Impact of massive deep-seated rock slope failures on mountain valley morphology in the northern Cottian Alps (NW Italy)

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ABSTRACT
Deep-seated rock slope failures represent effective mechanisms of natural rock mass-wasting, able to radically change mountain-valley morphology. In the northern Cottian Alps, an extraordinary concentration of instability phenomena occurs in extensive areas of the Susa and Chisone valleys. In the Main Map, at a scale of 1:30,000, a new representation of these deep-seated rock slope failures is proposed. Major effort has been invested in properly distinguishing between sackung-type deep-seated gravitational slope deformations and large landslides. Gravitational phenomena have affected the mountain landscape, with the development of impressive morphostructural features such as multiple-crested ridges and ridge top depressions. In the middle and distal portions of the slopes, sagging and toe bulging impose a marked change in the valley-slope profiles, in turn inducing secondary slope instabilities. Furthermore, mature deep-seated gravitational deformations and large landslides have, in some cases, made a significant impact on valley bottom morphology due to a partial or complete valley dam.

1. Introduction

Due to the large volumes involved and their kinematics, massive rock slope failures such as deep-seated gravitational slope deformations (DSGSDs) and large landslides represent effective mechanisms of natural rock mass-wasting, and can dramatically influence mountain-valley morphology, on a long-term basis and at a large scale. These instability phenomena can affect the mountain landscape in different ways:

- with the development of impressive linear morphostructural features such as multiple-crested ridges, uphill- and downhill-facing scarps, trenches and ridge top depressions (Agliardi, Zanchi, & Crosta, 2009; Crosta, 1996; Li, Bruhn, Pavlis, Vorkink, & Zeng, 2010);
- imposing a marked change in the valley-slope profiles due to sagging and toe bulging (Hewitt, Clague, & Orwin, 2008) that, in turn, induce secondary slope instabilities;
- causing valley obstructions (Evans et al., 2006; Schuster, 2006) and controlling the downstream transport of sediments (Fort et al., 2009; Korup, Strom, & Weidinger, 2006), sometimes resulting in complete stream blockage and the development of lakes that act as sedimentary traps;
- influencing the drainage network and changing the flow paths and the hydrogeochemical characteristics of groundwater due to the dilatancy of the involved rocks (Binet, Guglielmi, Bertrand, & Mudry, 2007; Bogaard et al., 2007; Madritsch & Millen, 2007).

Although deep-seated rock slope failures are widespread throughout the Alps (Crosta, Frattini, & Agliardi, 2013), the upper Susa and Chisone valleys (northern Cottian Alps) represent a peculiarity in the alpine landscape because of their extraordinary concentration. They are caused by a specific combination of many predisposing factors such as lithology (Mortara & Sorzana, 1987), structural setting (Giardino & Polino, 1997), glacial and post-glacial geomorphological history (Polino, Borghi, Carraro, Dela Pierre, Fioraso, & Giardino, 2002), local topographic factors, groundwater conditions and seismicity (Perrone, Eva, Cadoppi, Solarino, & Fioraso, 2011). Since the end of the Last Glacial Maximum (LGM), widespread deep-seated mass movements have changed the slope morphology and influenced the fluvial and torrent processes, sometimes imposing a drastic control in the transport and deposition of sediments.

As demonstrated by monitoring systems, there are presently a significant number of deep-seated instability phenomena that are affected by slow (<10 mm/yr) but continuous movements, sometimes with sudden accelerations soon after severe rainstorms and rapid snowmelt (i.e. the reactivation of the Cassas and Serre la Voute complex landslides, in the Susa Valley, which took place in June 1957; Forlati et al., 2004).
These slow movements resulted in the gradual, non-catastrophic damage of anthropic structures and linear infrastructure including human settlements (Alberto, Carraro, & Giardino, 2008; Fioraso, Tararbra, & Negro, 2010), highway tunnels (Ceccucci, Maranto & Mastroviti, 2008) and roads.

In this article, new detailed mapping of deep-seated instability phenomena in the upper Susa and Chisone valleys is presented. Much effort has been made to distinguish between DSGSDs and classical landslides, not always clearly understood in the previously available national inventories, namely the SIFRAP Project of the Agency for the Protection of the Environment of the Piemonte Region (http://webgis.arpa.piemonte.it/flxview/GeoViewerArpa/) and the IFFI Project of the Italian National Institute for Environmental Protection and Research (http://www.progettoiffi.isprambiente.it/cartanetiffi/). Particular attention was paid to map, in detail, surface gravitational phenomena related to deep-seated rock creep, and to highlight the impact of instability phenomena on river dynamics and valley bottom morphologies.

2. Methods

The Main Map, at a scale of 1:30,000, encompasses an area of 458 km² across the upper Susa and Chisone valleys in the northern Cottian Alps (Figure 1). Geological data were collected by original field work performed at a scale of 1:10,000 and integrated with geomorphological analysis carried out using photointerpretation of multi-temporal aerial images (1979–1980 photos 1:13,000 scale; 2000 photos 1:15,000/1:19,000 scale) of the Piemonte Region. In the map, DSGSDs, landslide accumulations and the related morphological features are shown. In addition, some glacial and post-glacial features (primarily alluvial, debris flow and lacustrine deposits) involved in slope collapses have been represented. The geological and structural setting of the bedrock is summarized in the accompanying tectonic sketch map at a scale of 1:82,000.

In order to better understand the deep-seated mechanisms of gravitational phenomena, 446 stratigraphic logs of drillholes and water wells (up to 460 m deep) were collected and analyzed (in the Main Map only those deeper than 30 m are represented). In some cases, the examination of rock cores allowed in-depth investigation of the litho-structural characteristics of the rock masses involved in the landslides and identification of rupture surfaces. The presence of many monitored landslides with inclinometer systems, as well as global positioning system networks, has allowed the detection of the active sliding surfaces. All field data are stored in a comprehensive database (Coordinate System WGS 1984 UTM Zone 32N), and represented on a vector topographic map derived from the Carta Tecnica Regionale Numerica at a scale of 1:10,000 of the Regione Piemonte and exported into editing software for final graphical output.

3. Geological and geomorphological setting

In the investigated area, a complex mosaic of tectonostratigraphic units of different paleogeographic origins, related to the Pennidic System, crops out (Cadoppi et al., 2002; Polino, Borghi, Carraro, Dela Pierre, Fioraso, Gattiglio, et al., 2002b) (see the tectonic sketch map in the Main Map) resulting in:

- oceanic units, made up mostly of pillow-basalts, gabros and serpentinitized peridotites (Chenaille unit), calcscists, micaceous marble and phyllites with intercalations of quartzites and masses of metabasites and serpentinites (Lago Nero, Albergien, Pelvo and Susa-Lanzo-Orsiera units);
- ophiolitic units, made up of monotonous calcscists with intercalations of micaceous quartzites, micaschists, marble, phyllitic calcscists and huge bodies of serpentinites and serpentine schists (Aigle, Vin Vert and Cerogne-Ciantiplagna units);
- incertae sedis units, made up of calcscists and subordinated quartzites, micaschists and intercalations of dolomitic marble (Puy, Venaus and Fenestrelle units);
- continental margin units, represented by a metamorphic basement (micaschists, quartzites, gneisses, orthogneisses and metaconglomerates of the Ambin unit), the related sedimentary cover (quartzites, marble and calcscists), the carbonatic successions of the Gad and Chaberton units (limestones, dolostones and calcareous schists) and the metasedimentary successions of the Valfredda and Vallonetto units (quartzites, carbonatic schists, marble, phyllites and calcscists).

In the upper Susa and Chisone valleys, major thrust faults juxtapose each other some oceanic (e.g. the Lago Nero unit), ophiolitic (e.g. the Cerogne-Ciantiplagna unit) and continental margin units (e.g. the Ambin unit). Tectonostratigraphic units are also bordered and/or crossed by sub-vertical post-metamorphic fault systems (Polino et al., 2002b):

- the NE–SW striking fault system, corresponding to several sub-parallel faults up to 20–25 km long and usually steeply dipping;
- the WNW–ESE fault system, well represented on the left side of the Susa Valley;
- the NNW–SSE system, well developed in the area SE of the South Chenaille Fault, corresponding to sub-parallel hectometric-to-kilometric faults and fracture zones.

In some places, huge masses of gypsum and/or anhydrite associated with carbonatic breccia and
involved in deep-seated dissolution are pinched out along tectonic discontinuities (e.g. the Gran Roc Fault).

In the northern Cottian Alps, major tectonic features have exerted a strong influence on the drainage network and slope morphology: sub-vertical NE–SW and NNW–SSE fault systems control the rectilinear pattern of the Dora Riparia and Chisone rivers and their tributaries, sometimes arranged in an almost orthogonal pattern; in the outcrop area of the Alber- gian unit, the presence of low-angle (20–35°) south-westward-dipping shear zones parallel to the regional foliation has imposed a cuesta morphology, giving rise to an asymmetrical cross profile of valley flanks. In the study area, altitudes range between 870 m (Exilles) and 3280 m a.s.l. (Punta Rognosa), with slope heights that can reach up to 2000 m. Diffuse landforms and sediments are indicative of the intensity of the glacial action that took place in the Late Pleistocene (Polino et al., 2002b). The geological activity accomplished by the Dora Riparia and Chisone glaciers includes scouring and overdeepening of valley bottoms, resulting in an increase of relief and, in turn, in the widespread disequilibrium of rock slopes soon after their rapid shrinkage. This has allowed the development of extensive instability phenomena at the expense of steep glacial-carved mountain slopes, such as translational and complex rock slides (Alberto et al., 2008; Fioraso, Baggio, Bonadeo, & Brunamonte, 2011; Forlati et al., 2004), rock falls, rock avalanches (Fioraso & Baggio, 2013) and DSGSDs (Fioraso et al., 2010;

Figure 1. Structural sketch map of the Western Alps (modified from Bigi et al., 1990). The red inset shows the area represented in the Main Map.
Mortara & Sorzana, 1987; Puma, Ramasco, Stoppa, & Susella, 1989).

4. Type and distribution of deep-seated rock slope failures

Due to the lithological and structural complexity of the investigated area, deep-seated rock slope failures are characterized by an extreme variability in terms of kinematics, size of the rock masses involved, morphostructural features and rate of movements. Since many large, complex landslides represent the progressive and sometimes extreme evolution of DSGSDs, particular attention has been paid to the attribution of each single gravitational phenomenon to a specific type: DSGSD or landslide. For this purpose, in the Main Map these two end members have been distinguished according to the presence or absence, respectively, of a continuous, morphologically evident failure surface (or rupture zone) that separates the collapsed rock volume from the undeformed bedrock (Dramis & Sorriso-Valvo, 1994; Sorriso-Valvo, 1995). This distinction is not always straightforward due to dense vegetation cover and dissection of ancient landslide accumulations by the stream network.

In the upper Susa and Chisone valleys, DSGSDs largely correspond to the sackung type (Zischinsky, 1966, 1969). They mostly involve the metasedimentary successions of the Cerogne-Ciantiplagna, Lago Nero and Alberghian units, which are made up of heterogeneous calcshists and phyllites. The single DSGSD extends over an area ranging between 0.1 and 7 km² (7.66 km² in the case of the Sportinia DSGSD; Figure 2(a)). The depth of the rock mass involved usually exceeds 100 m, in some cases 200 m (e.g. the Jouvenceaux DSGSD; Figure 2(a) and cross-section A–A’ in

Figure 2. (a) The composite DSGSD of Sauze d’Oulx in the Susa Valley. Jv: Jouvenceaux sector; Sp: Sportinia sector; Rc: Richardette sector. The Dora Riparia alluvial plain is visible in the foreground. Photo taken from Monte Pramand (2163 m a.s.l.), view looking SSE. (b) The DSGSD of San Sicario in the Susa Valley. The Dora Riparia River is visible on the left. Photo taken from Punta Rascià (2346 m a.s.l.), view looking NE.
the Main Map), and can reach up to 300 m (e.g. the San Sicario DSGSD; Figure 2(b)). Along the northern and north–western flank of the Susa-Chisone divide, between Mount Genevris and Mount Pintas, DSGSDs coalesce with a seamless collapse morphology and an overall extent of 28 km².

Movement of sackung takes place with prevailing creep processes along discrete sliding surfaces causing reactivation (where appropriate and depending on the orientation of the stress field) of pre-existing fault and fracture systems, shear zones or the regional foliation. The upper part of the slope mainly evolves in a passive way, with a prevailing extensional deformation concentrated along multiple, subparallel or listric surfaces, and with retrogressive sliding mechanisms (cf. cross-section B–B’ in the Main Map). In the middle and lower sectors of the slope, compressional creep mechanisms involve increasingly wider and deeper shear zones, so that the deformation is spread out throughout the whole rock volume.

In a few cases, slope deformation is controlled by deep-seated creep processes at the expense of ophiolites embedded in the metasedimentary succession of the Cerogne-Ciantiplagna unit. In the Jouvenceaux DSGSD (Figure 2(a) and cross-section A–A’ in the Main Map), the bedrock involved consists of a huge (up to 4 km²) highly fractured serpentinite mass, cross-cut by anastomosing metric-to-decamicth thick cataclastic shear zones; these latter consist of angular clasts dispersed within a finer-grained matrix and cross-cut by a stockwork of veins and veinlets composed of calcite and tremolite (Groppo, 2006). This results in a spectacular and well-defined fan-shaped morphology (Figure 2(a)) due to radial spread of the serpentinite flow (sensu Cowan & Mansfield, 1970) in the valley bottom (Fioraso et al., 2010).

DSGSDs can also result from karst phenomena. In the Rio Fenils Valley (left tributary of the Dora Riparia River), the DSGSD of Cima Curran is located along an NNW–SSE sub-vertical shear zone involving a slice of carbonatic breccia associated with huge masses of gypsum and/or anhydrite; many solution dolines reach up to 80 m in diameter and some sinkholes have recently opened up, indicating the intensity of the dissolution processes at the expense of the underlying evaporites.

Landslides and large landslides cover an area of 66.64 km², which is 14.55% of the investigated mountain region, and are mainly located on valley slopes involving DSGSDs. They include a broad range of instability phenomena, the most common being complex rock slides formed at the expense of the ophiolitic and oceanic units. Landslide accumulations range from 0.01 up to 3 km² (e.g. the Clot della Soma landslide, facing the confluence of the Chisone and Chisonetto rivers). Based on subsurface investigations and monitoring data (inclinometers), the displaced rock masses reach a maximum thickness of 80–100 m (e.g. the Champlas du Col landslide; cf. Figure 3(a) and cross-section C–C’ in the Main Map; Fioraso et al., 2011), although it is likely that some landslides could reach greater depths.

SE of the Gran Roc Fault, slopes are characterized by a typical cuesta morphology, with a strong morphostructural asymmetry due to the constant dip of the regional foliation. In this area, dip slopes are predisposed to the development of huge translational rock slides, with multiple retrogressive rupture surfaces coinciding with low-angle shear zones that are parallel to the regional foliation. In these cases, a predisposing role in the destabilization of slopes was played by glacial scouring and undercutting of valley bottoms, with the exposure of structural discontinuities prone to be reactivated by gravitational stress (e.g. the Monte Pelato landslide; cf. Figure 3(b) and cross-section E–E’ in the Main Map).

In addition to classical rock falls positioned at the base of steep rock walls (e.g. the Mount Pramand rock fall, located on the left slope of the Susa Valley between the villages of Oulx and Salbertrand), a huge impressive rock avalanche accumulation is present in the Chisone Valley. The landslide, presumably of late-glacial age, originated at 2605 m a.s.l. on the southern slope of the Monte Ciantiplagna (Figure 4), involving massive calcschists with subordinate masses of serpentinite and metabasite of the Cerogne-Ciantiplagna unit. The blocky deposit covers an area of 3.88 km², with a corresponding volume of 157 M m³ and a maximum thickness of 145 m. The rock avalanche traveled a horizontal distance of 4.6 km, with a vertical drop of 1460 m and stopped against a transverse moraine situated at the mouth of the Rio del Laux Valley (Fioraso & Baggio, 2013).

5. Morphological effects of deep-seated gravitational phenomena on the upper slope

In the study area, DSGSDs and some large landslides produced impressive geomorphic features, mostly concentrated along mountain ridges and, secondly, in the middle portion of the slopes. In the Main Map, the following morphostructural features were mapped:

1. Uphill-facing scarps, typically 2–30 m high, hectometric-to-kilometric in length, and approximately parallel to slope contours. Although in some cases scarps are isolated, most of them occur in groups that are several tens to hundreds of meters in width and up to several kilometers in length. These features develop when the rupture surface crops out behind the ridge crest; as a consequence, double-, triple- or multiple-crested ridges involve
Figure 3. (a) Panoramic view of the Ripa Valley. Main complex landslides are highlighted with dashed lines. A: Roche Rouge; B: Champlas Seguin; C: Champlas Janvier; D: Champlas du Col; E: Grange Sises; F: Bessen Haut; GRF: Gran Roc Fault. Photo taken from Punta Rascìà (2346 m a.s.l.), view looking ENE. (b) The Monte Pelato rock slide in the upper Chisone Valley. The Chisone River is visible in the foreground. Photo taken from La Grande (2606 m a.s.l.), view looking Est.

Figure 4. The Monte Ciantiplagna rock avalanche. The alluvial plain formed as a consequence of the blockage of the Chisone River is visible in the background. Arrows indicate the travel path of the rock avalanche. In the center of the image is visible the deep gorge carved by the Chisone River. Photo taken from the Serre Marie fort (2109 m a.s.l.), view looking West.
the drainage divide for long stretches. Impressive uphill-facing scarps are visible along the Susa-Chisone divide (Figures 5 and 6) and along the Monte Morefreddo – Clot della Soma ridge (Chisone Valley) (Figure 7(a)). Uphill-facing scarps are often associated with huge topographic closed depressions that lie upslope of the scarps: they are up to 20 m deep and 150–200 m in diameter (Figure 7(b)), and are sometimes filled with lacustrine and peat deposits. Occasionally, uphill-facing scarps delimit small graben-like structures, as can be observed at Colle Blegier, along the Susa-Chisone divide.

(2) Downhill-facing scarps, up to 40–50 m high, hectometric-to-kilometric in length and frequently with a semi-circular shape in plan view. These develop when a slip surface crops out ahead of the ridge crest that borders the failed slope.

Usually, scarps are bounded downslope by linear troughs and closed depressions up to 15–20 m deep filled with colluvial and lacustrine deposits, as well as peat bogs (Figure 8). These features can occur as individual scarps, or more frequently as a swarm of interconnected scarps and counterscarps in the middle and upper parts of the mountain slope; in addition, they give rise to a hummocky topography (Figure 8(a)), and to an approximately distinct segmentation of the slope profile (cf. cross-section B–B’ in the Main Map). Some scarps control the local drainage pattern, as is clearly observable on the Sportinia DSGSD.

(3) Trenches and open cracks develop as a consequence of lateral spreading of the rock masses resulting from gravitational stress. These tensional features are generally decametric-to-hectometric

Figure 5. (a) Impressive uphill-facing scarps along the Susa-Chisone drainage divide at Colle dell’Assietta. The Susa Valley is visible on the left of the image. Photo taken from Testa dell’Assietta (2555 m a.s.l.), view looking NE. (b) Hectometric long uphill-facing scarp along the south-eastern slope of the Monte Genevris. The Chisone Valley is visible on the right. Photo taken from Monte Genevris (2533 m a.s.l.), view looking ENE.
in length and decimetric-to-metric wide. They are linear or segmented and parallel to the dominant joint and fault systems. Trenches are partially filled with blocky or fine-grained material remobilized along slopes or detached directly from the rocky walls. Along the trench prolongation, small (up to several tens of meters) circular or elliptical closed depressions are commonly visible, indicating the presence of tension voids within the underlying bedrock. In slopes affected by active extensional deformation (e.g. Cima delle Vallette and Monte Ciantiplagna along the Susa-Chisone divide), sinkholes of a few meters in diameter can also develop due to the sudden collapse of the surface material into tensional voids. In the area of Chezal-Duc (Chisone Valley) involving large DSGSD, at a depth of 50–70 m a drill hole intercepted some deep-seated open fractures filled with homometric colluvial fine sands.

Some useful information on the relative chronology of sackung phenomena emerge by observing the relationship between morphostructural features and superficial deposits. In some cases, gravity-induced landforms are covered or filled with periglacial deposits (rock glaciers, gelifluction lobes and block streams), slope deposits (talus and rock falls), and lacustrine and peat deposits. Conversely, on slopes involving active gravitational phenomena, uphill- and downhill-facing scarps and trenches affect periglacial and slope deposits, in addition to older glacial and late-glacial deposits (Figure 9). Finally, it is noteworthy that some travertine masses spread out on slopes involving DSGSDs and which date back to the late Dryas (11,506

![Figure 6.](image-url)

(a) Multiple-crested ridge along the northern slope of the Cima delle Vallette, along the Susa-Chisone divide. The Susa Valley is visible on the left of the image. Photo taken from Gran Pèlè (2705 m), view looking East. (b) Multiple-crested ridge on the northern slope of the Monte Ciantiplagna, along the Susa-Chisone divide. The Susa Valley is visible on the left of the image. On the bottom left is visible the huge closed depression (130 m long and 15 m deep) of Colle delle Vallette. Photo taken from Cima delle Vallette (2705 m), view looking East.
± 66 U/Th years BP) and the early Holocene (10,145 ± 225 and 9475 ± 670 U/Th years BP) (Ali et al., 2006) are fractured and faulted by rock slope failures.

6. Morphological modifications at a slope-scale

The deep-seated gravitational deformation of a mountain slope causes, in the long-term, a complete redistribution of rock masses, and distorts the original post-glacial valley profile. In turn, morphological characteristics mirror the prevailing deformational style involving the different sectors of the mountain slope. As described in the previous chapter, on the upper portion of the slope, a swarm of subparallel scarps, counterscarps and other tensional features (e.g. trenches) have developed as a result of the downslope adjustment of unstable rock masses along well-defined multiple slide planes. This movement occurred over a long period, and in many cases is still ongoing, producing large cumulative displacement which ranges from a few tens of meters to several hundreds of meters (e.g. the Sportinia DSGSD; cross-section B–B’ in the Main Map). As a macroscopic consequence, the upper part of the slope assumes a marked concave profile (Figure 2(b)).

In the middle and/or distal portion of the failed slope, the deformation takes place through a broader zone characterized by deep-seated creep, together with dilatancy of the rock mass. Some DSGSDs do not show any clear downslope morphology, while in other cases the lower half of the slope bulges out into the valley; in this latter case a strongly convex, outwardly arched profile can be observed (Figure 2). In many DSGSDs, bulging induces secondary slope failures such as rock slides (e.g. the Ecclauser, Champlas Janvier and Champlas du Col landslides) and rock falls. Although the lower section of a sackung commonly shows a very low rate of movement, in a few cases prevailing compressional mechanisms are recognizable at

Figure 7. (a) Multiple-crested ridge along the Clot della Soma–Monte Morefreddo divide. The Chisone Valley is visible in the background. Photo taken from the NW ridge of Monte Morefreddo (2599 m a.s.l.), view looking NW. (b) Impressive closed depression (120 long and 15 m deep) along the eastern side of the Punta Rascià–Cima Saurel ridge, in the upper Susa Valley. Photo taken from Serre Granet (2294 m a.s.l.), view looking East.
Figure 8. (a) Multiple downhill-facing scarps along the northern slope of the Monte Triplex (Susa Valley). Photo taken from Rocca Nera (2479 m), view looking West. (b) Downhill-facing scarps along the southwestern slope of Rocce Platasse, in the upper Susa Valley. Photo taken from Rocce Plataste (2817 m), view looking SW.

Figure 9. Schematic representation of the relationship between morphostructural features induced by DSGSDs and glacial, periglacial and slope deposits as observed in the study area.
the slope toe, as evidenced by the monitoring network and by the severe damages caused to engineered structures and residential buildings. Moreover, it was observed that the toe of some mature DSGSDs and large landslides moved across the valley bottom displacing the valley thalweg (cf. cross-section C–C’ in the Main Map). Fioraso et al. (2010) demonstrated that since the end of the LGM, the DSGSD of Sauze d’Oulx advanced for about 500 m on the valley floor (cf. cross-section A–A’ in the Main Map).

In the investigated area, DSGSDs and large landslides impacted significantly on valley bottom morphology due to a partial or complete valley dam, sometimes with the contribution of tributary alluvial fans. In some cases, landslide dams impounded large-volume lakes, now filled with lacustrine and deltaic sediment of up to 125–150 m thick (Figure 10). The age of landslide dams is not well known; only for the Eclause–Sapè d’Exilles two wood samples were found at a depth of 84 and 42 m within a fluvio-lacustrine succession, and were radiocarbon dated to 9525 ± 85 and 8380 ± 95 years BP, respectively (Tropeano & Olive, 1993).

Valley dams constrain the ability of streams to transport sediments, thus resulting in a decrease and increase of the stream gradient upstream and downstream of the dam, respectively; as a consequence, longitudinal profiles of the Chisone and Dora Riparia rivers are characterized by a staircase-like morphology, with bedrock rarely outcropping along riverbeds (Figure 10). Overtopping, and the subsequent incision of the landslide dam, has led, in some cases, to impressive erosional landforms, such as the gorges (up to 145 m deep) carved within the blocky accumulation of the Monte Ciantiplagna rock avalanche (Figure 4).

7. Conclusions
Since the end of the LGM, in the northern Cottian Alps (mostly in the upper Susa and Chisone valleys) deep-seated rock slope failure such as DSGSDs and large landslides has occurred on a large scale. Instability phenomena involve around 285 km², equivalent to 38% of the investigated mountain region, much greater than the 5.6% estimated by Crosta et al. (2013) for the whole Alpine region. These massive rock slope failures develop as a combination of several factors: (i) the presence of extensive metasedimentary successions of the Piedmont-Ligurian Ophiolitic units with prevailing calcschists, phyllites and subordinated masses of serpentinite (Polino et al., 2002b); (ii) an intricate structural setting dominated by a pervasive ENE–WSW fault system influencing the morphostructural landscape of the area (Perrone et al., 2011); (iii) the high slope relief and the strong oversteepened valley slopes due to glacial scour. In addition, the northern Cottian Alps are located in an area of the Western Alps with a moderate seismicity, but characterized by a high tectonic mobility, as recently evidenced by Nocquet et al. (2016).

In the Main Map, a new detailed and complete mapping of deep-seated instability phenomena in the upper Susa and Chisone valleys is presented. Particular attention has been paid in the distinction between DSGSDs and large landslides, sometimes misinterpreted in
previously available inventories. Due to the considerable size (surface, depth and volume) of the involved masses, post-glacial mountain-valley morphology can be affected radically by massive rock slope failures. In the upper slopes, a wide range of morphostructural features guided by structural discontinuities were observed and mapped for an overall length of about 273 km. Scars and anti-slope scars – surface expression of a prevailing downhill dipping collapse – and trenches and open cracks – expression of lateral spreading of the involved rock mass – are distinguished in the Main Map. The presence of late Holocene slope deposits cut by morphostructural features (Figure 9) clearly suggests a recent phase of mobilization of some deep-seated gravitational phenomena.

In the lower slope, the main morphological changes consist of bulging, resulting in a distinctive concave-convex profile of the valley flank and in a narrowing or damming of the valley floor. At least four large accumulations (landslides or mature DSGSDs) have impounded large-volume lakes, which are now failed (e.g. Roche Rouge – Buon Soccorso) or filled (e.g. Monte Ciantiplagna, Monte Fraiteve and Eclause – Sapè d’Exilles) with thick lacustrine and deltaic successions (Figure 10).

The upper Susa and Chisone valleys provide a remarkable example of how massive deep-seated rock slope failures can induce radical changes on slope morphology, and how the interference between gravitational phenomena and drainage networks can force the accumulation of a large volume of sediments along the valley bottom for long periods.

Software

The topographic map, the geological map and the related database were created with QGIS 2.14.3 Essen, while the final map layout was created with Adobe® Illustrator® CS5. Photos were managed and compiled using Adobe® Photoshop® CS2.

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