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Structural and geomorphological framework of the upper Maira Valley (Western Alps, Italy): the case study of the Gollone Landslide

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ABSTRACT
An interdisciplinary study has been adopted to investigate the upper Maira Valley (Western Alps, Italy). A geological map of an unmapped area, of about 12 km^2, at scale 1:10.000, has been realized. The combination of field surveys, GIS database creation, aerial photo observation, local archival data consultation, geo-structural analysis and drillholes re-interpretation outlined a relationship between structures and landforms. A ductile and brittle deformation history with the definition of four discontinuity systems (F1-F4) has been detected. Where the fracturation is intense, rock-falls and topplings are triggered. In area associated with a homogeneous presence of weathered cover, debris flows were identified. The geo-structural pattern obtained from the surveys in the upper Maira Valley allowed characterizing detachment zones of the slope overlooking Acceglio town. The Gollone Landslide is an excellent case study to unravel the structural-morphological interaction and the kinematic evolution due to its framework.

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Structural survey; geological mapping; GIS; geomorphology; landslide hazard

1. Introduction

Gravitational processes are often conditioned by lithostratigraphy and morphostructural features, as recent studies deal with (Calista et al., 2019; Masetti et al., 2013). The identification of their interaction is helpful to figure out the landslide triggering reasons where, alongside weather conditions, it may be considered as one of the main predisposing factors. In Alpine context specifically, landforms and morphology are mostly controlled by lithology and structural setting (Bonnard et al., 2004; Fioraso et al., 2019; Morelli et al., 2003). In Piedmont Region (NW Italy), the main active landslides have been investigated on-site by SIFraP (Informative System of Piedmont Landslides; http://webgis.arpa.piemonte.it/geoportalserver_arpa/catalog/search/resource/details.page?uuid=ARLPA_TO:07.04.02-D_2011-03-24-11:43) and IFFI project (Inventory of Landslide Phenomena in Italy; https://www.isprambiente.gov.it/it/progetti/cartella-progetti-in-corso/suolo-e-territorio-1/iffi-inventario-dei-fenomeni-franosi-in-italia) available on Regione Piemonte (https://www.regione.piemonte.it/web/) and monitored by ARPA Piemonte (http://www.arpa.piemonte.it/). Nevertheless, an around-site structural model is often necessary. In this frame, the importance of different investigation approaches (GIS, geomechanical and geomorphological field survey, interpretation of aerial photos) stands out, as proposed by several previous works (e.g. Calista et al., 2016; Francioni et al., 2019; Lombardo et al., 2016). The collection of data in the upper Maira Valley has thus been based on the integration of geological, structural and geomorphological analysis (Bonasera et al., 2020), focusing then on the Gollone Landslide, one of the most active gravitational phenomena of the Cuneo province (Piedmont, NW Italy). Its moderately high activity and its location nearby Acceglio town make the investigation of its kinematic fundamental in terms of risk. In addition to Quaternary deposits and upper Maira Stream catchment morphological features, particular attention was paid to map the structural settings of the bedrock. This was crucial to highlight the strong relationship between the landslide features, brittle structures and rheological lithotype contrast.

2. Geological setting

The study area is located in the upper Maira Stream drainage basin, a right tributary of the Po River, running through the eastern Piedmont Region. Its source is in the Western Alps near the watershed marking the Italian-French state border. The landscape evolution was mainly led by glacial dynamics during Pleistocene, producing a U-shaped valley. The Holocene linear Maira Stream fluvial erosion creates a narrow valley with higher steepness slopes in which

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gravitational phenomena develop (Bonasera et al., 2020). The metamorphic bedrock includes both Upper Piedmont Zone (Schistes Lustrés; Deville et al., 1992; Lemoine, 2003) and Middle Pennidic Domain (Acceglio Unit; Figure 1) lithotypes. The Acceglio Unit (Schwartz et al., 2000) consists of a continental basement including meta-volcanoclastic rocks overlain by Mesozoic to Tertiary sedimentary cover with 'Ultra-briançonnais' affinities (Debelmas & Lemoine, 1957; Lefèvre, 1984; Lefèvre & Michard, 1976; Lemoine, 1957), characterized by an almost complete or complete erosion of the Triassic carbonates during Lias. The Ultrabriançonnais units are in contact with various units of the Schistes Lustrés, mainly with the ophiolite-bearing Piedmont-Ligurian units, but also with the Upper Piedmont Zone, including Upper Triassic dolomites and Liassic calcareous breccias and were formerly transitional between the Briançonnais and Piedmont-Ligurian domains (Lemoine, 1967; Lemoine et al., 1986; Michard, 1967). In the investigated area, the oceanic affinity unit is constituted by calcschists (Schistes Lustrés s.s.), whose foliation is defined by micaceous and quartz carbonate-bearing levels and contains lenticular bodies, from metric to kilometric dimensions, of metabasites, ophicarbonates and serpentinites. The continental affinity unit is composed of phyllites and metavolcanic rocks of Upper Carboniferous – Lower Permian (Lefèvre, 1984), conglomeratic quartzites (Middle Permian – Lower Triassic; Lefèvre, 1984) with graphitic phyllites and lenses in 'Verrucano' facies, and Triassic dolomitic marbles, with marble breccias and 'Cornieules' levels.

3. Methodology

A multidisciplinary investigation based on geological surveys, GIS database creation, aerial photo observation, local historical archival data consultation, structural analysis and drillholes re-interpretation has been performed (Table 1). Since part of the topography has radically changed during the landslides past events, new 10 m contour lines have been obtained using the LiDAR-derived DTM with 5 m grid resolution (DTM LiDAR 2009–2011 Piemonte ICE), integrated in a WGS 84, UTM 32N GIS spatial database to derive a Hillshade map and create 3D models. Geological and geomorphological field surveys were conducted at 1:5.000 scale to investigate the outcropping bedrock, ductile and brittle structures, the shallow deposits, and the different types of landforms, following Cruden and Varnes (1996) classification. A geological and geomorphological map at scale 1:10.000 in an area with very poor geological data of about 12 km^2, was realized. To improve the accuracy, fieldwork was integrated with photointerpretation of multi-temporal aerial images (PVCN 1975 colour photographs at 1:20.000), digital orthophotos (TerraItaly IT 2000; AGEA 2005-2008/2007-2009/2015; RiskNat 2008) and lithostratigraphic drillhole data (provided by ARPA Piemonte and Acceglio Municipality; Table 1). Historical information about landslide activity coming from excerpts, newspaper articles and church chronicles has been taken into account. To confirm the structural-geomorphological interaction in the Gollone Landslide area, Markland test (Markland, 1972) for planar and wedge sliding with Dips software has been carried out.

4. Structures-landforms interaction

A field-based geological, structural and geomorphological survey was conducted to understand the main lithologies, discontinuity sets and the distribution of the main landforms outcropping in the upper Maira Valley. The study area consists of metavolcanic rocks, quartzite and marble belonging to the Acceglio Unit and lenses of serpentinite and metabasite in calcschist belonging to the Upper Piedmont Unit (see the attached Main Map).

The main schistosity of the study area (Sp; Figure 2(a)) is the product of a folding process developing an axial plane foliation, which generally transposes a previous one (Sp-1), which sometimes is still preserved in marble or other rigid levels (Figure 2(b)). The Sp-1 foliation is parallel to the Sp foliation in the limbs of the Fp folds (Figure 2(b)). The Sp-1 foliation is affected by tight Fp folds, observable in all the lithologies from centimetre- to metre-scale. The contact between quartzite and marble crops out in the southwestern part of the map and in the on-site Gollone Landslide. There, a km-scale marble synform in quartzite, visible in the geological cross-section (A-A' in the Main Map), is developed during the main deformation stage. The Sp foliation, dipping to SW with dip angles varying from sub-horizontal to sub-vertical, is also associated to kinematic indicators with a top-to-the-SW and a top-to-the-NE normal and reverse sense of shear (e.g. S–C-C' fabric; Figure 2(c)). The presence of metre thick shear domains parallel to the main foliation and the progressive decrease in grain size moving toward the tectonic contact between the Upper Piedmont Zone and the Acceglio Unit has been detected. The Sp foliation is folded by two subsequent phases (D+1 and D+2). The Fp+1 folds show kink, chevron and/or symmetric geometry, with rounded hinges (Figure 2(d)). A crenulation lineation (*sensu* Piazolo & Passchier, 2002; Figure 2(e)), defined by the hinge lines of centimetric-folds, has been observed. During the last deformation phase, metric- and decimetre-scale open folds (Fp+2; Figure 2(f)) developed.

Four fracture/fault systems have been detected:

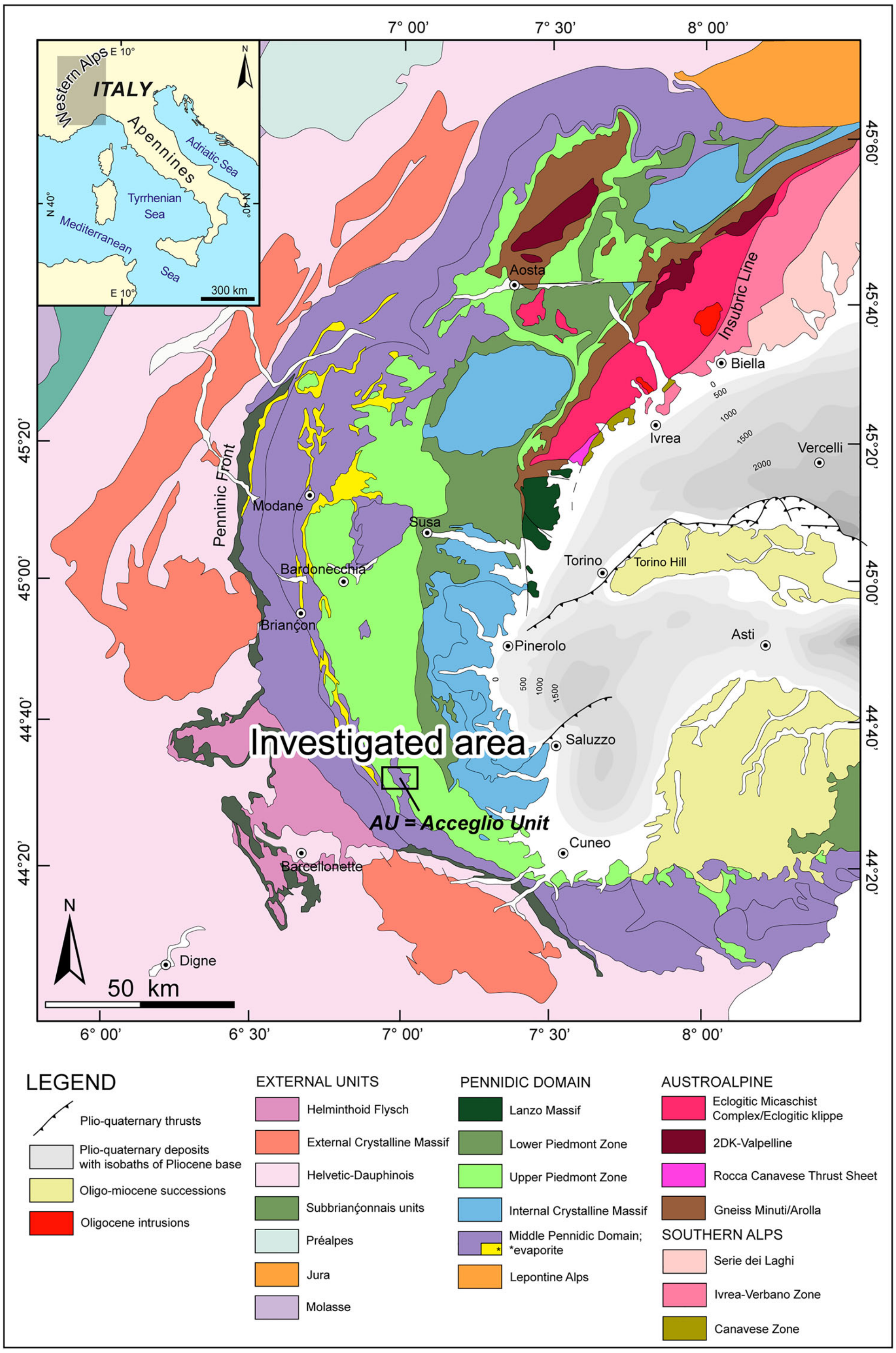

Figure 1. Skectch map of the Western Alps (modified from Beltrando et al. (2010) and Piana et al. (2017)) with its geographic location.

- the F_1 system consists of discontinuities generally associated with cataclasite and gouge, striking N – S and NNE – SSW, sub-perpendicular the main foliation (Figure 3(a)), with sub-vertical dip angles (Figure 3(b)). This system, well visible in the Mt. Midia Soprano area, often shows an important strike-slip component and locally a transtensive movement (Figure 3(a));
- the F_2 system is composed by close to open fractures with decimetric to metric spacing. The close fractures show flat and smooth surfaces, while open ones show wavy wrinkled surfaces and sometimes karst fractures. The mean direction is NW – SE, dipping NE with dip angles varying from about 30° to sub-vertical, generally opposite to the main foliation. Near the Gollone Landslide, the F_2 system is well exposed (Figure 3(c));
- the F_3 system reactivates the ductile shear zones previously cited, causing the formation of gouge and cracking. The mean direction is NW – SE, dipping SW with dip angles ranging from about 30° to 80°, mostly parallel to the main foliation Sp;

Table 1. Main sources of aerial photographs, orthophotos, LiDAR data and drillholes used in this work.

Resources		Scale/Resolution/Depth	Source
Aerial Photographs	PVCN 1975	1:20000	Open Geodata Regione Piemonte
Orthophotos	Terraltaly IT 2000	1:10000	Open Geodata ARPA Piemonte
	AGEA flight 2005–2008	1:10000	Open Geodata ARPA Piemonte
	AGEA flight 2009–2011	1:10000	Open Geodata ARPA Piemonte
	AGEA flight 2015	1:10000	Open Geodata ARPA Piemonte
	RiskNat 2008	1:10000	Open Geodata ARPA Piemonte
LiDAR data	2009–2011 Piemonte ICE	5 m resolution	ARPA Piemonte Resources
Drillholes	Pz-1 Piezometer	60 m deep	Regione Piemonte & ARPA Piemonte Resources
	Pz-2 Piezometer	60 m deep	Regione Piemonte & ARPA Piemonte Resources
	I1 Inclinometer	80 m deep	Regione Piemonte & ARPA Piemonte Resources
	I2 Inclinometer	80 m deep	Regione Piemonte & ARPA Piemonte Resources

- the F_4 system is characterized by close to few millimetres open (Figure 3(d)) fractures, with centimetric spacing, usually without filling. Their surface is very little wavy, but wrinkled, with variable length according to the thickness of the stratification. The mean direction is NNE – SSW, dipping NNW with dip angles of about 35° – 90°.

The morpho-geometric direction of the main ridges is influenced by the NNE – SSW and NW – SE (F_1 and F_2, respectively) fracture systems.

Spread over the area, the debris quantity is highly associated with the weathering condition of the bedrock. Where quartzite is involved, the percentage of fine material is almost absent, preferentially developing rock flows. Where marble outcrops, the detrital cover is poorly sorted; the availability of homogeneous fine material is higher and regularly aids slope deposits to be triggered by debris flows (Figure 4). All along the Maira Stream, gravitational phenomena generate several debris flow cones and wider interdigitating polygenic fans. Their emplacement is coupled with Maira Stream recent deposits and its tributaries large input materials (Mollasco and Onerzo streams). Downstream of Acceglio town, a thin alluvial plane formed due to the increase of the solid discharge and to a sudden decrease of the steepness. Regarding the orographic right side of Maira Valley, in the uppermost range the F_2 system influences rock falls and rock avalanches trigger. This fracturation alters physical and mechanical bedrock properties producing fine material feeding the fan-shaped area at the toe of the slope. The intersection between F_1, F_2 and F_4 fracture systems is a predisposing factor for larger gravitational movements of this sector, well-observable in the Markland test results in the Gollone Landslide case.

5. The Gollone Landslide case study

The Gollone Landslide, located on the north-eastern slope of the Mt. Midia Soprano (2341 m a.s.l.) of about 33° mean steepness, is the most active case in the upper Maira Valley. This phenomenon involves an overall area of approximately 130.000 m^2 with its crown located at about 1700 m a.s.l. and the valley bottom at about 1220 m a.s.l., a height difference of approximately 480 m. The detachment zone consists of a sub-vertical scarp about 250 m long and 70 m high; the accumulation body is located between 1630 m a.s.l. and 1430 m a.s.l. The crown is oriented approximately NW – SE and, behind it, depressions with the same orientation allow to hypothesize a regressive trend of the phenomenon. Periodically, the scarp collapse increments the detrital cover with bedrock portions. The first documented occurrences have been reported around the second half of the eighteenth century and the beginning of the 19th, when the north-eastern slope of the Mt. Midia Soprano underwent a significant landslide event, with an extraordinary supply of detrital materials in the creek adjacent to the town, where a debris flow detached and destroyed 15 residences (Tropeano & Turconi, 2000). In 1846, a debris flow occurred burying and destroying most of the houses in Acceglio, probably due to intense and prolonged rainfall. During 2008–2009, an avalanche event, nowadays testified by the almost complete absence of high vegetation, was recorded. The main scarp of the Gollone Landslide considerably regressed after many rock falls and topplings occurred on 4–6 December 2011. The entire rock fall volume was estimated to be around 20.000 m^3 and its areal extension was assessed in about 11.500 m^2. Further rock falls were also recorded on the night of 28–29 October 2019 (SIFraP).

As geomorphological surveys reveal, the landslide is composite but divisible in four main movement typologies without considering the snow avalanches (Figure 5(a)):

- A rock slide throughout its extension;
- A slow movement of the accumulation body from the foot of the main vertical scarp;
- Rock falls and topplings from the crown;
- Debris flows development in the two, deep incisions bordering the landslide.

In this light, the two most hazardous elements are the large portions of rock masses from the mentioned detachment zone and the unstable detrital cover as feeding area in the uppermost range of the two incisions. Regarding the rock fall detachment zone

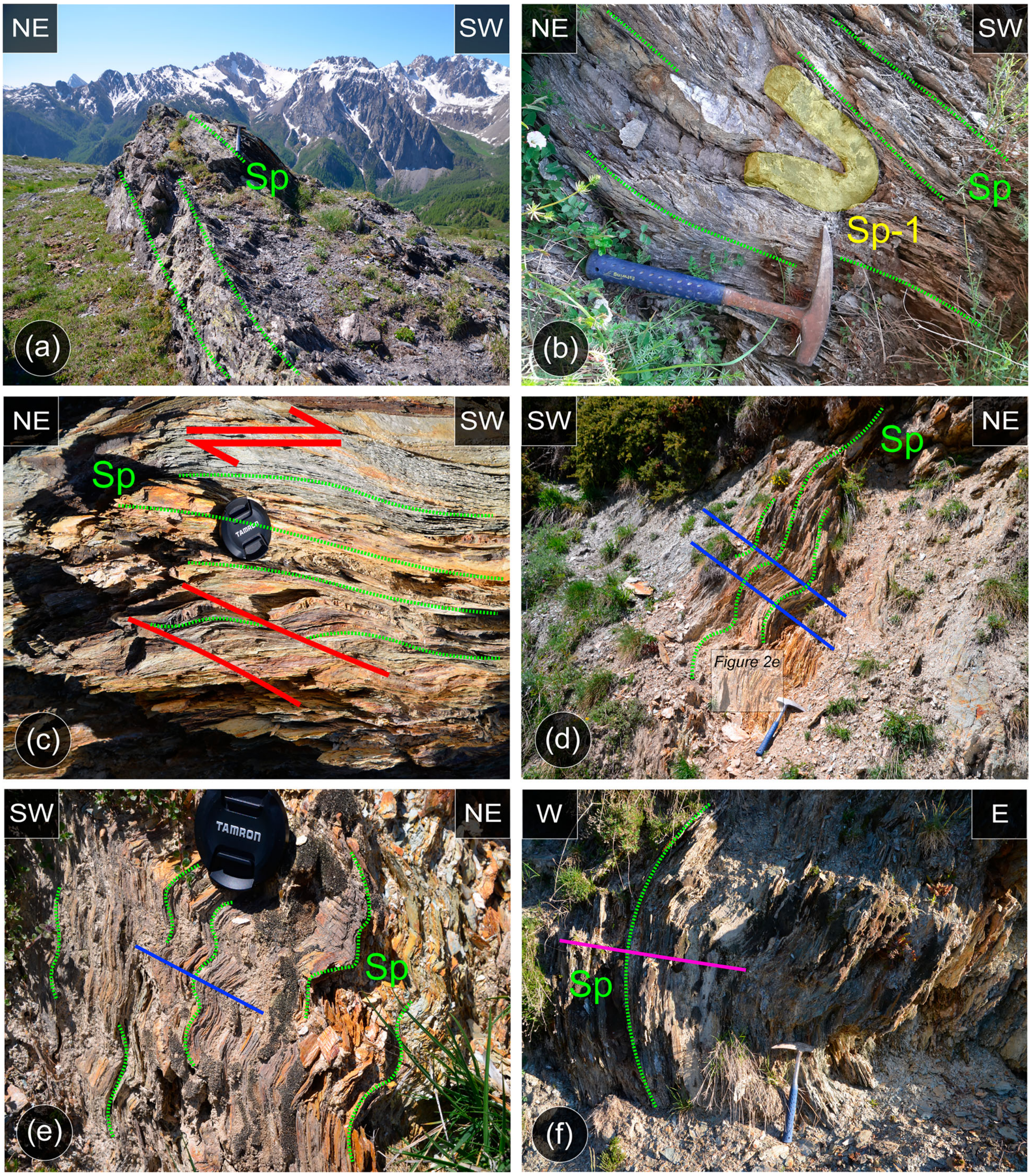

Figure 2. Ductile features. (a) Sp foliation in metavolcanic rocks dipping with a high angle toward SW. (b) Fp cylindrical folds deforming an older relict foliation (Sp-1) in quartzite and quartz-rich schist. Sp-1 foliation is parallelized to the Sp main foliation in the limbs of the Fp fold. Sp foliation is parallel to Fp fold axial plane. (c) C′-S fabric in metavolcanic rocks with a top-to-the SW sense of shear. (d) Kink folds (Fp+1) affecting the Sp foliation. (e) Detail of the previous kink folds with the development of an intersection lineation. (f) Late open folds (Fp+2) with sub-horizontal axes and axial planes deforming the main foliation (Sp).

(Figure 5(b)), the kinematic analysis on marble performed following the Markland test is reported in Figure 5(c). This kind of analysis indicates the susceptibility of the Gollone Landslide slope (Slope orientation; So; Figure 5(c)) for each discontinuity system. We performed the test using the marble friction angle average ($\varphi = 44°$). Markland test confirms that the intersection between the slope (So) and the F_2 system could involve planar sliding and the geometric relationships between F_1 and F_4 could involve wedge sliding. Topplings could be related to the F_1 system when it dips opposite to the Gollone Landslide slope (So). All the systems compromise the Gollone Landslide stability. On the contrary, the detrital cover is one of the parameters to be considered for debris flow and snow avalanches future susceptibility tests. Its thickness has been investigated using the stratigraphy of the drillholes (geological cross-section A-A’ in

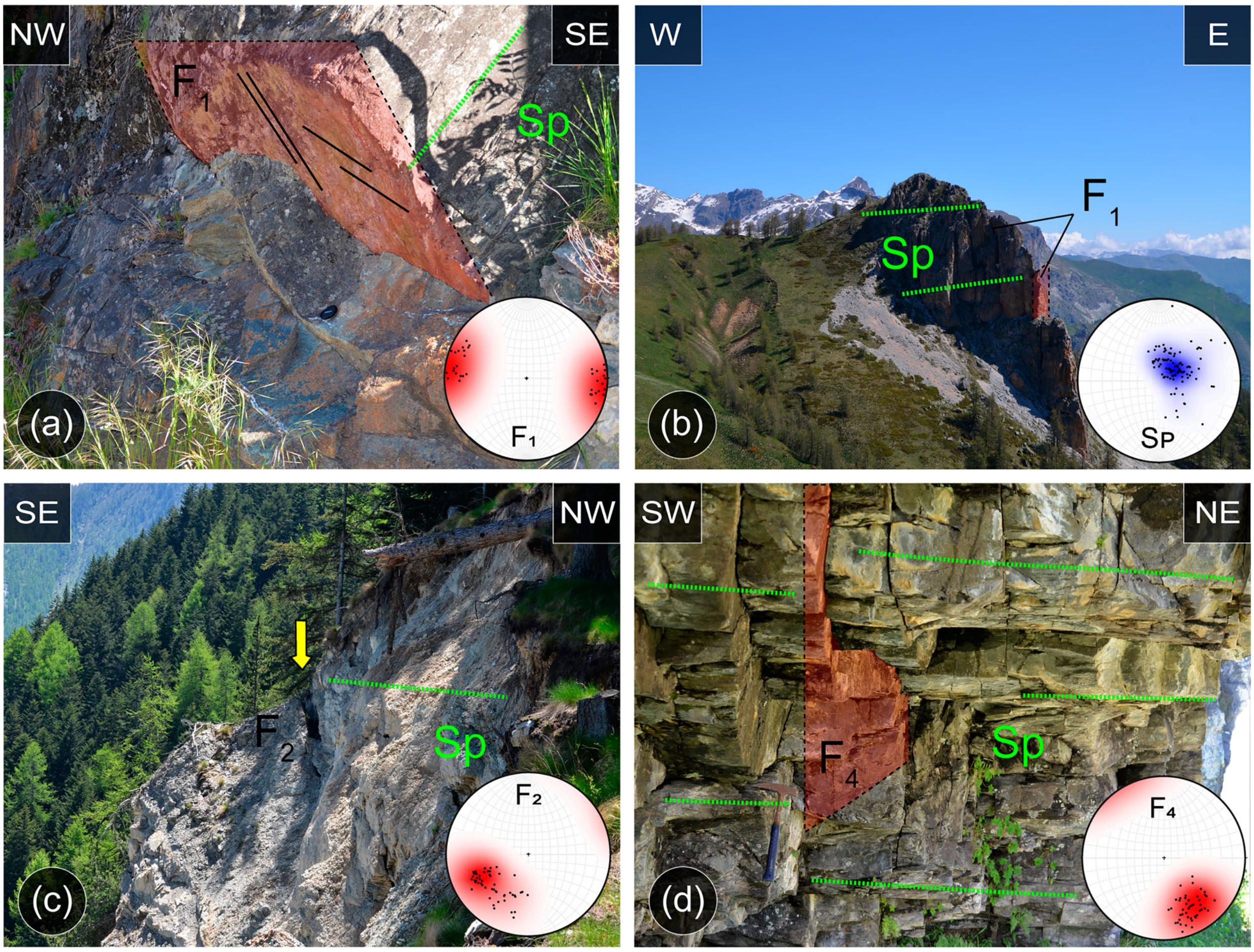

Figure 3. Brittle features with stereographs. (a) F_1 system surface on which have been highlighted two types of striae, indicating a combination of dip and strike-slip movement. (b) F_1 system with a sub-vertical surface, perpendicular to the Sp foliation. (c) F_2 fractures with metric opening, localized in the proximity of the Gollone Landslide. (d) F_4 sub-vertical discontinuity, perpendicular to Sp.

the Main Map). The bedrock-detrital cover contact was localized at about 18 m upstream and 32 m downstream.

6. Final remarks

The integration of different methods of survey and disciplines, such as geology, geomorphology and

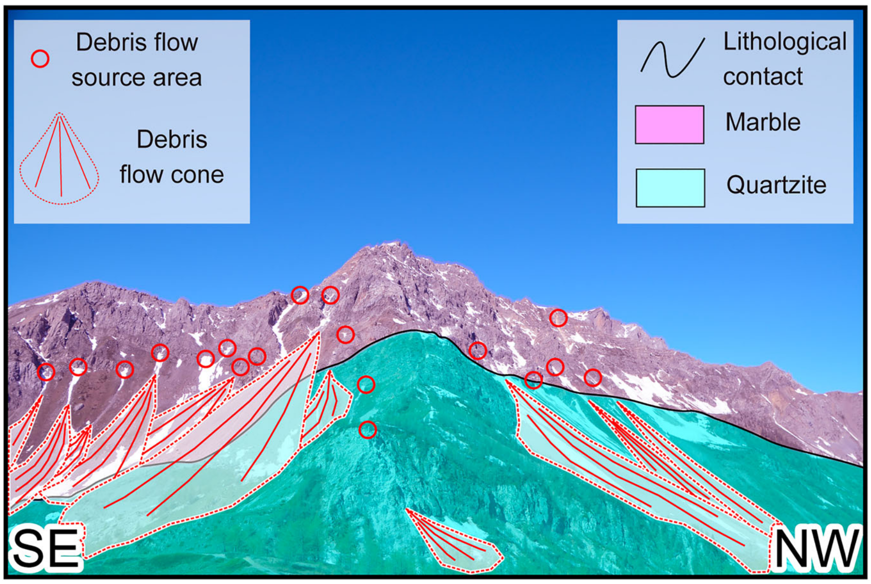

Figure 4. Landscape view of the contact between marble and quartzite located in the south-western part of the geological map. Basement and debris flows geomorphological features are indicated.

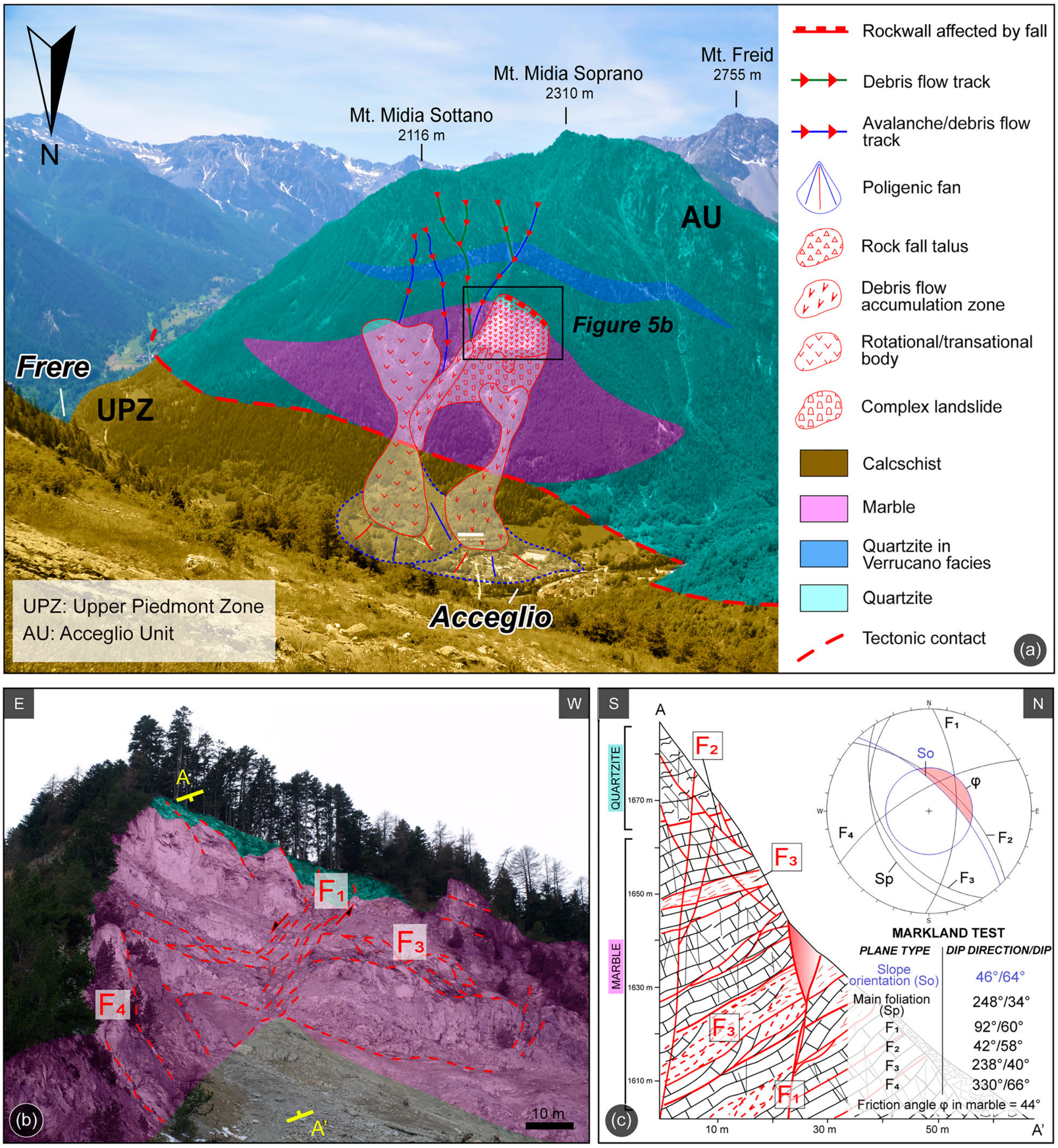

Figure 5. (a) Panoramic view of the Gollone Landslide located on the North-facing slope of upper Maira Valley, near Acceglio town. The main geomorphological elements and lithotypes observed on the field have been highlighted. (b) Mesostructural view from the base of the Gollone Landslide of the outcropping structures. (c) Structural-geological schematic cross-section indicated in Figure 5 (b), directed SW – NE, of the bedrock characterizing the Gollone Landslide. Markland test performed on the Gollone Landslide rock fall zone has been reported.

geomechanics allows the definition of the structures-landforms interaction in the upper Maira Valley, particularly in the Gollone Landslide area (Piedmont, NW Italy). The main findings could be summarized in the following points:

- A complex deformation history, due to the combination of ductile and brittle regimes, has been recognized. A polyphase ductile deformation has been detected and four discontinuity systems (F_1–F_4), developing complex unstable multifaceted polyhedron, have been described.
- The erodibility of lithologies significantly influences landslide typologies and their triggering conditions. The greatest difference in behaviour is between marble and quartzite, whose weathered covers have differentiated impacts on the gravitational movement styles and velocities.
- The emplacement of slope deposits and the large contribution of tributaries cause the Maira Stream erosion/deposition process variation in correspondence of Acceglio town.
- Due to the presence of predisposing factors (the lithological contact between marble and quartzite,

the intersection of all discontinuity systems and the high quantity of detrital cover), the Gollone Lanslide area plays a key role in understanding the most active phenomena in upper Maira Valley. The landslide movement, as a result of Markland test, is controlled by the F_1, F_2, F_4 fracture systems, for rock falls and topplings. The F_3 system, in addition to the previous ones, determines the development of detrital cover (about 32 m maximum thickness estimation), whose hazard requires more detailed studies to be assessed.

This approach could provide an effective base for the characterization and correct monitoring of similar complex landslide in an Alpine context. It offers essential tools for the mitigation of risk for towns in Maira Valley to be improved with further analysis on landslide susceptibility.

Software

The map has been drawn using the software QGIS (v. 2.18.26 Las Palmas) and Adobe Illustrator® CC 2018. Structural data have been projected with the software StereoNet©. The Markland Test has been performed using the Dips Software© (Rocscience-Dips).

Geolocation information

The study area is located in the upper Maira Valley, near Acceglio town, in the Western Alps (northwestern Italy). The area is placed between 44°26’28’’ N – 06° 56’59’’ E and 44°29’30’’ N – 07°02’0’’ E, Coordinate System: WGS 1984 / UTM Zone 32 N.

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Disclosure statement

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

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