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PRESERVATION OF QUATERNARY SEDIMENTS IN DSGSD ENVIRONMENTS: THE MONT FALLÈRE CASE STUDY (AOSTA VALLEY, NW ITALY)

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ABSTRACT: Deep seated gravitational slope deformations (DSGSD) in the Western Alps, which usually affect glacial valleys, produce strong deformation in both bedrock and Quaternary cover, generally favouring erosion. This research, which examines a DSGSD along the Mont Fallère southern slope in the Aosta Valley, suggests that DSGSD can also locally favour the formation and preservation of the Quaternary stratigraphic successions for the following reasons:
- the development of transversal elongated depressions, which are essentially connected with the onset of gravitational structures (trenches, minor scarps, and counterscarps) and filled by differentiated Quaternary successions;
- the occurrence of closed depressions along the slope, which originate from the gradual evolution of gravitational structures (trenches or minor scarps and associated counterscarps) and are occupied by lakes that are progressively filled by lacustrine and palustrine sequences;
- the occurrence of wide, flat, irregular surfaces that are characterized by lower erosional phenomena with respect to the surrounding steep slopes and preserve various Quaternary stratigraphic successions;
- the development of rounded reliefs and associated wide depressions, both of which exhibit topographic surfaces that hang over torrential incisions that are located along the main fractures; this morphology favours the preservation of glacial, outwash, lacustrine and palustrine sediments;
- wide colluvial and debris cover that buries and partially preserves older Quaternary sediments;
- the local occurrence of a travertine cover and cemented sediments, which preserve the older Quaternary sediments.

These morphological conditions are favourable to prehistoric human settlements, resulting in archaeological mountain sites that also provide a chronological reference for the evolution of DSGSD.

Keywords: Aosta Valley, DSGSD, Quaternary sediments, prehistoric human settlement

1. INTRODUCTION

Deep-seated gravitational slope deformations (DSGSD) are large mass movements on high-relief slopes that extend from the valley floor up to or beyond the ridge crest. These features have been found in most rock types and are generally characterized by discontinuous or poorly defined boundaries, large volumes (commonly >0.5 km^3) and thicknesses, conspicuous surface gravitational features and relatively low rates of movement over long periods (mm/y, in alpine areas) (Varnes et al., 1990; Ambrosi & Crosta, 2006; Agliardi et al., 2012).

The absence of a clear sliding surface could not be assumed as a DSGSD diagnostic feature compared to a landslide (Sorriso-Valvo, 1995). In detail, many "confined" landslides that have been described in the literature do not show a well-defined or complete sliding surface until their final collapse (Hutchinson, 1988; Cruden & Varnes, 1993) and many DSGSD that have been observed in the Central Alps display, instead, a basal sliding surface (Agliardi et al., 2001). This surface is sometimes partially coincident to a pre-existing tectonic discontinuity and is sometimes justified by the DSGSD's kinematics.

These phenomena cause the deformation and dislocation of the bedrock and the Quaternary cover, creating many similar surface gravitational structures to those that are observable at a smaller scale in cohesive soil landslides (Sorriso-Valvo, 1995).

The most common indicators of DSGSD are gravitational tensional structures at different scales, sometimes reported as morpho-structures including minor scarps, trenches and counterscarps along the deforming slopes and double or multiple ridges on the upper parts of the slopes (Agliardi et al., 2001). Gravitational compressional structures are also common at the slope toe as bulging reliefs and buckling folds (Chigira, 1992). Minor landslides occur inside the deformed rocky mass, and ancient collapses develop on the lower parts of slopes. The toes of many DSGSD lie below valley floors and are covered by alluvial or lacustrine fills (Agliardi et al., 2012).

Observations of many DSGSD in the Western Alps suggest that fractured and loosened bedrock and gravitational surface structures strongly affect the facies and distribution of Quaternary sediments (Forno et al., submitted). The original Quaternary cover in DSGSD is usually subjected to strong deformation, dislocation, erosion, and reworking. Nevertheless, this research notes that DSGSD locally favour the formation and preservation of Quaternary sediments. The present work only emphasizes the local environments that promote the preservation of pre-DSGSD Quaternary sequences and the sedimentation and preservation of a new syn-post-DSGSD stratigraphic record.

This research considers an example from the gravitational phenomena that occur on the Mont Fallère southern slope (locally called the "Conca del Fallère") along the left side of the middle Aosta Valley (NW Italy), which is drained by the Verrogne and Clusellaz Rivers (Fig. 1). This area, which is prevalently located between 3061 and 2000 m a.s.l., comprises the southern slopes of various summits (Pointe Leysser, Mont Rouge, Mont de Vertosan, Mont d'Ars, Mont de la Tsa, Pointe de Chaligne and Pointe de Metz), the Plan di Modzon area and the Becca France ridge (Fig. 2).

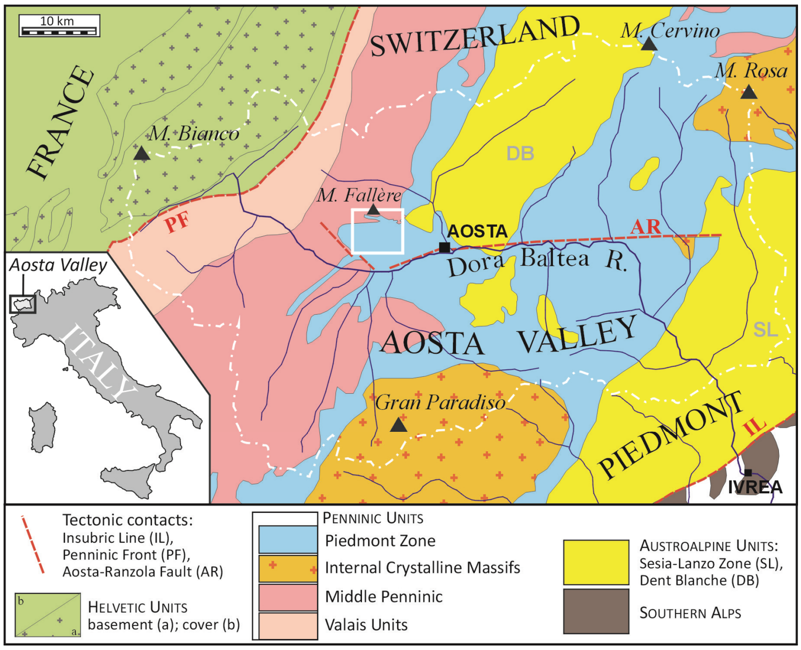

Fig. 1 - Schematic geological map of the Aosta Valley; the investigated area is shown (white box).

A traditional geological survey has provided data regarding the outcropping DSGSD structures and Quaternary sediments and landforms. Geophysical surveys and observations within archaeological excavations have supplied some information regarding buried structures and Quaternary sedimentary successions.

2. GEOLOGICAL SETTING

The Mont Fallère area is located in the axial sector of the Western Alps along the contact between the Middle Penninic (northern sector) and Piedmont Zone (southern sector) (Fig. 1). The Middle Penninic is represented by the Palaeozoic basement of the Gran San Bernard Nappe. This area consists of garnet micaschist and albitic paragneiss, with some minor bodies of metabasite, and is covered by discontinuous lower Mesozoic dolomitic metabreccia and marble. The overlying Piedmont Zone, which is represented by the Upper Tectono Metamorphic Units (as defined by Forno et al., 2012a), consists of prevailing carbonate calcschist that alternates with decimetric marble layers. This marble contains many centimetric layers of quartzite, which were probably derived from original chert. Few discontinuous layers of meta-rudstone locally occur and consist of marble and dolomite clasts in a calcite matrix. All the rocks in this area were strongly deformed under blueschist metamorphic conditions, followed by widespread recrystallization under greenschist facies metamorphism.

The entire area is now completely free of glaciers but was largely shaped by the wide Clusellaz Glacier during the Last Glacial Maximum (LGM) and Lateglacial (Fig. 2) (Forno et al., 2013b). This glacier previously drained through the Clusellaz Valley, only subsequently shaping the Verrogne Valley. The glacial valley floor and the low slopes show many rocky rounded reliefs and associated depressions that are linked to subglacial erosion. These landforms are locally covered by subglacial sediments and glacial marginal deposits, which form short and low lateral moraines. The same glacial valley floor and the low slopes also locally preserve horizontal surfaces, which consist of shallow lacustrine and peat sediments from the Lateglacial to the Holocene in age. Debris, colluvial, avalanche and torrential sediments that formed during the Holocene are widely distributed on the bedrock and the more ancient Quaternary sequences. Bedrock, Quaternary cover and landforms have also been fractured, loosened and dislocated by DSGSD structures (Fig. 2). The Plan di Modzon finally preserves ancient settlements (suggested by nine prehistoric sites) from the Mesolithic to the Copper Age, which were hosted in favourable morphological settings as promoted by glacial shaping and DSGSD evolution (Raiteri, 2015; Forno et al., 2013b).

Recent studies on the Mont Fallère southern slope examined the Becca France ridge and the Plan di Modzon area, which were affected by numerous gravitational structures (doubled ridges, minor scarps and trenches) that are linked to the Pointe Leysser DSGSD, also predisposing a large historical rock avalanche (Forno et al., 2012a; 2013a; 2013b; 2014) (Fig. 2). Geophysical investigations and archaeological excavations have supplied some information regarding the possible evolution of some buried gravitational structures and their influence on lacustrine and palustrine sedimentation (Comina et al., 2015).

Remarks on the P. Leysser DSGSD have been reported in the new official geological map (Polino et al.,

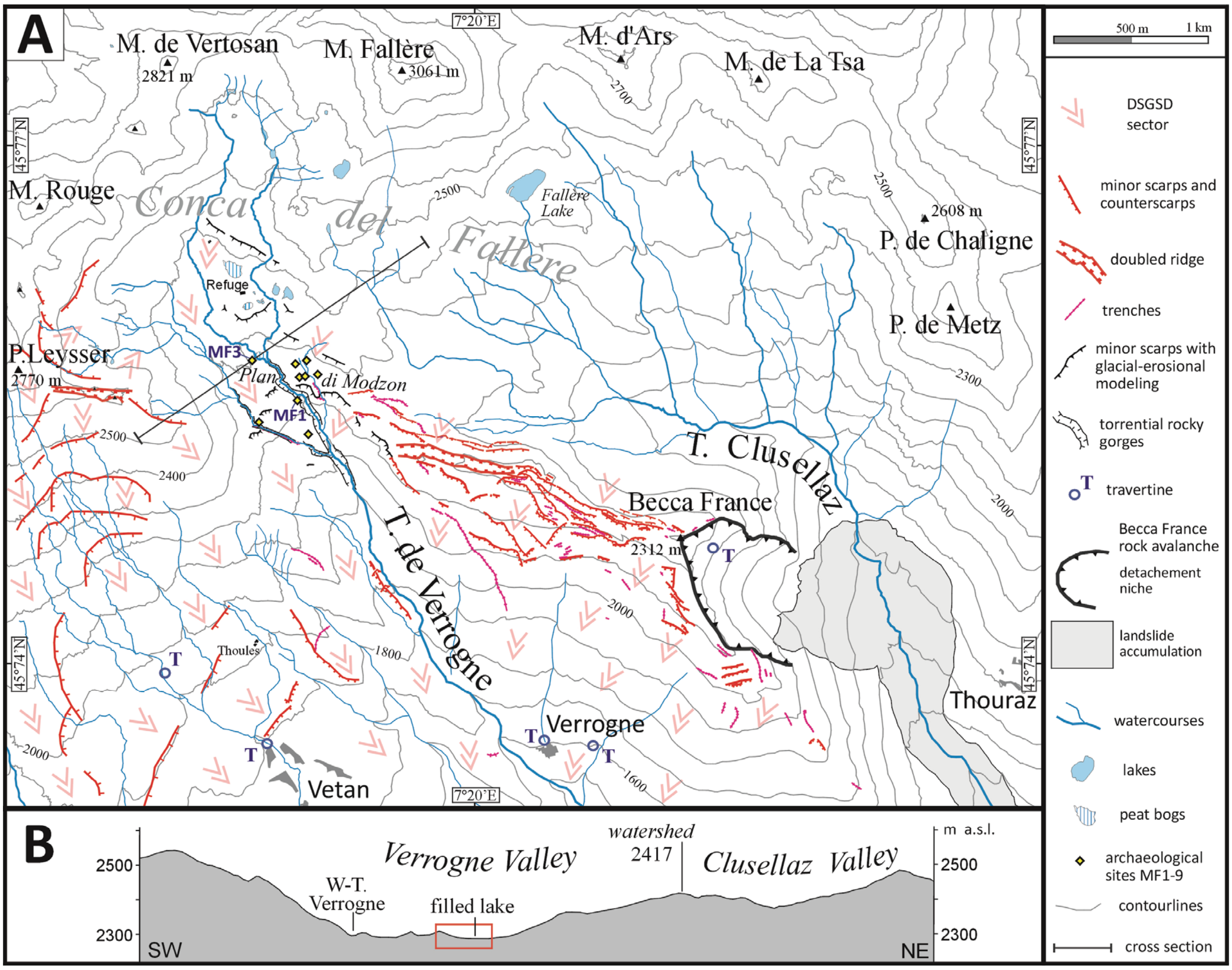

Fig. 2 - Topographic map of the Mont Fallère southern slope, or Conca del Fallère; gravitational structures and archaeological sites (MF1 and MF3) are also reported in the investigated central and southwestern sectors (A). Cross section of the Plan di Modzon; the red box shows the location of geophysical section in Fig. 15 (B).

in press). The surface evidence of this phenomenon suggests a remarkable sliding of the Dora Baltea left slope towards the main valley, with an amplitude of approximately 1 km. This map also reports the local sedimentation of travertine, which shows an adequate correlation with DSGSD areas.

3. MAIN GRAVITATIONAL STRUCTURES AND LANDFORMS THAT FAVORED THE PRESERVATION OF QUATERNARY SEDIMENTS

The sliding of bedrock in the upper part of a slope related to DSGSD creates remarkable doubled ridges, which consist of wide depressions that are sub-parallel to the watershed and exhibit lengths up to several kilometres and depths up to tens of metres (Agliardi et al., 2001; Forno et al., 2012a). The sliding of the bedrock along the entire slope, which often occurs through rotational surfaces, dislocates volumes of rock of varying sizes and forms many minor scarps, which usually exhibit heights greater than ten metres. The sliding surfaces that are observed in the bedrock can also locally preserve gravitational movement striae, which are partially buried by colluvial sediments (Fig. 3).

The opening of gravitational fractures along a DSGSD slope can result in the genesis of trenches (Agliardi et al., 2001). We can distinguish longitudinal and transversal trenches, which essentially develop according to the maximum slope or to the contour lines, respectively (Forno et al., 2012b). The evolution of antithetic sliding surfaces in a DSGSD slope can form some counterscarps, which usually create closed depressions (graben).

Various gravitational structures (doubled ridges, trenches, minor scarps and counterscarps) are widespread in the area (Forno et al., 2012a; 2013a; 2013b; 2014). The ensemble of these structures creates a modification from a relatively regular slope to an irregular landscape, completely changing the morphological features of the entire area and giving rise to the following gravitational landforms, which were variously modified by glacial shaping.

Elongated depressions of varying length (up to hundreds of metres) and depth (up to tens of metres),

Fig. 3 - Carbonate patinas inhibit the erosion of kinematic indicators on a sliding surface in the bedrock (western slope of the Becca France ridge).

Fig. 4 - Depression (d) connected to a buried sliding surface with a rotational component (red arrow), partially filled by debris (Verrogne Valley floor).

which are directly linked to transversal trenches, minor scarps and counterscarps, represent the most common gravitational evidence in the entire area (Fig. 4). The glacier usually uses these landforms to modify their original features.

Closed depressions of varying sizes (up to several hundreds of square metres) are also locally present in the area along the slope and the ancient glacial valley floor (Fig. 5). These landforms are directly connected to the gradual development of trenches or linked to the evolution of associated minor scarps and counterscarps, which form graben structures and often host lacustrine and palustrine basins (Fig. 6).

Flat surfaces, which exhibit extensions up to several square kilometres and appear irregular in detail, are common in the investigated area related to the gravitational evolution and extensive subglacial erosion (Fig. 7). In detail, gravitational evolution gives rise to many minor scarps, producing an overall enlargement of the topographic surface at the expense of the valley floor space and reducing the overall gradient. Glacial shaping often emphasizes this enlargement, creating numerous flat surfaces that are separated by scarps (Fig. 8). Various DSGSD flat surfaces and scarps show different morphologies (rounded or rough) according to their age, before or after the glacial evolution.

Rocky rounded reliefs and associated wide depressions are numerous in the ancient glacial valley floors of the area and are related to subglacial erosion that involves the progressively deformed bedrock of DSGSD (Fig. 9). The subsequent evolution of the gravitational structures further emphasizes this articulated morphology. These landforms (up to several hundred square metres) hang over the current torrential incisions and are locally cut by deep gorges. In detail, the rounded reliefs are located in less deformed rocks, while the gorges developed along the more fractured and loosened bends (Fig. 9).

4. QUATERNARY SUCCESSIONS THAT FILL THE GRAVITATIONAL LANDFORMS

The extensively fractured and loosened bedrock and the gravitational structures that are connected to

Fig. 5 - Lago dei Morti depression that was shaped by glacial erosion, which is favoured by many minor scarps.

Fig. 6 - Morphology of the gravitational closed depression that hosts the filled Plan di Modzon lacustrine basin. The lake was related to minor scarps and counterscarps that form a graben structure.

Fig. 7 - Wide, flat, irregular surface on the Mont Fallère southern slope that is connected to the DSGSD evolution and extensive subglacial erosion. This landform highly hangs from the

Fig. 8 - Detail of the wide flat surface on the Mont Fallère southern slope, which is connected to the evolution of DSGSD during the Clusellaz Glacier diversion. The glacier, before flowing along the Clusellaz Valley (on the background), subsequently flowed along the Verrogne Valley (on the right). A trench and small moraines are visible in the foreground.

Fig. 9 - Rocky rounded reliefs, with associated wide depressions, near the Mont Fallère Refuge that hang over the current torrential incisions, observed by SE. These features did not experience erosion, which was confined along the gorges fracture in the watercourse (Verrogne River in the foreground).

DSGSD strongly interfere with both erosional and sedimentary phenomena. Although the strong deformation of the rocks that promotes heavy subglacial and torrential erosion, Quaternary successions can be locally deposited and preserved.

4.1 Outcropping successions evidenced by direct observations

Elongated depressions along transversal gravitational structures, according to the contour lines and not hosting watercourses, are usually preserved over time and are progressively filled with Quaternary differentiated successions, which consist of varying types of sediments. The elongated depressions along longitudinal gravitational structures, according to the maximum slope, are not born as fluvial incisions, but instead are usually reused by watercourses and consequently not preserved over time with their original landforms because of deepening.

In detail, the transversal depressions that are located in the glacial valley floor of the area are often initially filled by subglacial sediments that directly cover the loosened bedrock (during the LGM and Lateglacial) and are subsequently buried by colluvial sediments (during the Holocene) (Fig. 10A). The Quaternary sequence usually consists of a lower body of angular fragments of rock with open texture (debris). Faceted pebble and cobble with an abundant over-consolidated sandy-silty matrix (subglacial sediments) cover the debris. Cross-bedded sub-rounded gravel in a coarse sandy matrix is locally present (proglacial outwash sediments) and alternates with subglacial sediments. The top of the succession consists of small angular fragments of rock with an abundant sandy-silty matrix (colluvial sediments) (Fig. 9 in Forno et al., 2013b).

The transversal depressions that are located along the slopes of the investigated area, laterally to the ice tongue, are usually filled by only debris and colluvium (Fig. 10B). The thickness of these successions can vary greatly (up to a few metres) according to the depression size. Locally, these morphologies also favoured the prehistoric settlements of the area, with sites built onto the gravitational landforms (Fig. 13) that can provide a stratigraphic reference for fracture openings (Forno et al., 2013b).

Closed depressions that are connected to gravitational evolution are progressively filled with Quaternary differentiated successions including glacial, lacustrine, palustrine and torrential sediments (Fig. 6). The infillings are usually characterized by horizontal morphology (Fig. 11). The extremely fractured and loosened bedrock favours the formation of small rocky fragments, which modified the usual fine lacustrine facies (Forno et al., submitted). The location of the closed depressions along the slope and the ancient glacial valley floor (outside the current torrential valley floor, where erosion is active) favours the preservation of the infills over time.

In detail, the Plan di Modzon closed depression (1.6 hectares), for example, shows a horizontal morphology in the central sector, where diffusely organic sediments (peat) with planar bedding outcrop (palustrine sediments). Laterally, the morphology weakly slopes downstream and exhibits clast-supported sediments that

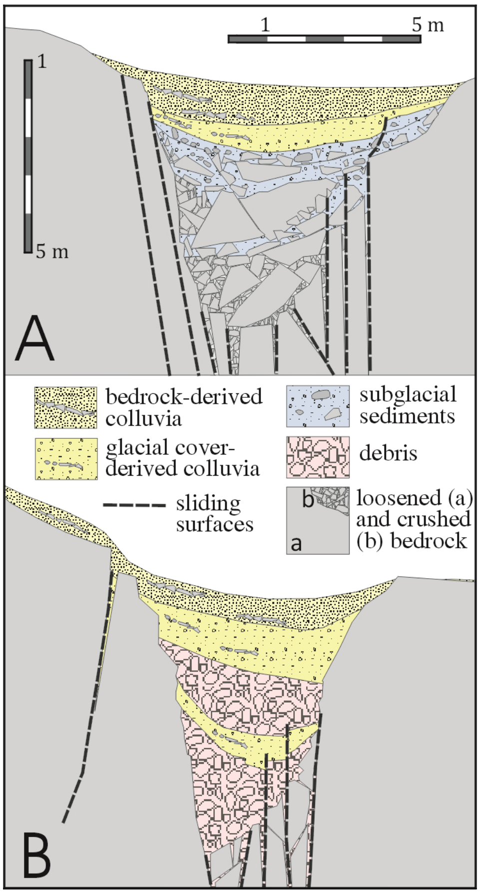

Fig. 10 - Schematic reconstruction of filled gravitational trenches. One depression along a transversal trench in an ancient glacial valley floor (A) was progressively filled by glacial and colluvial sediments, that directly cover the loosened bedrock. Another depression along a transversal trench on a slope (B) developed without a glacier and was progressively filled by debris and colluvial sediments.

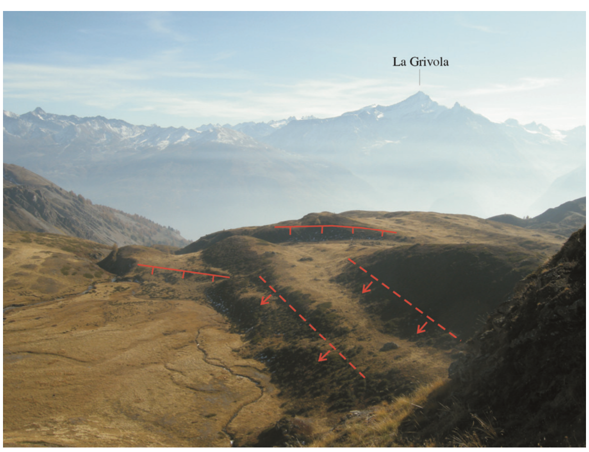

Fig. 11 - Wide horizontal surface that corresponds to the Plan di Modzon filled lake, bounded by minor scarps (shaped lines) and counterscarps (continuous lines) that form a barrier to the flow of watercourse.

consist of centimetric rocky sub-angular fragments with an abundant sandy-silty matrix (torrential sediments), forming an alluvial fan. This evidence indicates that a palustrine basin developed in this closed depression and was partially filled by a lateral fan. A previous lacustrine basin has only been suggested by geophysical investigations (see § 4.2). In this case, the formation of a lacustrine basin after glacial retreat is related to the typical morphological conditions of scarps and counterscarps, which form a barrier to flow of rivers (Fig. 11). In detail, this basin is connected to the formation of NNW-SSE scarps and WSW-ENE counterscarps during the glacial shaping and, subsequently, to the evolution of the same structures without a glacier (Comina et al., 2015).

An investigated peat bog is hosted in another lacustrine depression upstream from the Plan di Modzon, which was derived from subglacial erosion that involved the progressively deformed DSGSD area (Fig. 2). The lacustrine-palustrine succession that partially fills the bog has been the subject of palaeobotanical research: it suggests a more ancient phase at 11.6 ka cal BP, in which the treeline was lower, and a more recent phase at 8.5-6 ka cal BP, which corresponds to a period of high treeline elevation (Pini et al., 2012; Badino et al., 2012). These data also suggest a very different environment in this area during the Mesolithic and Copper Age, which is now a wide pasture completely without trees or high shrubs.

Flat, irregular surfaces also promote the sedimentation of varying types of Quaternary sediments, such as subglacial and outwash cover and local palustrine fills (Fig. 7). The flat morphology protects these surfaces from the erosion that involves the surrounding steep slopes. This morphology in the investigated area was also promoted by a glacial diversion, with the Clusellaz Glacier flowing SE along the Clusellaz Valley and subsequently flowing S, shaping the Verrogne Valley (Forno et al., 2014). The same morphology also promoted the ancient population in the area, favouring subsequent prehistoric settlements (Forno et al., 2013b) (Fig. 2).

Rocky rounded reliefs and associated depressions that hang over the current torrential incisions also represent areas preserved by erosion (Fig. 12). Instead, the torrential incisions (gorges) depict strongly eroded areas (Fig. 9). The erosional processes are therefore confined within the gorges, which often are the only sectors without ancient sediments.

A thin cover of faceted pebbles and cobbles mixed within an abundant over-consolidated silty matrix (matrix-supported subglacial sediments) is usually preserved on the rounded reliefs of the area, which therefore allows the preservation of subglacial sediments over wide areas, and along valley floors, which are subjected in other cases to subsequent torrential erosion. Small bodies of sub-angular fragments of varying sizes in a scarce sandy-silty matrix (clast-supported supraglacial sediments) are locally preserved, forming small moraines (Fig. 8). Additional infills of sub-rounded gravel in a sandy matrix (clast-supported outwash sediments) are usually preserved in the associated depressions.

In addition to the described landforms, the DSGSD areas show wide colluvium and debris cover, which is linked to the abundant production of rocky fragments from loosened bedrock that only locally outcrops. These areas display a discontinuous travertine cover, which is strictly favoured by gravitational structures (Polino et al., in press). Strongly cemented Quaternary sediments, which are promoted by the high infiltration of surficial water and are related to very fractured and loosened bedrock, are also common.

The Mont Fallère southern slope DSGSD also typically shows wide debris and colluvium cover, with higher thickness in the depressions (Fig. 13). Erosion that is linked to surface runoff mainly affects this cover, which buries and consequently partially preserves more ancient Quaternary sediments.

A locally developed travertine cover is visible along the P. Leysser southern slope (Fig. 2). It outcrops for example at the outlet of a deep incision, which corresponds to a longitudinal trench that was subsequently deepened by an ephemeral watercourse (Fig. 14). In detail, 3.5 m-thick travertine (phytohermal calcareous tufas) with 30° towards the SSE dipping stratification covers debris flow sediments (Fig. 14). This travertine is very rich in trees imprints (trunks and branches) with decimetric sizes. This sequence, which is characterized by a strong resistance to erosional phenomena, has protected the underlying debris flow sediments.

Another outcrop of travertine, which has a sub-vertical arrangement and is over one metre thick, is visible along the detachment niche of the Becca France rock avalanche. This travertine preserves the debris and colluvial sediments that fill the fractures (Fig. 2).

Other carbonate-cemented sediments are also observed along the entire Mont Fallère southern slope, where Quaternary sediments are usually very strongly cemented. This feature facilitates their preservation by erosion. The DSGSD structures often promote the carbonate-cementation of sediments under favourable climatic conditions. This cementation is favoured by strong infiltration, through loosened bedrock, also connected to the facies of different sediments that are particularly rich in small rocky fragments and scarce matrix.

4.2. Buried successions as evidenced by geophysical investigations

Geophysical surveys can be very useful to study the buried fills of the described landforms and to evaluate the features and thicknesses of various sedimentary bodies. Geophysical surveys (i.e., electric tomography) that have been performed along the Fallère southern slope allow us to evaluate the thickness of the Quaternary cover and reconstruct the facies of different sediments (Comina et al., 2015 in which details on the geophysical data acquisition and processing can be found).

This methodology was applied to an elongated depression less than 1 metre deep, which is located in the ancient Verrogne glacial valley floor and is connected to gravitational minor scarps and associated counterscarps through the prehistoric human site MF3 (Fig. 13). A resistivity section shows that the high resistivity, which is related to the bedrock of the valley floor (values above 2000 ohm.m), is truncated by low-resistivity anomalies with a sub-vertical trend (at progressive 60 and 80 m) (Fig. 15A a-a[1] stretch). These

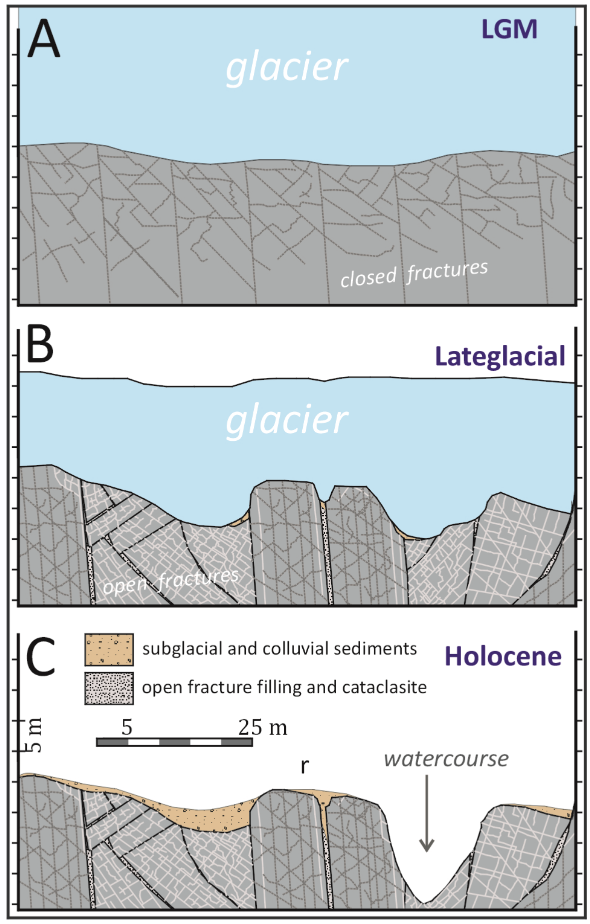

Fig. 12 - Typical morphology of the Plan di Modzon with rocky rounded ridges (r) and associated wide depressions, which were connected to the progressive evolution of fractures, trenches, minor scarps and counterscarps during glacial erosion. Steps A and B refer to different glacier thicknesses; step C refers to the development of a watercourse in a fracture after glacier retreat.

Fig. 13 - Archaeological site (MF3) during the excavation phase. The site is located in an approximately 1 m deep elongated depression, resulting from associated minor scarps (slopes dipping to the right) and counterscarps (only identified by geophysical investigations), partially filled by glacial and colluvial sediments (Verrogne glacial valley floor).

Fig. 14 - Local occurrence of a travertine cover (yellow and grey colour), which is significant for the preservation of more ancient debris flow sediments (grey colour) (P. Leysser southern slope).

features are probably related to the presence of less compacted material that likely contains higher water content. The collected geophysical data and related geological interpretations suggest that the first anomaly (at 60 m) represents a buried depression that is elongated in the NNW-SSE direction (as indicated by field work data) and bounded by minor sliding surfaces that dip in opposite directions (normal and antithetic) (Fig. 15B a-a^{1} stretch). This depression appears to be filled by a coarse and successively fine cover, which is interpreted as glacial and colluvial sediments, respectively. The second anomaly (at 80 m) has been referred to as a main antithetic sliding surface due to DSGSD's evolution, which dips to the WSW and is relatively continuous in the subsoil.

Geophysical research in the investigated area also suggests that a closed depression in the Plan di Modzon hosts complex sequences of varying sediment types (between 70 and 180 m) (Fig. 15A b-b^{1} stretch; Fig. 16A) (Comina et al., 2015). In detail, a succession of subglacial silty-gravel sediments (values between 500 and 750 ohm.m), lacustrine sands (values between 300 and 500 ohm.m) and local palustrine organic deposits (peat and gyttja with values between 150 and 300 ohm.m) can be distinguished (Fig. 15B b-b^{1} stretch; Fig. 16B).

The resistivity data also indicate that the closed depression is truncated in the SSE portion of the section (Fig. 16) by a DSGSD-buried surface. This scarp likely represents the prolongation in the subsoil of outcropping counterscarps (see § 4.1).

4.3. Buried successions evidenced by archaeological excavations

A prehistoric human settlement (site MF3) that was discovered by an archaeological excavation (Raiteri, 2015) allows us to directly observe the surficial succession filling within an elongated depression (Fig. 13) that is mainly related to gravitational minor scarps and associated counterscarps. The excavation exposed a sequence whose bottom consists of glacial boulders with a subordinate grey sandy matrix, forming a subglacial body. Yellowish-brown silty sand covers this body, which is referred to as a colluvial layer because of the reworking of glacial sediments by surface runoff (Fig. 17). Several artifacts of rock crystals (hyaline quartz) from the Middle Neolithic have been found above the colluvial body. In this example, the colluvial body buries the coarse glacial sediments, pro-

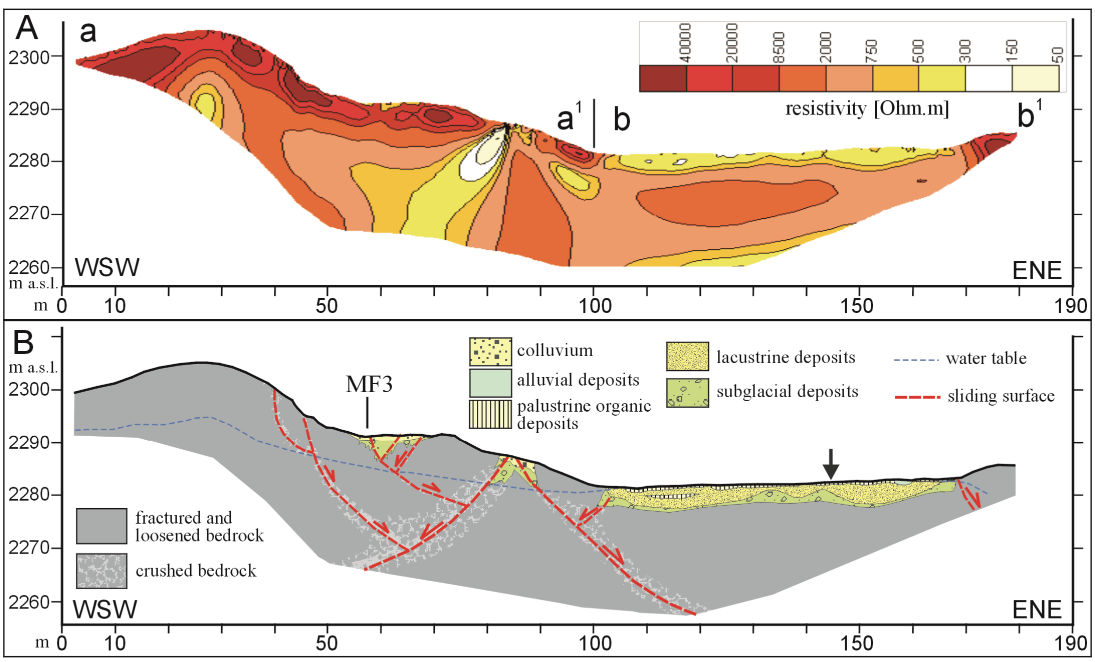

Fig. 15 - Geophysical cross section (A) and related geological interpretation (B) of the investigated area. The a-a1 stretch exhibits associated minor scarps and counterscarps that are partially filled by glacial and colluvial sediments, on which a prehistoric settlement was located (site MF3). The b-b^{1} stretch indicates a subglacial, lacustrine and palustrine succession in the filled ancient lake. The black arrow refers to the cross section in Fig. 16. Modified after Comina et al. (2015).

moting their preservation.

Numerous other sites developed on the bedrock's rounded ridges, showing a thin subglacial cover.

In detail, site MF1, which was discovered by an archaeological excavation, represents more typical and studied prehistoric evidence (Raiteri, 2015). This site was developed on a cover that consists of sediments with faceted boulders within a sandy-silty matrix that is connected to a subglacial environment. The yellowish colour of this cover suggests incipient weathering to form slightly evolved soil.

Detailed research on this site indicates a complex stratigraphy marked by the younger settlement (Copper Age) at the base of the sequence and older Mesolithic artifacts at the top. The Copper Age layer shows remarkable traces of settlement and use (rubefied areas and charcoal accumulations), which are superimposed by a hearth that preserves a large amount of charcoal inside a cuvette that is delimited by lithic fragments. Charcoal remains provide radiocarbon ages of 4306 ± 45 14C a BP (3030-2870 yr BC) and 3983 ± 40 14C a BP (2620-2400 yr BC) (Raiteri, 2015).

Mesolithic artifacts (approximately 3000) are obtained from rock crystals and subordinate flint (Forno et al., 2013b). The more significant retouched artifacts (94) indicate a probable Sauveterrian phase. Some double-back, back, cutting and triangular artifacts are the most indicative and a charcoal remain provides a radiocarbon age of 7795 ± 45 14C a BP (6700-6490 yr BC) (Raiteri, 2015).

Their most ancient age indicates that these artifacts were carried by a colluvial phenomenon, which was responsible for their reworking leading to a secondary arrangement.

Consequently, this settlement exhibits a reversed sequence that consists of in place more recent archaeological evidence that is covered by more ancient reworked (colluviated) materials.

5. DISCUSSION AND CONCLUSIONS

Generally, the preservation of a sedimentary stratigraphic record occurs in areas of active sedimentation and little or no erosion. As known, gravity plays an important role in the sedimentation and erosion on the Earth's surface, strictly because of local morphology. In detail, an increase in topographic elevation and steepness promotes erosional processes. Conversely, depositional processes, which favour the development of a stratigraphic record, are more developed with decreasing steepness and topographic elevation. This feature, which is evident in sea basins, is also observed in continental environments, which contain a high variability of sectors that are characterized by prevalent erosion or sedimentation and little extension.

Deep-seated gravitational slope deformations (DSGSD) usually produce strong deformation both within the bedrock and Quaternary cover, generally favouring erosion and gravitational reworking and producing a thick and widespread debris and colluvium cover that usually buries every structure and landform. However, the gravitational collapse of a mountain side and its resulting expansion in the valley floor occur in DSGSD areas, with the topographic surface consequently expanding. These processes lead to the reduction of the average steepness of the slope and the development of a very irregular topographic surface, which creates local environments with slower or absent ero-

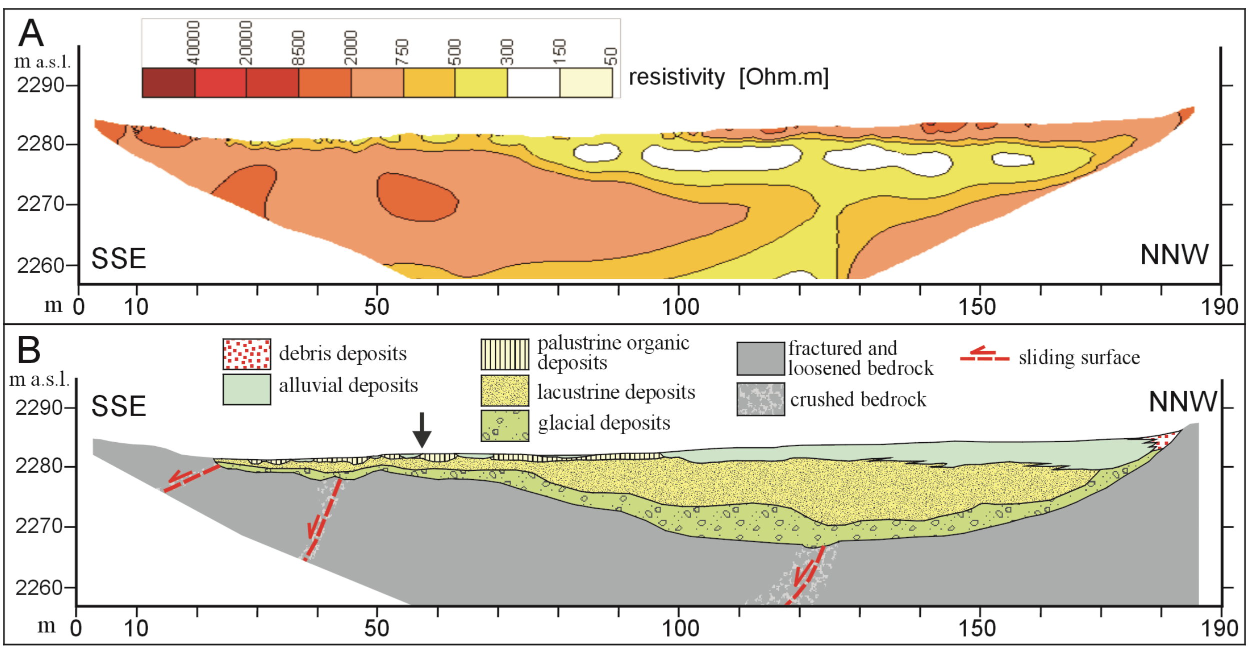

Fig. 16 - Geophysical cross section (A) and related geological interpretation (B) indicating that the Plan di Modzon represents a closed depression that was filled by sediments. The resistivity values suggest the occurrence of subglacial and lacustrine sediments below the surficial palustrine and torrential cover. The local low resistivity values in the bedrock below the closed depression is consistent with buried trenches. The black arrow refers to the cross section in Fig. 15. Modified after Comina et al. (2015).

sional processes, where sedimentation and the preservation of a Quaternary stratigraphic record can develop.

Recent observations of many DSGSD in glacial valleys in the Western Alps allow us to distinguish the typical effects of these phenomena on the facies and distribution of Quaternary sediments (Forno et al., submitted). An example of the DSGSD effects on the sedimentation and preservation of Quaternary successions has been presented in this research, with a focus on the Mont Fallère southern slope in the middle Aosta Valley. These effects on the outcropping Quaternary sediments, DSGSD structures and landforms were derived from traditional geological surveys. Notes on buried structures and successions were also obtained by means of geophysical surveys and observations of archaeological excavations.

This research suggests that DSGSD can locally favour the sedimentation and preservation of the oldest successions, in areas that usually experience erosion, for the following reasons. First is the occurrence of wide, flat, irregular surfaces (Fig. 7), in which various Quaternary successions can easily be deposited and protected from erosion, which instead particularly develops along the surrounding steep slopes. Moreover, the typical irregular morphology of DSGSD, which are characterized by rocky rounded reliefs and associated wide depressions that hang over the current torrential incisions (Fig. 9), favours the local sedimentation and preservation of a Quaternary stratigraphic record. These sediments are instead completely eroded in torrential incisions that developed along the main fractures, that are subsequently deepened by watercourse. DSGSD structures further favour the development of environments where sedimentation processes are active. In detail, many elongated depressions (connected to gravitational transversal trenches or minor scarps and associated counterscarps) form very local sedimentation basins in which various Quaternary successions can be easily deposited and preserved. On the contrary, the depressions that are linked to longitudinal trenches, subsequently used by the current watercourses, and then deepened and partially filled by torrential and debris flow sediments, usually do not preserve evidence of more ancient fillings, with the exception of debris flow sediments that are preserved by travertine. Furthermore, the local occurrence of closed depressions along the slope and glacial valley floor (because of gravitational trenches or minor scarps and associated counterscarps that gradually evolve) are occupied by lakes after glacial retreat. These depressions are progressively filled by essentially lacustrine, palustrine and torrential successions, which are subsequently preserved by erosion because they are not deepened by the current watercourses. The reported geophysical data allow us to better image the preserved stratigraphic record and observe gravitational structures that are not visible on the surface through traditional geological surveys.

The typical conditions of DSGSD areas promoted the development of prehistoric human settlements. The morphology usually comprised flat, irregular surfaces, which favoured the formation and preservation of prehistoric mountain sites, which also provides a chronological reference for sediments and landforms.

Fig. 17 - Archaeological excavation of site MF3, which shows a succession of coarse glacial sediments (grey) and fine colluvium (yellow, visible in the central part of the picture) (Verrogne glacial valley floor).

These conditions that favour ancient settlements are also observed in the investigated area. Nine mountain sites have been recognized in the Plan di Modzon area and are located on glacial rounded reliefs with associated wide depressions (Fig. 9) (Forno et al., 2014). The reported glacial diversion created a very wide flat surface, which favoured the development of prehistoric settlements. These ancient settlements were also favoured by the location of the area near the treeline and the absence of geological hazards (floods, landslides, and avalanches) that are present in surrounding areas. The prehistoric settlement MF3 was likely favoured, in addition to its proximity to water, by the location of the depression in the valley floor, which was perched approximately 10 m from the filled Plan di Modzon lacustrine basin. The prolonged use of the MF1 site, as indicated by archaeological artifacts of varying ages, confirms the suitability of the Plan di Modzon to preserve archaeological stratigraphic records.

Finally, as reported, the sedimentation and preservation of the Quaternary stratigraphic record was encouraged by the strong fracturing of the bedrock related to DSGSD. This fracturing favoured well known processes as: a) the production of large amounts of debris and colluvium, which covered more ancient sediments and landforms; b) a decrease in erosional processes from surficial runoff, which was caused by the high permeability of the very fractured bedrock; and c) the percolation of water in the strongly fractured rocks, which promoted the dissolution and deposition of carbonates and, consequently, the active sedimentation of chemical rocks and cementation of older Quaternary successions.

The trenches, minor scarps and counterscarps that developed in these DSGSD areas further favoured the development of environments where subsidence prevailed and sedimentation processes were active. In conclusion, DSGSD conditions can promote both the local preservation of Quaternary pre-deformational successions and the formation of many localized records that consist of syn-deformational and post-deformational sediments.

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