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DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATION EFFECTS ON QUATERNARY DEPOSITS IN THE WESTERN ALPS (NW ITALY).

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ABSTRACT: Deep-seated gravitational slope deformations (DSGSDs) are well-known to affect the landscape and the morphology of Alpine valleys. In contrast, little is known on their influence on Quaternary deposits. This paper, focused on the Western Italian Alps, aims to fill this gap. Eight case studies, identified after a long term field experience, are presented, representative of different geological settings. To fully define their distinctive features, such sites have been characterized using various methods: geological surveys, geophysics and geomatic techniques.

DSGSD proved to influence the sediment deposition primarily with the continuous supply of centimetric/decimetric angular clasts. This have different consequences on sediments, depending on their features, in some cases deeply modifying their typical facies (i.e., glacial, colluvial and lacustrine sediments), whilst in other cases their influence is less evident (i.e., debris, avalanche and torrential deposits). This paper can be a useful tool when dealing with DSGSD-related deposits, helping avoid misinterpretations.

Keywords: sedimentological features, Quaternary sediments, deep-seated gravitational slope deformation, Western Alps.

1. INTRODUCTION

Field sedimentological observations are a valuable tool that can be used to infer the genesis, depositional environment and stratigraphic setting of a sedimentary body (Catuneanu et al., 2009; Jaboyedoff et al., 2013; Shea et al., 2008). The correct identification of facies is of utmost importance and constitutes a basic criterion for geological mapping. The experience gained during numerous geological mapping projects and field survey campaigns performed in the Western Alps suggests that Quaternary sediments located in mountain regions that have been affected by deep-seated gravitational slope deformation (DSGSD) are often atypical, meaning that their sedimentological features can be peculiar and different from those of sediments outside areas of DSGSD (Bollati et al., 2019; Coviello et al., 2015; Polino et al., 2015). Although these differences can be significant, the influence of DSGSD on the sedimentological features of sediments has not been previously well investigated.

This paper aims to evaluate the influence of DSGSD on the characteristics of Quaternary sediments recognized in the field (glacial, torrential, debris, lacustrine, colluvial, avalanche deposits), omitting the landslide sediments already treated by other studies (Ostermann et al., 2016). The diagnostic features of various Quaternary sediments observed in mountain DSGSD sectors are compared with those found outside areas of DSGSD (see Tab. 1). The features described for each facies are those where the deposit developed entirely in DSGSD areas and were therefore essentially influenced by gravitational processes. In contrast, the cases in which the Quaternary succession is fed by a wider catchment basin partly outside DSGSD areas and is related to the overall conditions of the basin (lithology, structure, morphology) are not considered here.

This research on the DSGSD Quaternary cover is based on a field survey of eight case studies, each of which shows a high number of outcrops (up to several hundred). These case studies derived from areas of the Western Alps characterized by different geological settings (see section 3), comprising the Dora Baltea Valley (La Saxe, La Salle, Fallére southern slope and Scalaro Basin), the Dora Riparia Valley (Bardonecchia and Moncellier), and the Chisone Valley (Fenestrelle and Rodoretto Basin) (Fig. 1).

The term DSGSD refers to mass movements involving large volumes of rocks, possibly affecting areas larger than 10 km^2, that encompass entire valley flanks and are propagated at very low velocities (mm/year) (Agliardi et al., 2012; Dramis & Sorriso-Valvo, 1994; Radbruch-Hall et al., 1976). These moving masses, which are characterized by a minimum thickness of 100 m and are up to several kilometres long (Alberto et al., 2008; Ambrosi & Crosta, 2006; Carraro et al., 1979; Kojan & Hutchinson, 1978; Radbruch-Hall, 1978), develop in regions with high relief-energy (Agliardi et al., 2001; Agliardi et al., 2009; Agliardi et al., 2012). Slope deformation usually started during the Lateglacial triggered by post-glacial debutressing following the withdrawal of the glaciers and evolved during the Holocene (Agliardi et al., 2009). The displacement of a DSGSD is small compared to its extent (Massironi et al., 2003) and its rate is usually around 4-5 mm/y (Agliardi et al., 2001; Coquin et al., 2015; Varnes et al., 1990).

These long-lasting slope deformations have modified glacially-sculpted relief, also reducing slope inclinations, and have significantly contributed to the long-term denudation of active orogens (Agliardi et al., 2013). The slope deformation has been linked to the interactions among glacially oversteepened valley flanks, weaknesses in the rock mass, such as schistosity, fractures, faults and high slope values (Agliardi et al., 2009; Agliardi et al., 2013; Crosta, 1996; Massironi et al., 2003; Morelli et al., 2018; Radbruch-Hall, 1978; Zorzi et al., 2014). Clearly-defined failure planes/zones are not necessary for a DSGSD to develop (Dramis & Sorriso-Valvo, 1994), and the lateral margins of these phenomena are often poorly defined (Agliardi et al., 2013).

A DSGSD will result in the formation of multiple fractures that progressively dilate, inducing very fractured rock volumes and their dislocation. Numerous gravitational morpho-structures, such as double ridges, scarps, counterscarps and open trenches, are essentially connected to gravity, although previous tectonic fractures and faults are often reactivated (Agliardi et al., 2001; Agliardi et al., 2009; Forcella & Orombelli, 1984). Minor landslides may occur inside the deformed rocky mass, especially in its marginal sectors. The toes of many DSGSDs lie below the present valley floors, where they are covered by alluvial or lacustrine fills (Agliardi et al., 2012).

Such phenomena are common in mountain belts and have been extensively studied in recent decades (Crosta et al., 2013; Massironi et al., 2010; Ostermann & Sanders, 2017). Some considerations regarding DSGSD areas also derive from research aimed at the hydrogeological reconstruction of large volumes of unstable intensely fractured and loosened rocks (Binet et al., 2009). However, while various studies have focused on the genetic mechanism of DSGSDs and the influence on the bedrock and valley flank morphology, the impact on the features of Quaternary sediment assemblages has been poorly investigated.

The interactions between DSGSD processes and the facies of Quaternary sediments in alpine environments have potential relevance in accurate, large scale field geological surveys. This research exclusively considers the sediments of areas already involved in gravitational processes prior to the deposition of Quaternary bodies, as their sedimentological features can be influenced by DSGSDs.

This research intends to contribute to the definition of some guidelines for the field identification, interpretation and mapping of Quaternary successions in DSGSD, although taking into consideration the influence of local geological and geomorphological conditions in different areas of the Alps.

2. MATERIALS AND METHODS

The study areas were investigated through detailed geological surveys (1:10,000 or 1:5,000 scale), allowing us to define the sedimentological features of the Quaternary sediments recognized in the field. The features of the Quaternary successions in different contexts along the Western Alps (inside and outside DSGSD) were described using the method by Baggio et al. (1997). The use of this method is finalized to have rigorous criteria and is also used by the recent Piedmont 1:50,000 scale official maps of Italy.

Clasts are described in this paper in terms of their volume, rather than the commonly used mean diameter (e.g., the Udden-Wentworth grain-size scale; Udden, 1914; Wentworth, 1922; 1935). The study areas are characterized essentially by schistose lithotypes, that usually form tabular clasts, with a side remarkably smaller than the others. Being so, the volume allows to better evaluate the clast grain size without introducing additional terms to describe the clast shape, as suggested by other authors (e.g., Terry & Goff, 2014).

Where no significant outcrops were present, geophysical methods, such as combined electric resistivity tomographies (ERT), were applied, focusing in particular on the reconstruction of the shallow subsoil, helping to estimate the distribution and thickness of sediments (Comina et al., 2015) (see case study 4).

Aerial photos helped us describe the morphology of DSGSD sectors; these were particularly useful for obtaining an overall view and for examining sectors that were difficult to access. Topographic surveys were performed using "unmanned aerial vehicles" (UAVs). This tool allowed us to obtain detailed aerial photos of the landscape and to create various types of maps (digital surface models, digital terrain models with 4 cm of resolution and orthophotos) which also provided evidence of the morphological features of Quaternary sedimentary bodies in DSGSD areas (Piras et al., 2017) (see case study 8).

3. GEOLOGICAL SETTING OF CASE STUDIES

The Western Alps (NW Italy) were built during the Alpine orogeny. The original rocks formed in oceanic and continental margin environments and now crop out as deeply deformed and metamorphosed rocks. The investigated case studies are located in different valleys of the Western Alps with various geological settings, which have already been examined by detailed geological surveys (Fig. 1). These valleys were deeply carved by glaciers during the Last Glacial Maximum (LGM) and were partly affected by extensive DSGSD phenomena widespread in the Alps (Agliardi et al., 2009; Forno et al., 2013a; 2013b) and other mountain areas (Coquin et al., 2015).

The Quaternary successions in the study areas are essentially fed by metamorphic bedrock consisting of schistose lithotypes, with prevailing calcschist and subordinate micaschist, greenschist and gneiss. In detail, case study 1 (La Saxe) regards the phyllite of the Ultrahelvetic Domain and the gneiss of the Mont Chetif tectonic slice, which involves brittle deformed rocks arranged along the Penninic Frontal Thrust (Elter, 1987). Case study 2 (La Salle) concerns an Upper Carboniferous succession consisting of coal-bearing slate and meta-clastic sediments. Here, the effects of gravitational deformation on tributary torrential sedimentation were investigated by Polino et al. (2015).

Case studies 3, 5, 7, and 8 (Falléré southern slope, Bardonecchia, Fenestrelle and Germanasca Valley) are developed in prevalent calcschist, with minor bodies of mafic and ultramafic rocks (e.g., meta-peridotite, serpentinite, meta-gabbro, and green-schist) strongly deformed along the regional schistosity and referred to the ophiolitic Combin-like units of the Upper Piedmont Zone (Polino et al., 2015). We focused on the Becca France ridge (Falléré southern slope, case study 3) where numerous landforms related to DSGSD (i.e., doubled ridges, minor scarps and trenches) were among the predisposing factors of a large historical rock avalanche, dating back to 1564 AD (Forno et al., 2012a). The same DSGSD has also been described in the surrounding Plan di Modzon area (Forno et al., 2013a), where the presence of gravitational trenches and the evolution of minor scarps on lacustrine and palustrine sedimentation have been detected by geophysical approaches (Comina et al., 2015). Some geological information is also reported for the Susa Valley (Bardonecchia, case study 5), where a significant spring is fed by strongly fractured bedrock (calcschist) (De Luca et al., 2015). A DSGSD in the Chisone Valley (Fenestrelle, case study 7) is reported as a predisposing factor for the occurrence of thick landslides that hindered the T. Chisone flow (Carraro & Forno, 1981; Fioraso & Baggio, 2013).

DSGSD phenomena were also well investigated in a Chisone Valley tributary (Germanasca Valley), also using geomatics techniques, highlighting numerous gravitational morpho-structures that split the glacial sediment bodies, which resulted in numerous isolated flaps (Forno et al., 2011; Forno et al., 2012b; Piras et al., 2017) (case study 8).

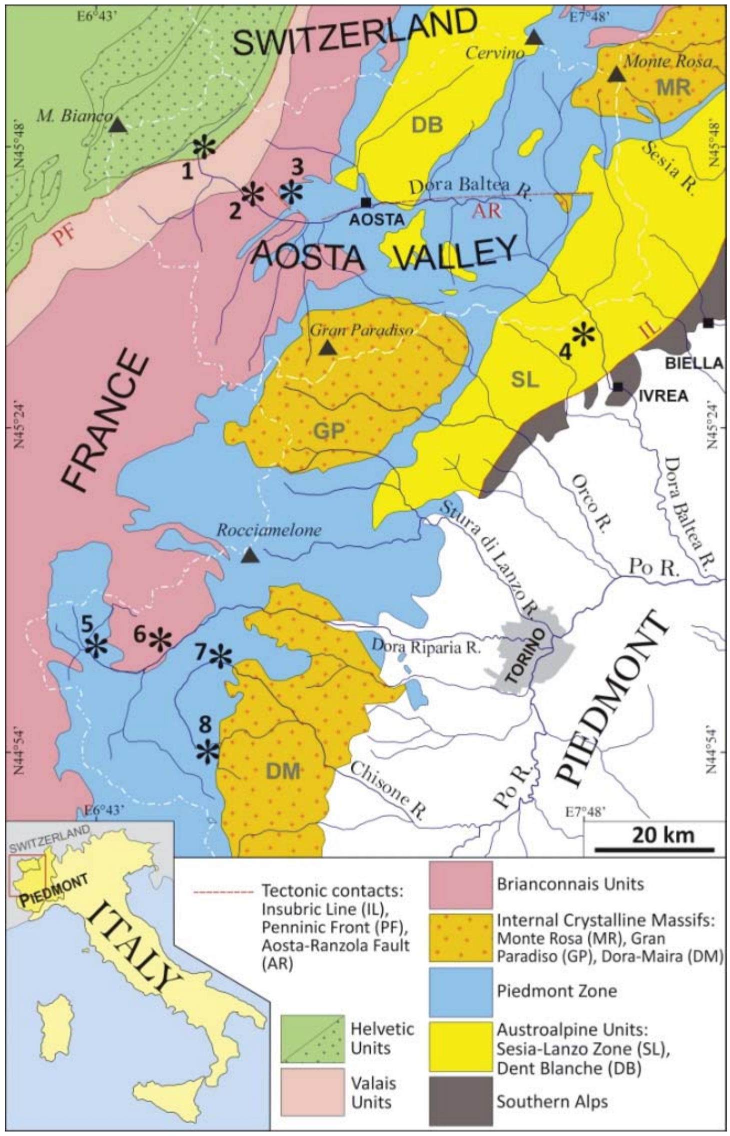

Fig. 1 - The investigated areas are located in the Western Alps (NW Italy) and refer to different geological contexts. Case studies (1) La Saxe, (2) La Salle, (3) Fallére southern slope and (4) Renanchio Basin are located in the Dora Baltea Valley. Case studies (5) Bardonecchia and (6) Moncellier are located in the Dora Riparia Valley. Case studies (7) Fenestrelle and (8) tributary Germanasca Valley are located in the Chisone Valley.

Case study 4 (Renanchio Basin) is located in eclogite micaschist and gneiss with minor bodies of marble, calcschist and mafic rocks referred to as Austroalpine Units (Sesia-Lanzo Zone). This area, which is strongly influenced by both DSGSDs and the glacial and torrential evolution of the lateral Renanchio Valley, is significant for the interconnection between gravitational deformation and hydrogeological setting. Specifically, a spring with high water discharge (average 160 ls^{-1}) located in the area is supplied by groundwater hosted in the loosened bedrock linked to this deformation (De Luca et al., 2015; De Luca et al., 2019; Lasagna et al., 2013).

Finally, case study 6 (Moncellier) includes micaschist with some meta-conglomeratic levels of the Ambin Complex in the Ambin Massif (Grand Saint Bernard Nappe). The springs, as in previous cases, have been regarded as connected to an aquifer hosted by the fractured and loosened rocks of a DSGSD (De Luca et al., 2009).

4. RESULTS

4.1. Influences of DSGSDs on subglacial sediments

A significant example of subglacial sediments (lodgement till) in a DSGSD area is visible on the western slope of the Germanasca Valley, E of the Balma village along the T. Rodoretto tributary (case study 8) (a in Fig. 2). The outcrop is approximately 70 m wide and 10 m high and does not reach the bedrock (Fig. 3A). The top of the outcrop has a regular surface, represent-

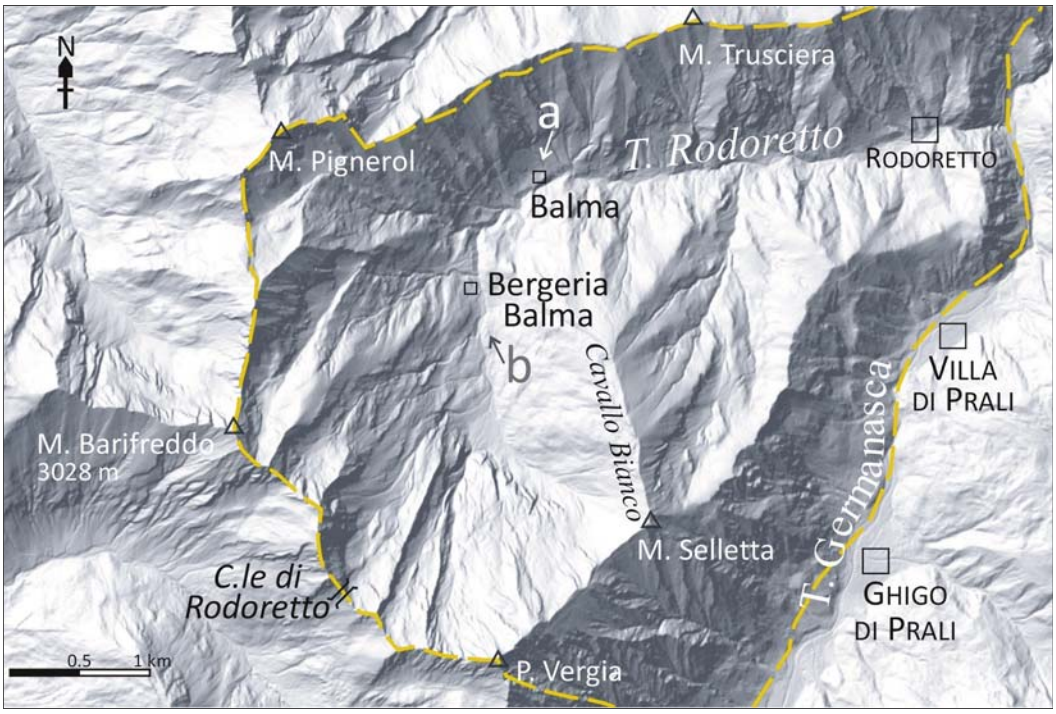

Fig. 2 - Topographic map of case study 8, in the Germanasca Valley. Location of the examples reported in the text: subglacial sediments (a) and ice-marginal sediments (b). The yellow dotted line marks the edge of the investigated DSGSD area.

ing the side of the glacial valley.

These sediments are formed by tabular clasts of various sizes mixed in a subordinate unsorted matrix (Fig. 3B). The decimetric clasts (10 cm^3-0,5 m^3) are numerous in the whole outcrop, while boulders of great size (essentially 0,5-3 m^3) are few and more abundant in the lower band of the outcrop, where rare boulders, with up to a 70 m^3 volume, are also observed (Fig. 3D). The clasts have poor roundness: the centimetric fragments are angular, while the decimetric and metric boulders are from subangular to subrounded. The fragments and boulders show a preferential dip of 30-35°, according to the slope of the glacial valley (Fig. 3C). The petrographic composition of the clasts is very monotonous, essentially comprising calcschist (phyllitic and carbonate) with subordinate prasinite, basaltic metabreccia, quartzite and rare marble, according to the local bedrock fed by the high Rodoretto Valley. Some clasts preserve carbonate patinas suggesting poor cementation of sediments.

The matrix, which is variably present (10-20%), is mostly subordinate to the clasts, but enough to determine the matrix-supported texture, responsible for the poor permeability (Fig. 3E). The matrix essentially consists of very abundant millimetric to centimetric rock fragments ($\leq$10 cm^3) with subordinate fine sand and silt. These sediments show high consolidation. The unweathered clasts and matrix (grey colour) and location in the valley floor can agree with the reference to the last glaciation.

Another example of subglacial sediments in the DSGSD context is visible near Saint Nicolas village along the Gaboè Valley, a northern tributary of the Dora Baltea River, filled by a thick sedimentary succession (case study 3) (b in Fig. 4).

This Gaboè stretch appears entrenched in a previous incision of the Dora Baltea Glacier (Fig. 5A). Evident badlands on the southern slope allow us to observe a 700 m-wide and 30-35 m-high outcrop, showing a succession of glaciolacustrine (gl, 10 m of visible thickness), subglacial (lodgement till) (sg, 15-18 m thick) and cemented ice-marginal sediments (im, 6 m thick) (Fig. 5 B and C).

The subglacial sediments are dominated by abundant clasts mixed in a poor matrix (Fig. 5D). The body consists of decimetric thick layers of massive sediments, variably inclined 10-30° towards the SE (Fig. 5C). Groups of strata with little difference in orientation and dip are visible, separated by unconformable low to mid-angle erosional surfaces. The clasts have various sizes mostly comprising centimetric ($\geq$10 cm^3) and decimetric fragments (10 cm^3-0,5 m^3), with rare boulders (up to 1 m^3), locally concentrated in the low band of sediments (Fig. 5B). The clasts are essentially angular with very subordinate subrounded shapes (Fig. 5E). The petrographic composition of the clasts is monotonous, formed by prevailing calcschist with subordinate quartzite.

The matrix, which is variably present (10-20%), is mainly formed of millimetric to centimetric rock fragments ($\leq$10 cm^3) with a lower silty component and appears subordinate to clasts (Fig. 5D). These matrix-supported sediments mostly show high consolidation and not appear cemented, despite the occurrence of surficial carbonate patinas, supplied by the overlying cemented ice-marginal sediments. The prevailing grey colour and the unweathered clasts agree with the refer-

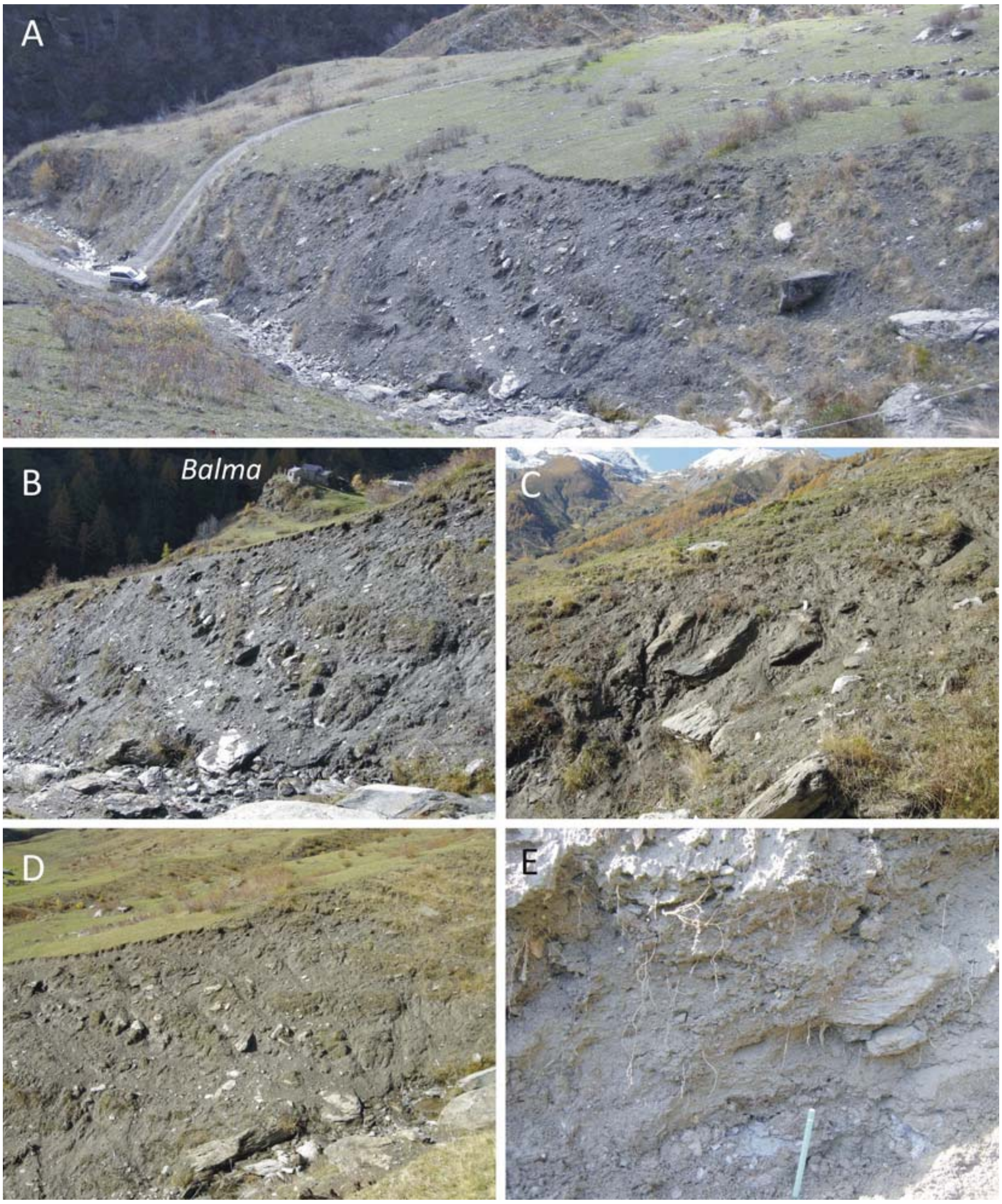

Fig. 3 - Outcrop of subglacial sediments (lodgement till) E of Balma village (case study 8). A) Panoramic view of the outcrop seen from the east: the regular morphology of the original preserved glacial slope is evident at the top of the sediments (slope of 26°). B) The sediments are formed by clasts of various sizes mixed to in a poor matrix. C) The clasts have a poor roundness and show a preferential arrangement according to the glacial slope. D) Boulders of great size (volume up to 70 m^3) are relatively abundant in the lower band of the outcrop. E) Detail of the outcrop in which the relationship matrix/clasts is observed.

ence to the last glaciation.

The uncommon features of the subglacial sediments in the investigated DSGSD areas can be evaluated comparing them with their analogues outside DSGSD areas, which are characterized by a strong predominance of the sandy-silty matrix (Tab. 1). Only locally, under some conditions (slightly weathered bedrock with a large amount of available debris for tectonic fracturing), could the matrix be poor. The clasts are normally very subordinate and plunged in the matrix with faceted shapes and are subangular to subrounded. The petrographic composition of the clasts is usually representative of the entire basin, except for the bottom which can be enriched by the local bedrock. Typical pebbles (i.e., faceted, polished and striated pebbles) are also common. These sediments are normally overconsolidated due to ice loading (Goldthwait & Matsch, 1988).

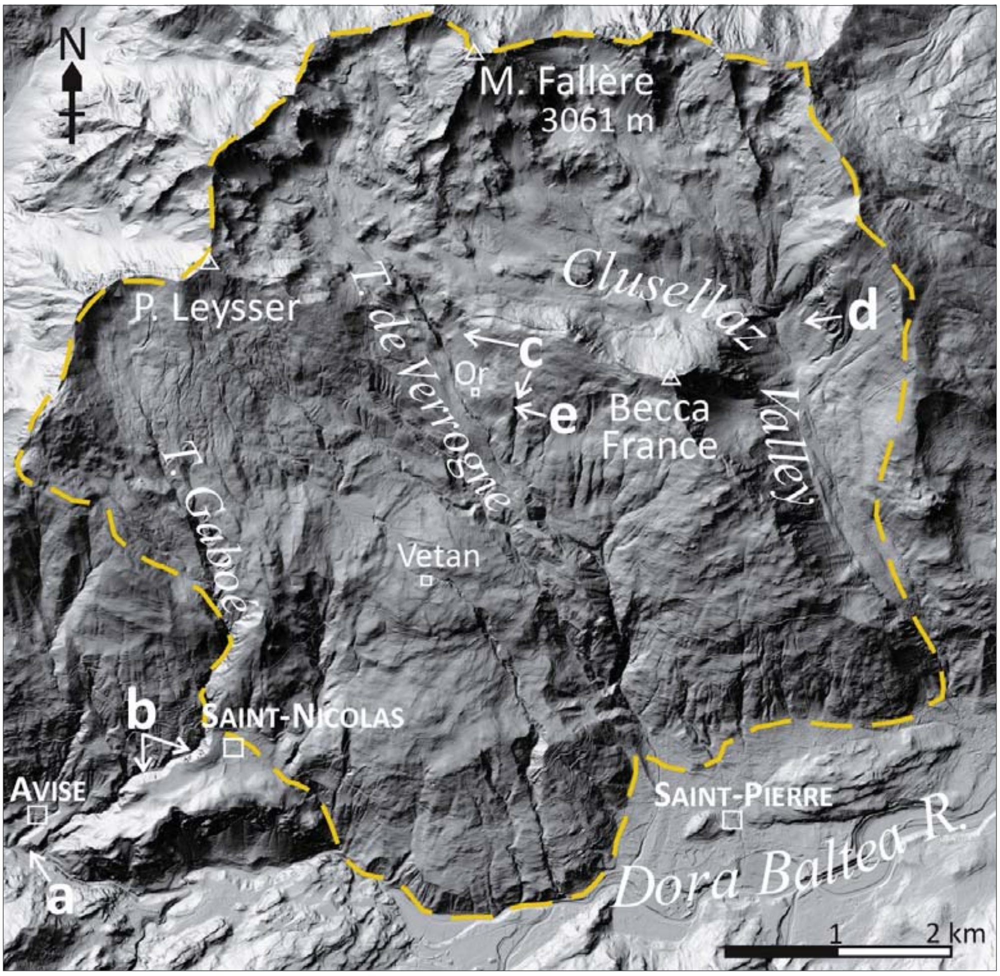

Fig. 4 - Topographic map of case study 3, located on the northern slope of the Aosta Valley in the P. Leysser DSGSD. Locations of the examples reported in the text: lacustrine sediments (a), subglacial sediments (b), debris (c), avalanche sediments (d) and colluvial (e). The yellow dotted line marks the edge of the investigated DSGSD area.

In contrast, the subglacial sediments (lodgement till) in the investigated DSGSD case studies usually show significantly less matrix (Fig. 5E), a greater abundance of various size clasts (Fig. 3D) and essentially angular clasts with the absence of faceted, polished and striated pebbles. Moreover, the clasts show a local and monotonous petrographic composition derived from the bedrock involved in DSGSD phenomena. The typical overconsolidation of subglacial sediments outside DSGSD areas is also less evident in DSGSD areas caused by the scarcity of the sandy-silt matrix. The prevalence of a coarse fraction in the matrix also leads to a greater permeability and consequent local carbonate cementation (Fig. 5D).

The peculiar features of the described subglacial sediments located in the Fallére southern slope (case study 3) (Fig. 5), referred to the late LGM, were already described as characterized by the prevailing presence of angular clasts made of local lithotypes (calcschist and marble) with abundant sandy-gravelly matrix. Subrounded allochthonous clasts are also present, but in lesser amount than usual glacial sediments (Polino et al., 2015 - Colle San Carlo Subsynthem).

4.2. Influences of DSGSDs on ice-marginal and supraglacial sediments

An exemplificative and well-exposed outcrop of ice-marginal and supraglacial sediments is located on the western slope of the Germanasca Valley, approximately 700 m SSE of Bergeria Balma along the T. Rodoretto tributary (case study 8) (b in Fig. 2). This outcrop is approximately 25 m wide and 30 m high (Fig. 6A), reaching the bedrock in its southern sector allowing to evaluate the overall thickness of these sediments of approximately 30 m and covered by colluvium in the lower band (Fig. 6B). These sediments crop out in the internal flank of the frontal-lateral sector of a right moraine.

The ice-marginal sediments are essentially formed by centimetric to decimetric clasts (the clast size essentially varies between 5 cm^3 to some dm^3) mixed in a sandy-silty matrix (Tab. 1) (Fig. 6C). The sediments also contain rare boulders up to 1 m^3 in size. The clasts display subangular to angular shapes (Fig. 6C) and have a monotonous petrographic composition exclusively

Fig. 5 - Glacial succession in the Gaboè Valley, SW Saint Nicolas (case study 3). A) The Gaboè Valley seen from the NW, characterized by evident badlands, entrenched in a Dora Baltea glacial valley floor (green valley). B) Succession of subglacial (lodgement till) (sg, dark grey) and cemented ice-marginal (im, yellow-grey) sediments; the regular morphology of a moraine is evident at the top of the sediments. C) Succession of well-stratified glaciolacustrine (gl) and overlying massive to stratified subglacial sediments (sg). D) Subglacial sediments formed by prevailing small subangular clasts mixed in a poor matrix. E) Details of the clast-rich subglacial sediments.

formed by calcschist and subordinate marble, representative of the local bedrock. Numerous clasts show arrangement towards the E (Fig. 6D), defining inclined bedding according to a right lateral moraine. The poor matrix (essentially ranging from 10% and 20%) is unsorted and rich in millimetric rock fragments with a very subordinate silty component (Fig. 6E). The sediments essentially have a matrix-supported texture and are normally consolidated and weakly cemented. The grey colour and the unweathered clasts also suggest a reference to the last glaciation.

The uncommon features of the ice-marginal and supraglacial sediments in the investigated DSGSD areas can be evidenced by comparing them with the same sediments outside DSGSD areas. These last areas typically have abundant large and giant boulders of various petrographic compositions (Dreimanis, 1988; Goldthwait & Matsch, 1988), although a remarkable

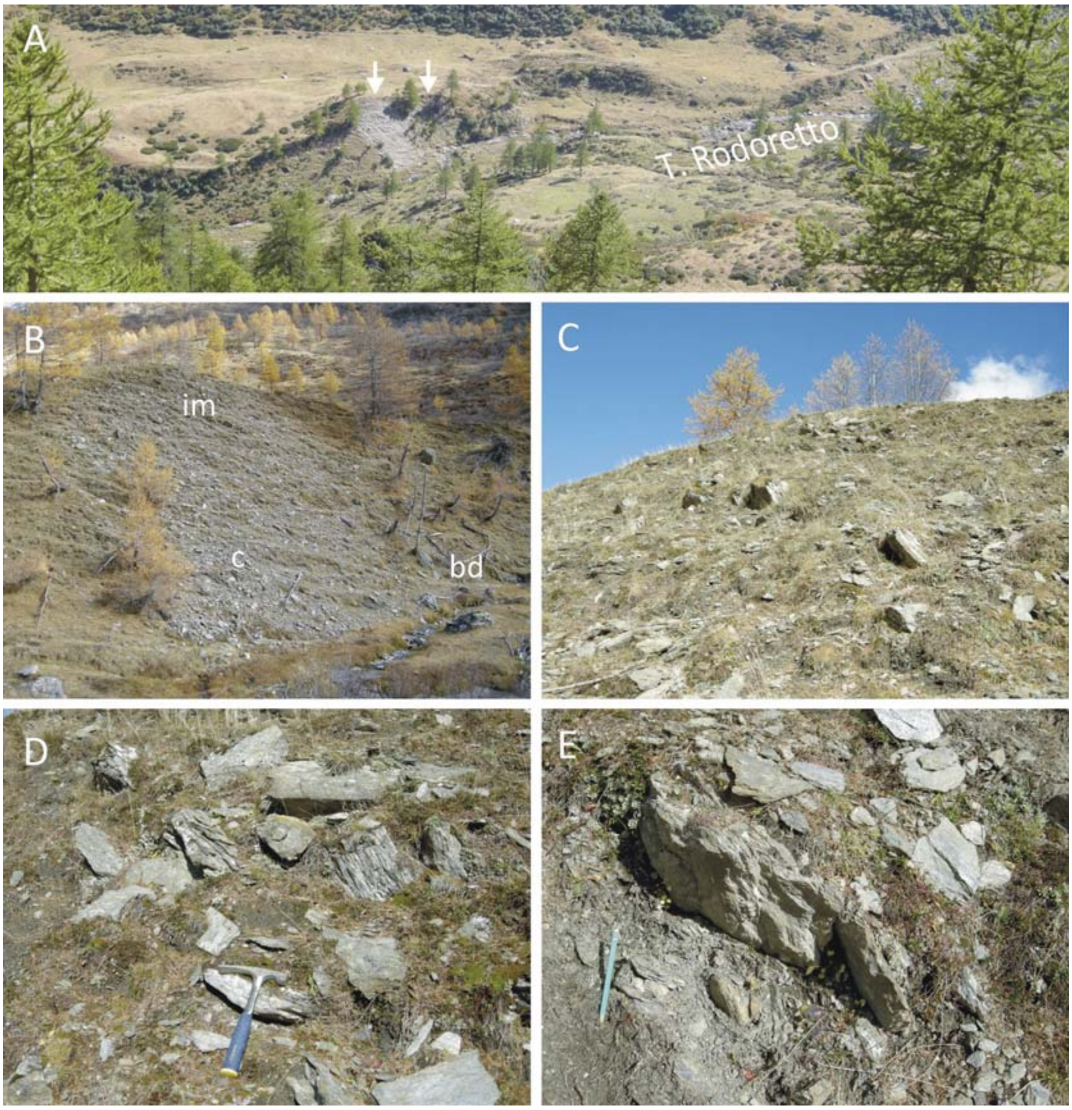

Fig. 6 - Outcrop of the ice-marginal sediments SSE of Bergeria Balma (case study 8). A) Panoramic view of the outcrop seen from the west: the morphology of a moraine is evident at the top of the sediments (white arrows indicate the moraine ridge). B) The upper part of the outcrop shows ice-marginal sediments (im) lying on the bedrock (bd), while these sediments are covered by colluvium in the lower band (c). C) Angular shape and arrangement of most clasts towards the east (right). D) Details of the abundant clasts. E) Poor amount of matrix.

local fraction can occur. Such boulders are defined as "erratic" and are essentially different than the local bedrock, possibly deriving from remote regions. Moreover, these sediments are also characterized by a large amount of sandy-silty matrix, often prevailing.

In contrast, the ice-marginal and supraglacial sediments in the DSGSD case studies show a scarcity of large boulders (Fig. 6A) caused by the extreme fracturing of the bedrock and a great abundance of millimetric-centimetric clasts. The petrographic composition, which is mainly local, represents another difference with analogous sediments outside DSGSD areas that can also contain many clasts of various lithotypes. The scarcity of matrix favours a carbonate cementation, which increases the differences with the ice-marginal and supraglacial facies outside DSGSD areas.

Carbonate fluids circulating in the ice-marginal sediments are recognized to promote their cementation and even deposition of travertine. Such fluids are common in DSGSD areas characterized by the presence of deeply fractured carbonate bedrock. As an example, the Fallére southern slope (case study 3) is characterized by a great concentration of travertine (Polino et al., 2015; Forno et al., 2016).

4.3. Influences of DSGSDs on torrential sediments

The best outcrop of torrential sediments is on the northern slope of the Aosta Valley, along the Dora Baltea fluvial incision into the wide La Salle fan (case study 2) (Fig. 7A). This outcrop, approximately 200 m wide and 30 m high, is covered by colluvium in the lower band. The typical flat morphology of a large alluvial fan,

Fig. 7 - Outcrop of the torrential sediments S of La Salle village (case study 2). A) Morphology of the wide La Salle alluvial fan, supplied by a small basin (a), view seen from the SW (outcrop indicated by the white arrow). The yellow dotted line marks the edge of the DSGSD area. B) Subangular shape of most clasts forming torrential sediments mixed in an abundant matrix. C) Details of the not very evident inverse graded bedding.

despite being supplied by the small d'Echarlod basin, develops at the top of sediments (Fig. 7A).

The torrential sediments are essentially formed by centimetric to decimetric clasts (the clast size varies between 5 cm^3 to some dm^3) mixed to an abundant matrix (Tab. 1) (Fig. 7B). The clasts have subangular shapes with smooth edges (Fig. 7B) and a petrographic composition exclusively formed by gneiss, grey marble, micaschist, graphitic schist and quartzite, representative of the catchment basin bedrock. The clasts define an inverse graded bedding (Fig. 7C), despite not being evident, suggesting an environment also fed by debris-flow phenomena. The relatively abundant matrix, essentially ranging from 20% to 30%, is partly formed by millimetric rock clasts with a subordinate unsorted sandy component. The dark grey colour of the matrix is essentially due to the remarkable graphitic schist component (Fig. 7C). These sediments essentially have a matrix-supported texture, appearing normally consolidated and weakly cemented.

The peculiar features of the torrential sediments in the investigated DSGSD areas can be highlighted by comparing them with torrential sediments outside DSGSD areas, which usually have abundant rounded to subrounded pebbles and cobbles, centimetric to decimetric in size, mixed in a poor sorted, sandy matrix defining a clast-supported texture (Thorne et al., 1987). Moreover, the torrential sediments show evident cross-bedding with local imbricate clasts.

In contrast, the torrential sediments in the DSGSD case studies show a scarcity of rounded pebbles and cobbles (Fig. 7B). These sediments are characterized by relatively few sub-angular decimetric clasts, a great abundance of millimetric-centimetric angular clasts and sandy matrix, which also favour carbonate cementation. The scarcity of coarse-grained clasts determines the lack of evident bedding and the texture between clast-supported and matrix-supported.

4.4. Influences of DSGSDs on debris (scree)

The debris in the DSGSD investigated case studies shows some differences compared to the debris outside DSGSD areas. An approximately 300 m wide and 100 m high outcrop of these sediments (Fig. 8A) is located on

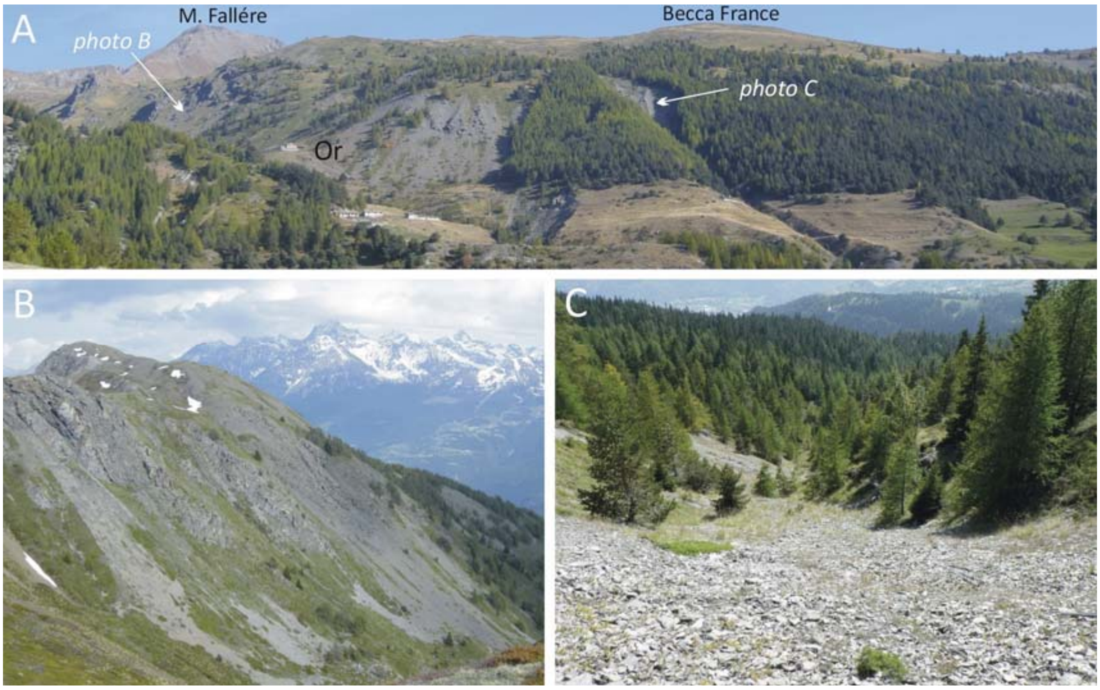

Fig. 8 - Outcrop of the debris NW of Verrogne village (case study 3). A) Panoramic view of the slope seen from the south. B) Morphology of the slope at the top of the sediments, consisting of a debris talus, seen from the west. C) Angular tabular shape of centimetric clasts forming the debris.

the northern slope of the Aosta Valley along the T. Verrogne tributary, 2 km NW of Verrogne village (case study 3) (c in Fig. 4). The topographic surface at the top of the outcrop shows a regular SW-sloping morphology, according to a talus slope (Fig. 8B).

The outcropping debris is formed by centimetric clasts, with rare decimetric elements (Tab. 1) (Fig. 8C). The clasts and millimetric fragments are angular and essentially display an irregular tabular shape and have a monotonous petrographic composition, formed by prevailing calcschist with rare quartzite, strictly depending on the composition of the upper slope. The debris is characterized by an open texture and structures ranging from a massive to an inclined bedding and appears unconsolidated and locally cemented. The large calcschist component determines the grey colour of the sediments.

The increasing of potential debris and small rockfalls also highlighted in the Cenischia Valley, especially in the uppermost sectors of the catchments, was connected to the presence of well-developed DSGSD resulted in producing debris and torrential deposits up to dozens of meter thick (Coviello et al., 2015).

The debris in the investigated DSGSD areas is usually formed by centimetric clasts, whereas outside DSGSD areas, debris is usually decimetric in size (Tab. 1).

4.5. Influences of DSGSDs on lacustrine sediments

A significant outcrop of lacustrine sediments in the DSGSD areas is located on the northern slope of the Aosta Valley, 150 m SE of Avise village, at the confluence between the Dora Baltea incision and its northern tributary (Gaboè R.) (case study 3) (a in Fig. 4). This outcrop is exposed in the deep incision due to the current hydrographic network (Dora Riparia and Gaboè rivers), with a depth of approximately 45 m (Fig. 9B). The top of the outcrop shows S-sloping flat morphology entrenched in the Gaboè R. incision, suggesting a torrential fan of this watercourse (Fig. 9A).

This outcrop, approximately 40 m high and 200 m long, allows the observation of a succession of three overlapping sedimentary bodies, a glaciolacustrine body (27 m of visible thickness), a lacustrine body (5 m thick) and an alluvial body (6 m thick) (Fig. 9B). The lower and the upper bodies contain clasts of various petrographic compositions (comprising the Monte Bianco granite) referred to the Dora Baltea Valley (interpreted as directly supplied by the Dora Baltea Valley for the lower body and as reworked glacial Dora Baltea sediments for the upper body) and therefore are essentially not connected with DSGSD areas. The intermediate body is, on the contrary, rich in local clasts, suggesting an exclusively local supply by the Gaboè basin, developed into the P. Leysser DSGSD. Therefore, it can be used as an example of lacustrine sediments supplied by a DSGSD area.

The lacustrine body has a basal surface consisting of a weakly N-dipping concave erosional surface, with a counter-slope trend (Fig. 9D). These sediments are formed by centimetric to decimetric clasts (the size essentially varies between a few cm^3 to a few dm^3) mixed in an abundant unsorted matrix, mainly comprising millimetric angular tabular rock fragments and a poor sandy-silty component (Tab. 1) (Fig. 9C). The clasts essentially are subangular to subrounded (Fig. 9E) and have a monotonous petrographic composition, formed by prevail-

Fig. 9 - Outcrop of the lacustrine sediments 150 m SE of Avise village (case study 3). A) The top of succession, seen from the west, shows an alluvial fan typical morphology (arrow indicates the outcrop). B) A succession, seen from the south, of Dora Baltea glaciolacustrine (Dgl), Gaboè R. lacustrine (Gl) and alluvial (Ga) bodies. C) Details of the sedimentary succession. D) Basal surface of lacustrine sediments (Gl). E) Relatively coarse-grained facies of the Gaboè lacustrine sediments formed by angular clasts mixed in a sandy matrix of dark grey colour.

ing calcschist with rare prasinite and quartzite, representative of the local bedrock of the Gaboè Basin. These sediments have matrix-supported texture and bedding weakly inclined towards the south, according to a foreset body deposited in a lacustrine environment, defined by alternating clast-rich and matrix-rich levels. The sediments also appear normally consolidated and have a dark grey colour, resulting from the large calcschist component (Fig. 9E).

The uncommon features of the lacustrine sediments in the investigated DSGSD areas can be evidenced by comparing them with the same sediments outside DSGSD areas that are usually fine-grained and frequently have a sandy-silty texture, as well as a more varied petrographic composition and high roundness of clasts.

In contrast, the lacustrine sediments in the DSGSD case studies are essentially gravel with a great abundance of millimetric angular tabular rock fragments and various amounts of sandy-silty matrix.

4.6. Influences of DSGSDs on colluvial sediments

A valuable outcrop of colluvial sediments, approximately 50 m wide and 3 m high (along an erosional scarp), is located on the northern slope of the Aosta Valley along the T. Verrogne tributary, 2 km NW of Ver-

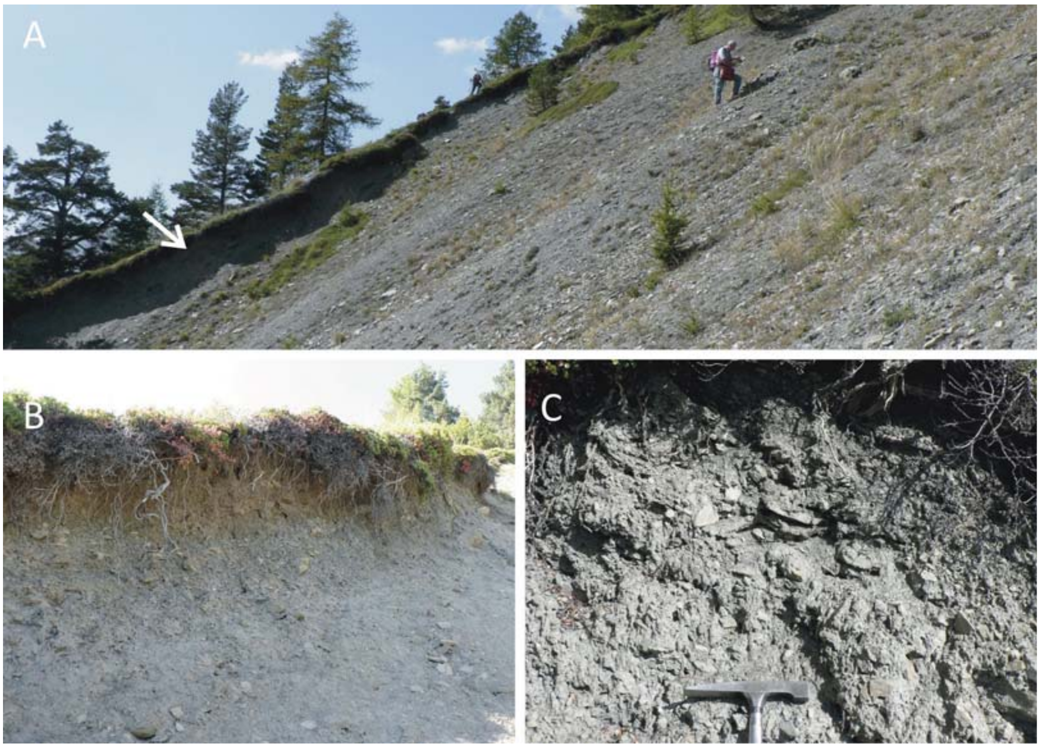

Fig. 10 - Outcrop of the colluvial sediments NW of the Verrogne village (case study 3). A) View of the outcrop (arrow) seen from the east and morphology of the slope at the top of the sediments. B) Facies of the grey investigated colluvial sediments and of the brown colluvial sediments deriving from reworking of glacial sediments. C) Details of angular tabular centimetric clasts mixed in a subordinate matrix.

rogne village (case study 3) (e in Fig. 4). The top of the outcrop, which is characterized by a brown cover of other colluvial sediments, likely reworked glacial sediments, shows a regular S-sloping morphology (Fig. 10A).

The outcropping colluvial sediments, at least 2-3 m thick (Fig. 10B), are formed by small clasts mixed in a matrix rich in millimetric rock fragments (Tab. 1) (Fig. 10C). The clasts, essentially centimetric in size with rare decimetric elements, and millimetric fragments of the matrix are angular and have an irregular tabular shape. The clasts and fragments have a monotonous petrographic composition, with prevailing calcschist and rare quartzite, strictly depending on the lithology of the upper slope. The colluvial sediments are characterized by a clast- to matrix-supported texture and structures ranging from massive to inclined bedding according to the slope. The sediments appear unconsolidated, locally cemented and of grey colour connected to their petrographic composition.

The colluvial sediments in the investigated DSGSD areas have partly uncommon features with respect to the same sediments outside DSGSD areas, which usually consist of sand, slightly gravelly and silty, with rare clasts and evident matrix-supported textures. In contrast, the colluvial sediments in the DSGSD case studies are silty sandy gravel formed by prevailing centimetric angular clasts of local petrography. The poor unsorted matrix (mainly formed by angular tabular millimetric fragments) is responsible for the various textures, i.e., matrix or clast-supported.

4.7. Influences of DSGSDs on avalanche sediments

A well-exposed outcrop of avalanche sediments (Fig 11A) is located on the northern slope of the Aosta Valley, 3 km NNW of the Sarre village, along the upstream scarp of a mountain pasture road in the tributary Clusellaz Valley (case study 3) (d in Fig. 4). The topographic surface at the top of the outcrop shows a regular SW-sloping morphology, according to a T. Clusellaz avalanche fan (Fig. 11A). This outcrop, which is approximately 12 m high and 60 m long, allows the observation of a succession of two sedimentary bodies, a low subglacial (5 m of visible thickness) and an upper avalanche body (7 m thick) (Fig. 11B).

In detail, the lower body contains clasts of a various petrographic compositions referred to the Dora Baltea Valley and is therefore essentially not connected with DSGSD areas. The upper body is, on the contrary, rich in local clasts, suggesting an exclusive supply by the Clusellaz basin developed into the P. Leysser DSGSD, and it can be used as an example of avalanche sediments supplied by a DSGSD area.

The avalanche body has a basal surface consisting of a convex surface in the cross-section, visible along the road scarp, connected with a previous ridge shaped in the subglacial sediments (Fig. 11B). The avalanche sediments are formed by centimetric to decimetric clasts (the clast size essentially varies between some cm^3 to some dm^3) mixed in a poor unsorted matrix, essentially formed by millimetric angular tabular rock fragments and a scarce sandy-silty component (Tab. 1) (Fig. 11B). The clasts essentially have angular to subangular shapes

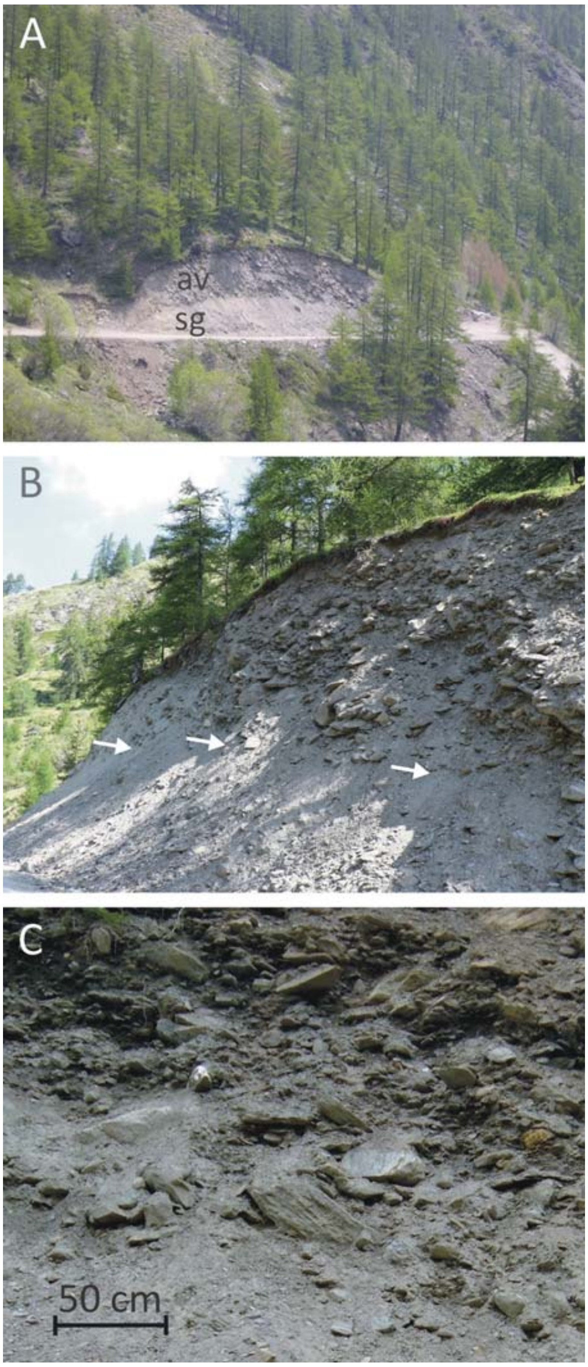

Fig. 11 - Wide outcrop 3 km NNW of Sarre village (case study 3). A) Succession of subglacial (sg) and avalanche (av) sediments. This last body forms an extended avalanche fan. B) Basal surface of avalanche sediments (arrows) that cover a glacial ridge. C) Detail of coarse grained facies of the avalanche body visible above the subglacial sediments.

(Fig. 11C) and a monotonous petrographic composition (prevailing calcschist and prasinite with rare quartzite and cellular dolomite) representative of the local bedrock outcropping on the upper slope. These sediments have a clast-supported texture and 20° SW dipping bedding, according to the fan surface and defining a body deposited in an avalanche environment. The sediments, which have a grey colour, also appear normally consolidated and weakly cemented.

The partly uncommon features of the avalanche sediments in the investigated DSGSD areas can be evaluated by comparing them with the avalanche sediments outside DSGSD areas, which are usually matrix-rich with subordinate clasts, defining a matrix-supported texture. In contrast, the avalanche sediments in the DSGSD case studies consist of centimetric up to decimetric angular clasts of local lithotypes with a poor matrix containing millimetric angular tabular rock fragments, forming a clast-supported texture (Jomelli & Francou, 2000; Luckman et al., 1977; Matthews et al., 2011).

5. DISCUSSION

The various facies observed in the investigated DSGSD cases show sedimentological features that are partly very different and partly common to those outside DSGSD areas regarding the grain size, clast shape and roundness, clast abundance and petrographic composition and the amount and texture of the matrix (Tab. 1).

Regarding the anomalous features in the investigated case studies, the subglacial facies is characterized by the great abundance of small subangular to angular clasts mixed in a matrix mainly formed by millimetric rock fragments, resulting in a coarse-grained texture. This lithofacies is very different compared to that of traditional subglacial sediments (outside DSGSD areas), which are characterized by an essentially fine texture, with a prevailing fine sandy-silty matrix, and subrounded, smoothed, polished and striated pebbles.

Additionally, the ice-marginal sediments have a peculiar texture in the investigated case studies with an abundance of millimetric to metric fragments, scarcity of fine sand and silt in the matrix and absence or rareness of large boulders (larger than metric in size). These characteristics are unusual compared to those of traditional ice-marginal sediments outside DSGSD areas, which generally have many large boulders and an abundant fine matrix.

The occurrence of many small angular rocky fragments of local lithotypes also characterizes the colluvial, avalanche, lacustrine and debris sediments outcropping in the investigated DSGSD areas, which are partly coarser than traditional sediments (colluvial, avalanche, lacustrine) or finer (debris) than traditional sediments.

Finally, the prevalence of small angular rock fragments is observed in DSGSD examples both in the cases in which the traditional sediments are usually fine (subglacial and lacustrine sediments) and in the cases in which the sediments usually contain very large boulders (ice-marginal sediments).

This look can be the consequence of high bedrock fracturing despite the fractures not being homogenously distributed throughout the whole rock volume, which has both highly fractured and completely loosened sectors (Fig. 12). This conclusion applies only for DSGSDs that evolved before or at the same time as the deposition of Quaternary successions, which are therefore fed by fractured bedrock, while gravitational phenomena that

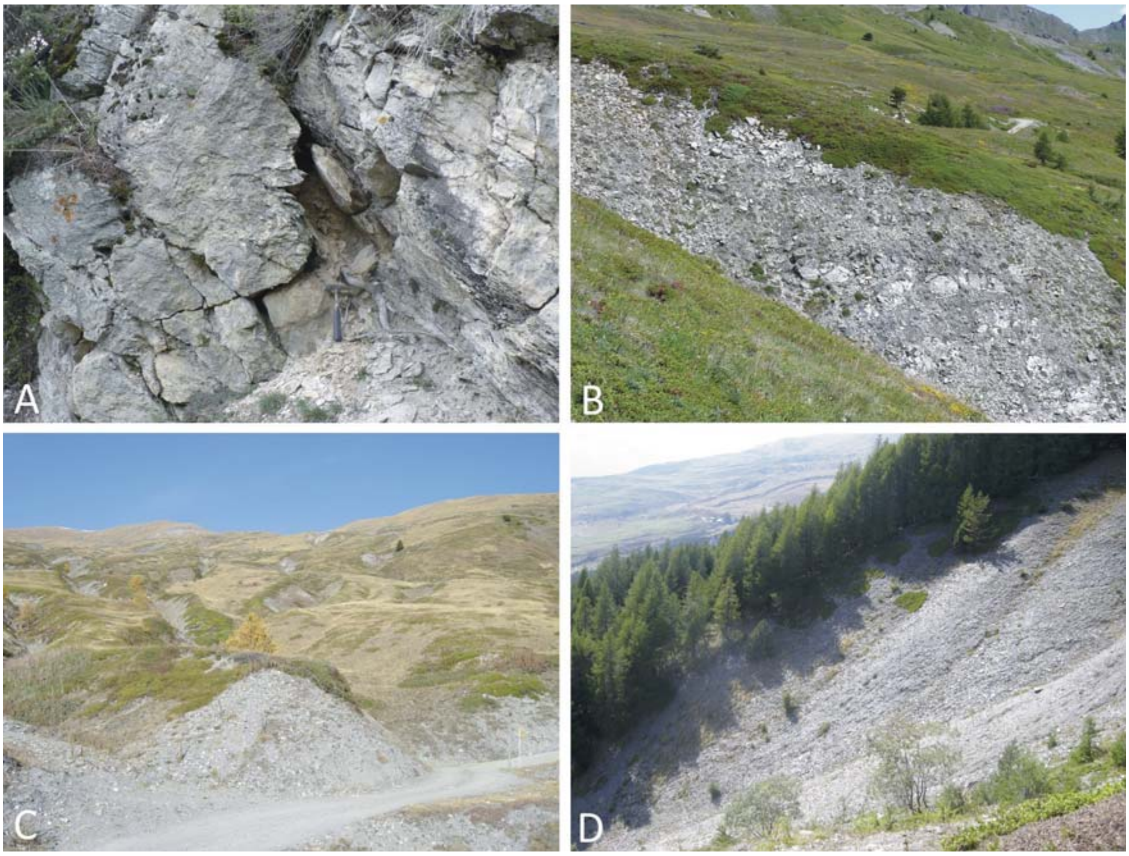

Fig. 12 - Various fracturing of the bedrock in DSGSD areas. Fractured (A, Moncellier, case study 6) or completely loosened bedrock (B, Or village on the Fallére southern slope, case study 3). The fractured bedrock can simulate ice-marginal sediments forming a moraine (C) or debris (D) (western side of the Becca France ridge, on the Fallére southern slope, Dora Baltea Valley, case study 3).

evolved subsequently do not affect the sedimentary features but only dislocate and deform the geological bodies, influencing their distribution and conservation degree.

Fracturing and slackening cause a downgrading of the geo-mechanical properties of the bedrock, favouring the high production of angular rock fragments of local lithotypes. The fragments usually have flattened shapes in loosened schistose rocks, which are the prevalent lithotypes in the study area. It should be emphasized that a fractured bedrock is not exclusive to DSGSDs and can also derive from a strong tectonization linked to a brittle deformation zone.

Furthermore, the production of small rock fragments can be favoured by the occurrence of many gravitational morpho-structures, which are mainly represented by steep rock walls along minor scarps and elongated depressions corresponding to trenches. These slope irregularities favour their strong erosion by various exogenous agents. The removal of bedrock fragments is essentially due to glaciers, during glacial phases, and to watercourses, running water, snow avalanches and gravity during the post-glacial period. Moreover, the morphological renewal of these walls, linked to the progressive reactivation of morpho-structures, further increases the availability of centimetric rock fragments.

Another significant feature of the sediments in the studied DSGSD areas is the monotonous petrographic composition of most of the clasts caused by a prevailing local supply. This composition differs especially for glacial sediments with respect to that of traditional facies (outside DSGSD areas), which are usually rich in various lithotypes representative of the entire glacial basin, although the local component can sometimes be significant for ice-marginal sediments or near the bottom for subglacial sediments. However, if the glacier or the watercourse has a basin upstream of the DSGSD areas, some subordinate allochthonous clasts can be present.

The abundance of rock fragments in the DSGSD examples can also promote high permeability in the sediments and consequent carbonate cementation due to the various contents of $CaCO_3$ in water, depending on bedrock composition. In contrast, in traditional sediments outside DSGSD areas, carbonate cementation can be hindered by normal abundance of silty matrix.

The high fracturing of bedrock in DSGSDs produces large sectors with juxtaposed centimetric angular fragments that can be confused with Quaternary sediments (Fig. 12C). For example, the loosened bedrock can be, at first glance, totally mistaken as debris, despite the absence of a source upstream (Fig. 12D). More accurate observations indicate that the foliation inside individual fragments appears prevalently aligned with the regional schistosity and that all fragments have the

sediment facies in mountain areas	*type of sedimentological features*	*sedimentological features within DSGSD areas*	*traditional sedimentological features outside DSGSD areas*
subglacial (lodgement till)	*grain size*	sandy-silty gravel	weakly gravelly sand and silt
	clast volume	centimetric to metric	centimetric to decimetric
	clast roundness	subangular and angular	subangular and subrounded
	typical clasts	/	smoothed, polished and striated pebbles
	clast petrography	mainly local	various
	matrix	scarce unsorted rich in millimetric rock fragments	abundant unsorted sandy silt
	texture	matrix-supported	matrix-supported
	structure	massive	
	consolidation	highly consolidated	overconsolidated
	cementation	locally cemented	uncemented
ice-marginal and supraglacial	*grain size*	silty-sandy gravel with rare boulders	silty-sandy gravel with many large boulders
	clast volume	centimetric to metric	centimetric to thousands of cubic metres
	clast roundness	subangular to angular	subangular
	typical clasts	/	smoothed
	clast petrography	mainly local	local or various
	matrix	very scarce and rich in millimetric rock fragments	abundant unsorted silty sand
	texture	matrix to clast-supported	mainly matrix-supported
	structure	inclined bedded or massive	
	consolidation	normally-consolidated	
	cementation	cemented	locally cemented
torrential	*grain size*	sandy gravel	gravel
	clast volume	millimetric to decimetric	essentially decimetric
	clast roundness	subangular to angular	rounded to subrounded
	clast petrography	representative of the catchment basin	representative of the catchment basin
	matrix	abundant and rich in millimetric rock fragments	scarce well-sorted medium to coarse sand
	texture	matrix to clast-supported	clast-supported
	structure	massive bedded	trough cross-bedded
	consolidation	normally-consolidated	
	cementation	locally cemented	
debris	*grain size*	gravel	
	clast volume	mainly centimetric	mainly decimetric
	clast roundness	angular	
	clast petrography	monotonous, representative of the upper slope	
	matrix	/	
	texture	open	
	structure	massive or inclined bedded	
	consolidation	unconsolidated	
	cementation	locally cemented	
lacustrine	*grain size*	sandy-silty gravel	sand and silt
	clast volume	centimetric	/
	clast roundness	angular	/
	clast petrography	mainly local	/
	matrix	abundant, rich in millimetric rock fragments	/
	texture	matrix-supported	/
	structure	plane-parallel bedded	
	consolidation	unconsolidated	
	cementation	locally cemented	uncemented
colluvial	*grain size*	silty sandy gravel	weakly gravelly silty sand
	clast volume	centimetric	centimetric to decimetric
	clast roundness	mainly angular	
	clast petrography	local	
	matrix	scarce unsorted weakly clayey silty sand	abundant unsorted weakly clayey silty sand
	texture	matrix to clast-supported	matrix-supported
	structure	weakly inclined bedded	
	consolidation	unconsolidated	
	cementation	locally cemented	
avalanche	*grain size*	sandy-silty gravel	weakly gravelly silty sand
	clast volume	centimetric to decimetric	
	clast roundness	angular to subangular	
	clast petrography	representative of the upper slope	
	matrix	scarce unsorted weakly clayey silty sand	abundant unsorted weakly clayey silty sand
	texture	clast-supported	matrix-supported
	structure	weakly inclined bedded	
	consolidation	unconsolidated	
	cementation	locally cemented	

Tab. 1 - Sedimentological features of the different facies of Quaternary sediments in the mountain areas.

same attitude of schistosity. Consequently, these fractured patches are directly shaped in the bedrock and can be considered "in situ" (Fig. 12C).

This research started to solve well-known difficulties in the survey and mapping of Quaternary successions in DSGSD areas of the Western Alps since the uncommon facies of some sediments in these areas can hinder their identification. In detail, recognizing the sediments as such is often hard in this context because the sediments can sometimes be confused with loosened bedrock and it is difficult to distinguish between the different types of sediments. For example, subrounded faceted pebbles formed by allochthon lithotypes, which normally characterize subglacial sediments, do not occur, and consequently, these sediments cannot be recognized and mapped. Loosened bedrock or soils or colluvia connected to bedrock weathering/reworking are alternatively reported (for example Carraro et al., 2002; Polino et al., 2002). Consequently, some DSGSD areas seem strangely poor in Quaternary sediments, while the extreme fracturing of bedrock should have favoured the deposition of surficial sediments (Forno et al., 2016).

6. CONCLUSIONS

This research derives from extensive field experience in the survey of Quaternary continental successions in the Western Alps. Some case studies suggest that the Quaternary sediments located in DSGSD areas are often unusual and partly different from their analogues in successions outside DSGSD areas. The sediments in the reported examples proved to be strongly enriched in centimetric angular rock fragments, their presence being promoted by the high degree of rock fracturing and the numerous gravitational scarps typical of DSGSD areas.

The differences between the sedimentological features observed in the investigated case studies and those outside DSGSD areas vary according to the depositional environment. Debris, avalanche and torrential sediments, which are typically made of angular clasts, show almost equal facies both inside and outside DSGSD areas. In contrast, sediments that are normally fine (i.e., subglacial, colluvial and lacustrine deposits) or very coarse (i.e., glacial deposits) show low textural variability inside the DSGSD area, giving rise to a sort of "facies convergence".

This research is based on case studies from the western sector of the Alps, where the geological context, climate and morphology are relatively homogeneous. Although the presented considerations need to be confirmed in different settings, before extending them to other sectors of the Alps or to other mountain ranges, geologists working on Quaternary successions in Alpine areas should be aware that the facies of deposits located in DSGSD areas can differ from those normally found. This paper can be a useful tool to avoid misinterpretations of these deposits using only sedimentological features, regardless of their morphological expression.

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