating a slope involved by sliding at various scales. The displacement is certainly proven when greenstone bodies (that form lenses within calcschist) are involved, where it is also possible to discern the amount of movement. The movement is also established by dislocations at different elevations of primary glacial terraces and their sediments as well as by tilting of moraines in counterslope. In addition to the well-known DSGSD-related features, other types of morpho-structures were recognized as related to gravitational phenomena. The most common are the gravitational valleys, which are elongated depressions mainly formed by gravitational sliding along significant scarps.

Moreover, some morpho-structures may be recognized with difficulty, as gravitational. For example, some longitudinal trenches can be at first interpreted as common torrential incisions; however, they are likely gravitational elements because no hydrographic basin is developed upstream.

The presence of gravitational morpho-structures evolved in different times and at different scales gives rise to a complex geological setting. The clearest gravitational morpho-structures are the significant scarps that involve the mountainsides of the Rodoretto Valley, which detach wide sectors that show prevalent sliding and translation movements towards the east. The distribution of these morpho-structures suggests a possible development of sliding surfaces that lie below the current Rodoretto Valley floor, likely correlated with the deeper Germanasca Valley floor.

The observed large-scale distribution of glacial sediments suggests that glacial shaping involved strongly fractured bedrock and a valley characterized by an irregular morphology, due to the reported

morpho-structures (Forno et al., 2016; Forno, Gattiglio, et al., 2013b). This morphology is typical of gravitational phenomena and usually promotes the formation and preservation of Quaternary sediments, as observed in other DSGSDs contexts (Comina et al., 2015; De Luca et al., 2019; Forno et al., 2016).

The most extended glacial sedimentary bodies and landforms were shaped by a significant glacier supplied by the upper Rodoretto Valley with the contribution of wide glacial lobes coming from the Germanasca Valley, which flowed through the Rocca Galmont, Miande and Clot della Rama glacial saddles. This reconstruction is proven by the petrographic compositions of clasts that are provided by lithotypes outcropping in the Germanasca Valley (metabasic rocks, micaschist, gneiss and dolomitic marble). We also collected evidence that the tributary valleys exposed to the north (partly involved in glacial diffluences) hosted glaciers that survived for a long time compared to glaciers in valleys exposed to the south and to glacier developed in the main valley. Several small lateral or frontal moraines observed in the upper valley also suggest that DSGSD-related depressions (due to trenches, scarps and asymmetrical valleys) favour the formation of local glaciers. Moreover, the coarse-grained texture of glacial sediments and poor rounding of clasts are due to strongly fractured rocks related to DSGSD (Forno et al., 2020).

Furthermore, several watercourses present a segmented trend that followed the orientation of gravitational morpho-structures as well as tectonic fractures. This trend suggests that the hydrographic network is strongly conditioned by DSGSD features. The studied springs in the upper valley prove that several gravitational depressions retain rainfall, which favours infiltration in the strongly fractured rock mass (Gizzi et al., 2020).

The relationship between DSGSD morpho-structures and glacial shaping allows us to conclude that the gravitational phenomena essentially occurred coeval to later respect to the Last Glacial Maximum. In detail, we infer that some morpho-structures were active during the LGM, and consequently were filled by glacial sediments, while other developed later displaced the LGM glacial sediments and landforms.

The reported data suggest that the DSGSD evolution of the investigated area is connected to the high-energy of the relief, even conditioning the significant shaping by glaciers and the great deepening by watercourses, as recognized in many alpine sectors. In addition, we propose that the critical geomechanical conditions of the bedrock are strictly related to the intersection of the three major tectonic discontinuity systems (N–S, N50° and N140° oriented). This observation suggests an inheritance of the described morpho-structures from regional tectonics. These three tectonic systems are also well recognized in

surrounding areas, where they condition the post-metamorphic evolution of the alpine mountain chain (Malusà et al., 2009). In detail, the N–S fracture system ubiquitously cuts the entire area and is referred to the regional Cenischia-Nizza System (as defined by Forno & Massazza, 1987). The N–S upper Rodoretto Valley is developed along the same fracture system.

Regional studies on post-metamorphic brittle deformations indicated that the Western alpine belt is characterized by N–S transtensive/normal faults that currently undergo general uplift with respect to the adjacent Po Plain, as confirmed by GPS data (Perrone et al., 2013). Post-metamorphic brittle evolution may be partly related to the gravitational collapse of the Western Alps, and DSGSDs are inevitably linked to this collapse.

The occurrence of various types and sizes of gravitational morpho-structures, with also peculiar uncommon landforms, suggests a great geodiversity of the Rodoretto Valley which may be subject to valorization through the establishment of a complex geosite.

## Software

The map was drawn using the software QGIS (v. 3.16.4) and Adobe Illustrator® 10.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## Data availability statement

The data that support the findings of this study are available from the corresponding author [SG], upon reasonable request.

## ORCID

M. Gabriella Forno  <http://orcid.org/0000-0003-4783-8524>

Marco Gattiglio  <http://orcid.org/0000-0002-1885-2872>

Stefano Ghignone  <http://orcid.org/0000-0002-1295-6291>

Glenda Taddia  <http://orcid.org/0000-0001-9766-3860>

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# DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATION INVOLVING GLACIAL EVIDENCE IN THE RODORETTO VALLEY (NW ALPS)

Gabriella Forno<sup>(1)</sup>, Marco Gattiglio<sup>(1)</sup>, Stefano Ghignone<sup>(1)\*</sup> & Glenda Taddia<sup>(2)</sup>

(1) Department of Earth Science, University of Torino, Via Valperga Caluso 35 - 10125 Torino, Italy. \*Corresponding Author: s.ghignone@unito.it  
 (2) Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24 - 10129 Torino, Italy

