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GEOLOGICAL CONTEXT OF THE BECCA FRANCE HISTORICAL LANDSLIDE (AOSTA VALLEY, NW ITALY)

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ABSTRACT: The wide historical Becca France landslide occurred at dawn on July 6th, 1564. It involved the Becca France ridge (2313 m a.s.l.) a few kilometers NW of the town of Aosta (Aosta Valley, NW Italy). This event buried the Clusellaz Valley floor (a Dora Baltea left tributary) destroying the populous ancient village of Thora and resulting in an unknown number of victims (120-545).
The occurrence of this landslide is documented in the local historical literature. Despite this, the geological and morphological features of the accumulation have never been investigated. The aim of this work is to map the geological context of the area affected by the gravitational event, to reconstruct the phenomenon and to make a first evaluation of the causes of the landslide.
The examined area is located along the contact between the Middle Penninic and the Piedmont Zone. The geological survey has allowed to distinguish, above the tectonically deeper continental unit (Gran San Bernardo Nappe system), two oceanic units (Lower and Upper TMU of the Aouilletta Unit). This area was largely interested by the Pleistocene glaciers and by a wide deep-seated gravitational slope deformation (P. Leysser DSGSD).
The detachment niche extends in the right side of the Clusellaz Valley and is shaped in the E slope of the Becca France ridge. It corresponds to a very steep cirque-like scarp, very remarkable for its width (about 850 m), height (more than 500 m) and the lack of vegetation cover. It consists of two calcschist units (the lower one with prasinite) separated by a tectonic contact underlain by cargneule and gypsum. The niche cuts the doubled Becca France ridges and other gravitational evidence of the P. Leysser DSGSD.
The landslide accumulation, some tens of meters thick, also exhibits a wide extent (about 1.26 km^2). It climbed for about 80 m on the opposite side of the valley. The landslide body partially developed immediately below the detachment niche (proximal sector) is probably connected to a rockfall. Most of the accumulation is lengthened for approximately 3 km into the Clusellaz Valley floor (middle-distal sector), showing several longitudinal ridges, up to ten meters high and some hundreds meters long. This sector, having travelled down the slope a long distance, is an example of a landslide body with longitudinal ridges, linked to a rock avalanche.
The slope failure was triggered by the concurrence of various predisposing causes: i) the sufficiently strong relief energy, with difference of level of 700 m between the mountain crest and the glacially-deepened valley floor; ii) the fractured and slackened bedrock connected to the DSGSD; iii) the poor geomechanical properties of the outcropping calcschist; iv) the chemical dissolution of cargneule and gypsum along the tectonic contact between the two calcschist units.
An interval of extremely heavy rainfall, that produced an increase in interstitial pressure, was probably the triggering cause.

Keywords: rock avalanche, DSGSD, Aosta Valley, Becca France.

1. INTRODUCTION

The Becca France historical landslide is known in the Aosta Valley local literature as the worst natural disaster causing victims of the region. It developed in the tributary Clusellaz Valley, a few kilometers NW of the town of Aosta (Fig. 1). Nevertheless, the geological features of the landslide body (distribution, thickness, morphology and petrographic composition) and of the detachment niche (extent, morphology, gradient, lithology and fracturing) have never been investigated and described in detail.

The geological context of the area involved in the event has now been studied. It includes a geological mapping of the Becca France sector (see Fig. 6) and a first evaluation of the landslide's predisposing causes. The link with the Pointe Leysser deep-seated gravitational slope deformation (P. Leysser DSGSD), a very extensive gravitational phenomenon, is particularly investigated.

The local historical literature has described the wide landslide that occurred at dawn on July 6th, 1564, as coming from the eastern slope of the Becca France ridge (Cerutti et al., 1993). The landslide accumulation quickly buried the ancient village of Thora, described as a nice place located in the Clusellaz Valley floor. Currently, a new village (named Thouraz) occurs 1 km SE from the possible location of the ancient village. This ancient village was very important for its residential population (52 families) and its commercial activities (10 watermills and 14 weaving factories) (Fénoil, 1883), although the accuracy of these data is disputed (Caniggia et al., 1999). The first remarks about the disaster occur in some administrative acts (dated to 1565, 1576, 1581 and 1583), reporting a different number of victims (545 according to the inhabitants and 120 according to the authorities). These acts include a request for compensation for the victims and the landslide damage (loss of wood, vines and the Ville-sur-Sarre irrigation canal) (references in Bollati, 1988). An old memorial plaque preserved in the Parish Church of Sarre, containing the landslide date, is mentioned in Caniggia et al. (1999). Fénoil (1883) also relates a catastrophic flood in the T. Clusellaz during the 1566. On June 10th, 1851 another significant alluvial event ravaged the Sarre Parish House garden on the Clusellaz fan (Caniggia et al., 1999).

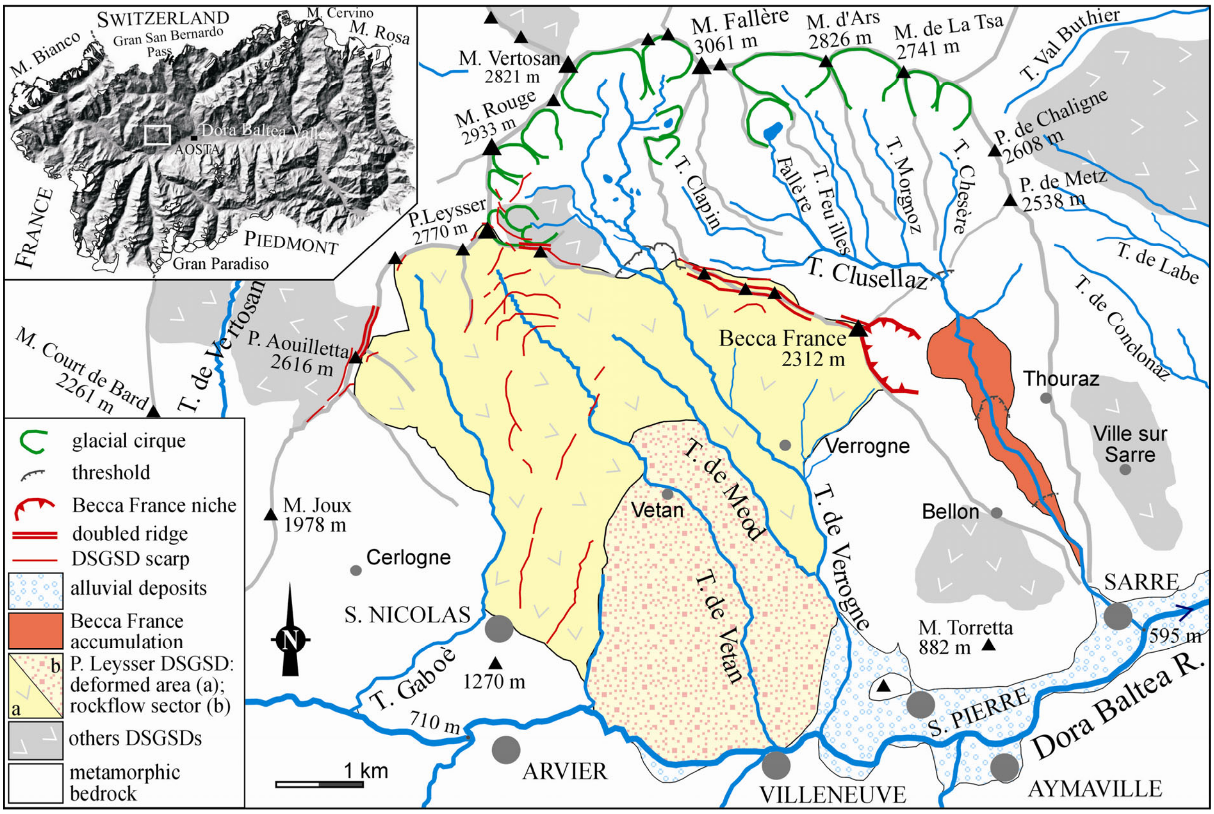

Fig. 1 - Geographical and geomorphological sketch of the area, comprising the P. Leysser DSGSD. The Becca France ridge is involved in a remarkable set of WNW-ESE doubled ridges. The Digital Terrain Model of the Aosta Valley, in which the present glaciers are mapped, shows the location of the area of investigation.

2. METHODS

A detailed geological survey and photo interpretation have been performed for the Becca France area, mapping the bedrock, the Quaternary cover and the morphological features. The geological succession was first mapped at a scale of 1:5000 and then simplified in schematic form (see Fig. 6).

The tectono-stratigraphic units of the bedrock are based on their lithostratigraphic features and on lithological correlations with other units outcropping in the Western Alps.

In the field, the regional foliation, i.e. the most pervasive metamorphic surface in the rocks (S1), has been considered for the structural reconstruction. This surface is sub-parallel to the lithological layering and represents a composite foliation generated by the transposition of an older and locally still recognizable metamorphic surface.

Fracture systems and fault surfaces have also been measured, to determine the direction of the movement. Meso-structural data, related to the sets of fractures and faults, have also been represented by stereodiagrams, consisting of equal-area projections plotted in the lower hemisphere with the Stereonett software.

The Quaternary sequence has been identified based on the distribution, facies of sediments and morphological features (morainic ridges, fluvial fans and landslide bodies).

The difficulties encountered in the fieldwork were related to the scarcity of outcrops and the wide distribution of debris and colluvial deposits. These sediments, diffusely covering the bedrock and the other Quaternary sediments, are essentially linked to the P. Leysser DSGSD.

3. GEOGRAPHICAL, CLIMATOLOGICAL AND SEISMOLOGICAL SETTING

The examined area is located in the central Aosta Valley (NW Italy), one of the main valleys of the Western Alps (457480N latitude and 072190E longitude).

The Aosta Valley is a wide mountain basin (3262 km^2), consisting of a 100 km long main valley (Dora Baltea Valley) and of about thirty major tributary valleys. Monte Bianco (4810 m), Monte Rosa (4634 m), Monte Cervino (4478 m) and Gran Paradiso (4061 m) are the highest peaks (Fig. 1). This basin shows high average gradients between the valley floors and the ridges of more than 1500 meters (3500 m is the largest difference in height, recorded in the Monte Bianco Massif). The altitude (2100 m on average) promotes the development of numerous glaciers (209). According to the Aosta Valley Catalogue of Glaciers (data of 2005), they have an overall extent of approximately 135 km^2 (4.1% of the basin).

The Becca France landslide event occurred in the Clusellaz Valley, a small (15.6 km^2) tributary valley now completely free of glaciers (**CV** in Fig. 2). A rocky threshold occurs (150 m height) above Arpy (1758 m) (**At** in Fig. 2), deeply incised by the watercourse. This threshold separates the valley floor into two stretches.

The upper Clusellaz Valley (9.8 km^2) shows a very large W-E valley floor. This 3.3 km long stretch has a markedly asymmetrical cross section. Its left side, including the southern slopes of Mont Fallère (3061 m), Mont d'Ars (2826 m), Mont de La Tsa (2741 m), Pointe de Chaligne (2608 m) and Pointe de Metz (2552 m), is much wider and higher than the opposite side, including only the northern slope of the Becca France ridge (2347-2312 m) (**BF** in Fig. 2). The left side is also shaped by five short tributary NNW-SSE valleys (Clapin, Fallère, Feuilles, Morgnoz and Chesère) (Fig. 1).

The lower Clusellaz Valley (5.8 km^2), deeply incised, has a WSW-ENE quite symmetrical cross-section. Most of the valley floor (3.3 km of a total length of 4 km) is filled by the Becca France landslide accumulation (1605-800 m). Another rocky threshold occurs (**t** in Fig. 2), buried by the landslide body, in which the hanging tributary valley overlooks the main valley (1200 m). An alluvial fan, on which the Sarre village is located, extends in the Dora Baltea Valley floor at the T. Clusellaz incision outlet (700 m).

The Aosta Valley has a temperate oceanic climate, transitional to hemi-continental, lacking of a dry season (Mercalli et al., 2003). The mean annual temperature is 10÷12°C in the valley floor and -7.5°C at 1200 m. January is the coldest month and July is the warmest. Rainstorms are frequent in July and, to a lesser degree, in August.

The region has an alpine sublittoral pluviometric regime, with two maxima in the middle seasons and two minima in the summer and winter. In the central sector of the region, comprising the Becca France area, the maximum rainfall occurs in the autumn (October-November) and the minimum rainfall is in the summer (July). The middle Dora Baltea Valley floor is one of the driest sites in the Alps (550 mm/y in S. Marcel). The mean annual precipitation of about 950 mm increases both with the altitude and towards the watersheds. On the northern watershed, the Gran San Bernardo (2476 m), 14 km NNW of the Becca France, records an average of 2000 mm/y (data set since 1817!). Two weather stations are located near the survey area, in Saint Nicolas (5 km SW, 1196 m) and in Aosta (8 km ESE, 583 m).

In Aosta (data set since 1840) the average annual temperature ranges between 10°C and 14.5°C, with a mean January T ranging between -1° and 4°C and a mean July T of 20.4°C. The average annual precipitation is 561 mm, with the maximum rainfall in October (70.5 mm) and the minimum rainfall in July (33 mm). November, October, September, May and June are the months

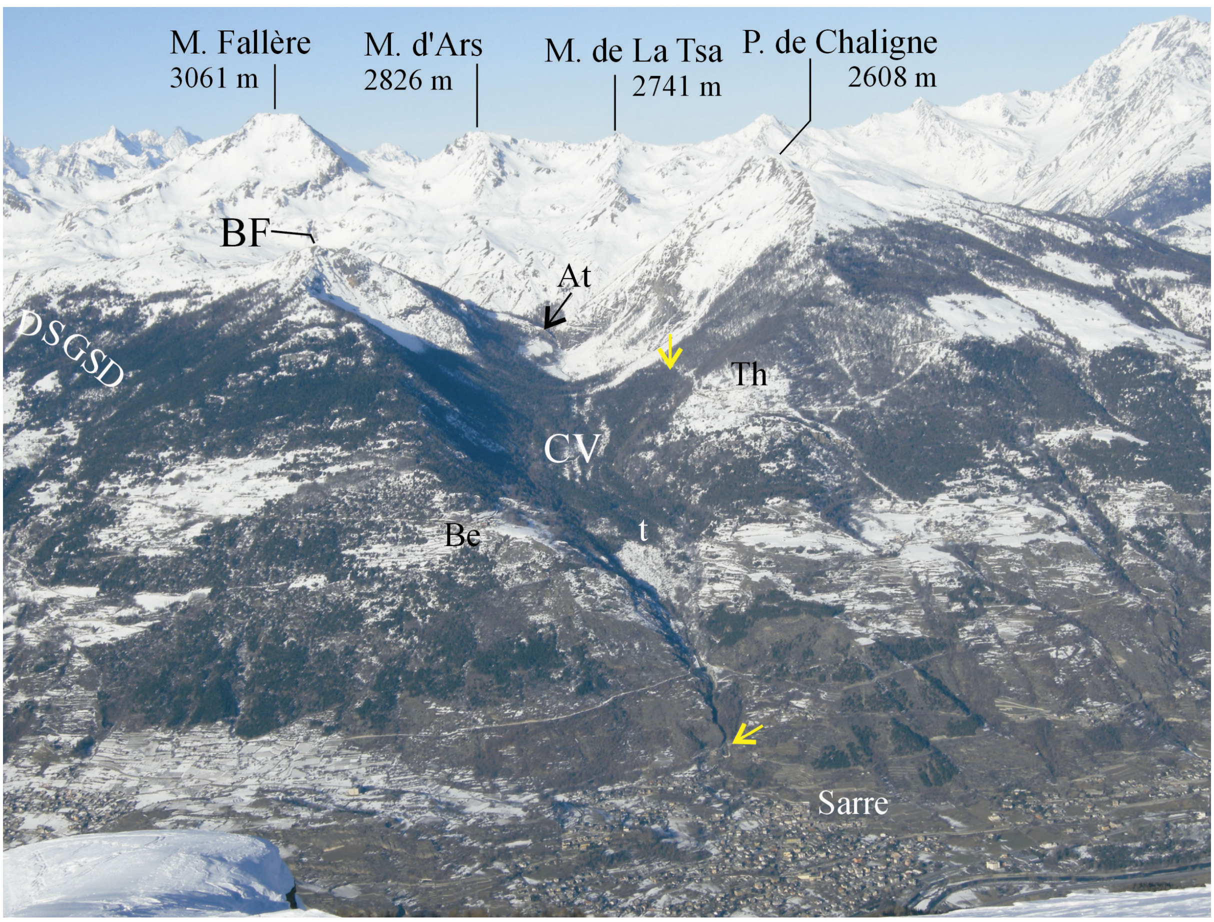

Fig. 2 - The Becca France (**BF**) historical landslide involves the Clusellaz Valley (**CV**). It shows the typical features of a tributary glacial valley, separated from the main valley by a hanging threshold (**t**). Another threshold near Arpy (**At**) divides the lower Clusellaz Valley from the upper one. A wide fluvial fan develops at the valley outlet, built from the Sarre Village. The arrows indicate the distal edge of the landslide. The location of the Bellon (**Be**) and of the present Thouraz (**Th**) villages is also indicated.

with the longest series of rainy days, with a record of 13 rainy days (overall 97.4 mm) in November 1996. The highest rainfall noted is 287 mm in 8 days (2000), 118 mm in 24h (1947) and 24.7 mm/h (1981). In Saint Nicolas (data set 1913-1961), the average annual precipitation is 658 mm (maximum 75.1 mm in October and minimum 40 mm during February).

The Aosta Valley is a relatively low seismic region. A few historical major earthquakes are known for the damage (Valensise & Pantosti, 2001). The earthquake of 1905 in Chamonix (Monte Bianco Massif) (M = 6) and the earthquake of 1855 in the Ayas Valley (M = 5.8) are the strongest.

The Aosta Valley has middle-low seismicity according to the instrumental data (data set 1968-1997). Specifically, some tens of events of a magnitude 2-3 and only two events of magnitude 4 are recorded.

A significant correlation of the regional seismicity is inferred with the right Rodano-Chamonix and the left Ospizio Sottile strike-slip fault systems. During the Neogene, these faults displaced the Pennine and Graian Alps rigid block to the SE. These fault systems bound the NW and SE block edges, respectively (Bistacchi et al., 2000).

The E-W Aosta-Ranzola fault system, the main brittle system inside this block, does not exhibit any significant recent seismicity. Instead, a concentration of shallow earthquakes of a magnitude 3 is recorded NW of the examined area into the Gran San Bernardo Nappe, displaced by the Aosta-Fallère fault system.

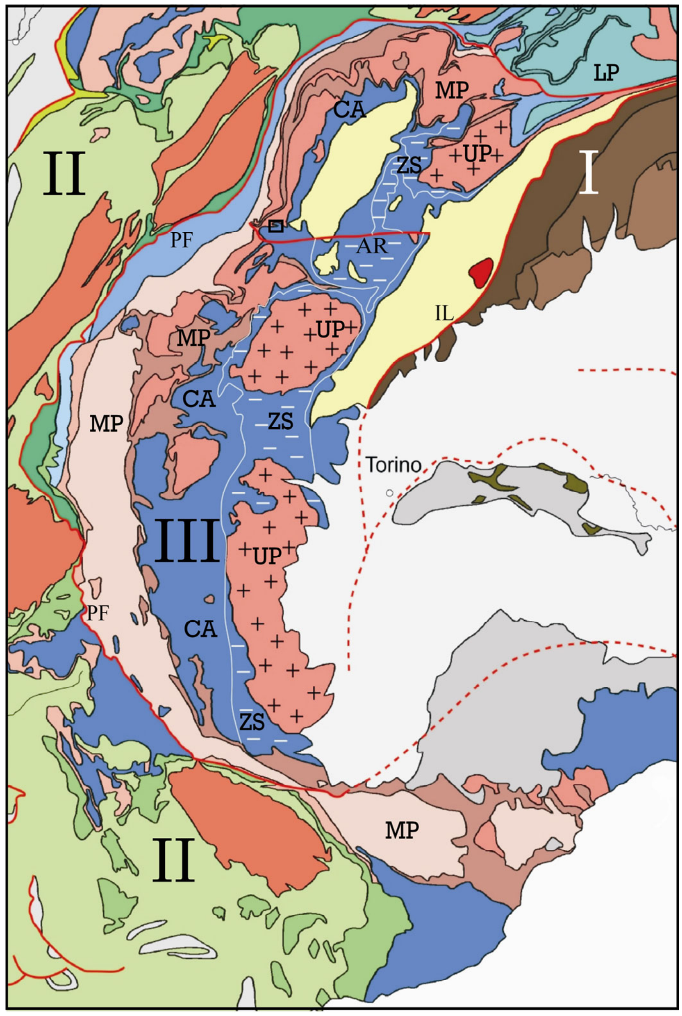

Fig. 3 - Geological schematic map of the Western Alps: (**I**) the internal domain, corresponding to the Southern Alps; (**II**) the external domain, consisting of the Helvetic-Dauphinoise domain; (**III**) the axial sector of the Austroalpine and Penninic continental domains, separated by oceanic units of the Piedmont Zone. **IL**: Insubric Line; **PF**: Penninic Front; **AR**: Aosta-Ranzola Fault; **LP**: Lower Penninic; **MP**: Middle Penninic; **UP**: Upper Penninic; **ZS**: Zermatt-Saas like-Units; **CA**: Combin-Aouilletta like-Units.

4. GEOLOGICAL SETTING

4.1. Lithostratigraphic setting of the bedrock

The Western Alps consist of three main structural domains (e.g. Polino et al., 1990). The internal domain (I) corresponds to the Southern Alps. The external domain (II) consists of the Helvetic-Dauphinoise Zone. The axial sector of the chain (III), between the Penninic Front and the Insubric Line, represents a composite nappe pile that includes the Austroalpine and the Penninic continental units and the Piedmont Zone oceanic units (Fig. 3).

The Penninic Domain is usually subdivided into the Lower Penninic, including the Ossola Valley nappes, the Middle Penninic, consisting of the Gran San Bernardo Nappe system, and the Upper Penninic, corresponding to the Internal Crystalline Massifs of Monte Rosa, Gran Paradiso and Dora Maira Massifs.

The Piedmont Zone consists of two main groups of units, the lower and the upper one, known as the Zermatt-Saas Units (Southern Valais) and the Combin-Aouilletta Units (Aosta Valley) (Bearth, 1967; Dal Piaz, 1974; Dal Piaz & Ernst, 1978; Dal Piaz, 1999; Dal Piaz et al., 2010; ISPRA - Servizio Geologico d'Italia, 2010). The Lower Units preserve several eclogite relicts and consist of different ophiolite complexes. Likewise, the Upper Units, showing a blueschist imprinting, are composed of Upper Jurassic (De Wever & Caby, 1981) to Upper Cretaceous calcschist (Lemoine et al., 1984), with minor slices of serpentinite, metagabbro and green schist derived from the oceanic lithosphere (e.g. Lagabrielle & Lemoine, 1997).

The examined area is located along the tectonic contact between the Middle Penninic and the Piedmont Zone. The geological survey allows us to recognize two distinct oceanic units related to the Aouilletta Unit, covering the tectonically deeper continental unit referred to as the Gran San Bernardo Nappe system (see Fig. 6).

The Gran San Bernardo Nappe outcrops in the northern sector of the mapped area. It consists of garnet micaschist and albitic paragneiss, with some minor bodies of metabasite (Palaeozoic basement) and dolomitic metabreccia and marble (Mesozoic cover).

In the Piedmont Zone, two tectonic units, called the Upper and Lower tectono-Metamorphic Units (TMU), have been distinguished. Certain stratigraphic markers are absent from each of these units and a strong Alpine

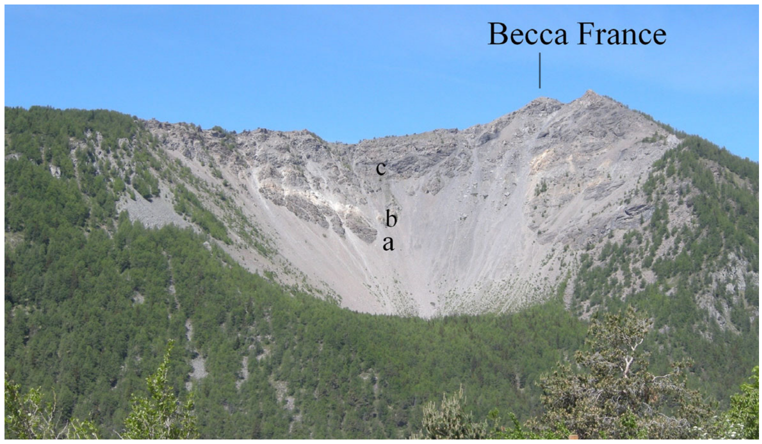

Fig. 4 - The detachment niche of the Becca France historical landslide. The tectonic contact between the Lower Calcschist Complex (a) (Lower TMU in Fig. 6) and the Upper Calcschist Complex (c) (Upper TMU in Fig. 6) is underlined by a cargneule and gypsum level (b). The niche cuts the noticeable doubled ridge developed near the summit.

deformation is observed. These features do not allow the reconstruction of specific stratigraphic successions.

The Lower TMU, outcropping in the central-eastern and southern sectors of the mapped area, consists of calcschist with major prasinite and paragneiss bodies.

This unit is formed by phyllitic calcschist alternating with meter to hectometer bodies of prasinite with compositional banding, diffusely outcropping near the Thouraz village. In the NW slope of Bellon minor bodies of quartzitic gneiss, whitish albitic gneiss and micaschist, are also present. These lithological types are often closely associated with up to 20-cm-thick layers of white mica marbles.

The Upper TMU, outcropping in the central-western sectors of the examined area, consists of carbonate calcschist alternating with marble in decimeter thick layers. Marble, locally prevalent, sporadically contains many centimetre thick layers of quartzite, probably derived from chert. Layers of meta-rudstone (meta-conglomerate or meta-breccia), slightly laterally extended and up to 10-m-thick, consist of marble and dolomite clasts in a calcite matrix probably linked to debris flows.

The contact between the Upper and Lower TMU is highlighted by a deformation zone that is marked by tectonic flakes with prevailing cargneule, gypsum and minor bodies of prasinite, micaschist and quartzite. The lithological types within the deformation zone show only random reciprocal relationships. The deformation zone, a few tens of meters thick, has important lateral discontinuity. It is well exposed in the niche of the landslide (**b** Fig. 4) and occasionally outcrops in the NE slope near the Verrogne village, where it has been involved in the P. Leysser deep-seated gravitational slope deformation. The deformation zone is completely covered by the Quaternary deposits N of the Becca France ridge. Here the boundary between the Upper and Lower units can only be found by comparing the different lithological features of the two juxtaposed units.

The Upper and Lower TMU lie tectonically above the Gran San Bernardo Nappe: all these units are folded together.

An antiformal structure, developed in the Plan di Modzon area, involves the Gran San Bernardo Nappe. A synformal structure is, instead, responsible for the outcropping of the Upper TMU in the Tsa de la Comba area. Both these structures, developed on a hectometer scale, deform a sin-regional foliation and show an axial NW-SE trend.

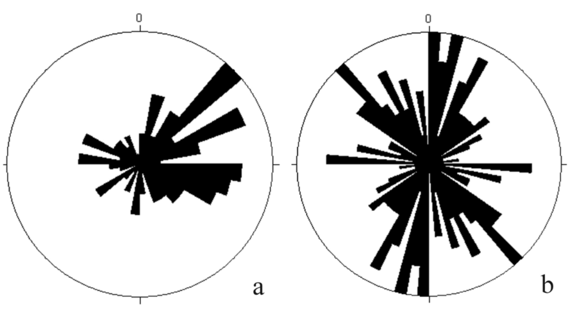

Fig. 5 - Equiareal projection (lower hemisphere) of fractures in the Becca France ridge (151 data). Dip direction (**a**); strike direction (**b**).

The tectonic contact between the Gran San Bernardo Nappe and the Lower TMU is also involved, N of the Arpy and Moron localities, in a decameter S-verging open fold. This E-W trending structure deforms the regional foliation dipping 70-75° towards the S. The regional foliation dips lower than 30-35° towards the S-SW in the remaining area.

The bedrock is affected by numerous faults and fractures, decreasing in pervasiveness towards N. Many fracture systems have been identified in the bedrock (Fig. 5).

In detail the fracture systems are:

- NW-SE trending fractures NE dipping and defining the orientation of the trenches;
- NNW-SSE primarily trending fractures ENE dipping. The southwestern stretch of the detachment niche is parallel to these fractures;
- N-S primarily trending fractures E dipping. These structures are emphasized, into the detachment niche, by fault breccia with calcschist clasts in a carbonate matrix. Where the matrix prevails, it constitutes cargneule type-rocks encrusting the detachment plane, as seen just below the niche crown;
- NNE-SSW primarily trending fractures ESE dipping; this fractures seem to have had the role of basal sliding surfaces in the Becca France failure;
- NE-SW trending fractures SE dipping;
- WNW-ESE trending fractures NE dipping. The lateral (northern and southern) stretches of the detachment niche are parallel to it.

The area of the Becca France ridge is instead involved in several trenches, especially trending WNW-ESE and NW-SE, connected with the P. Leysser DSGSD (see Fig. 6). These trenches results from the opening of similar trending fractures, not equally represented in the gravitationally not-deformed bedrock.

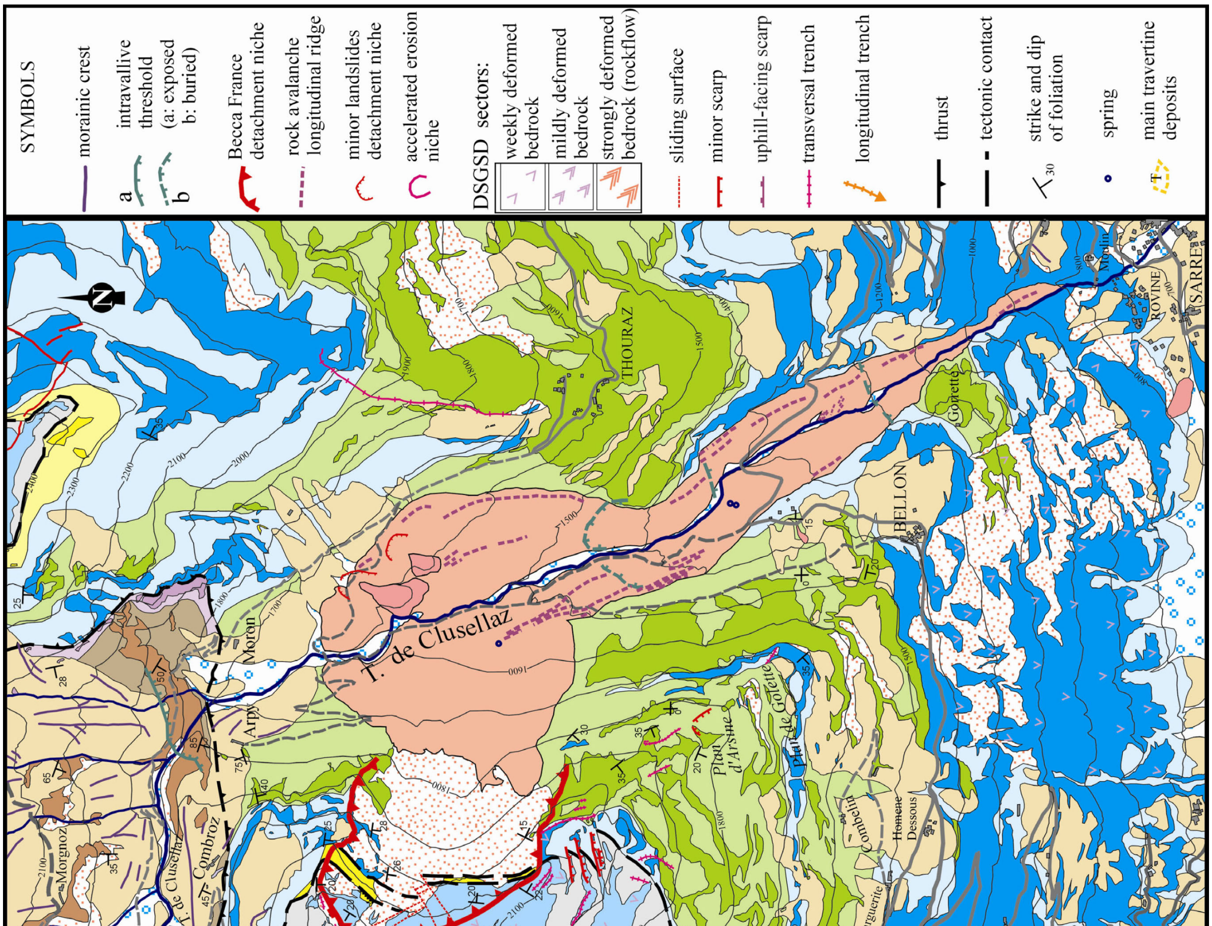

Fig. 6 - Geological map of the Becca France area.

Fig. 7 - The Verrogne Valley shows the typical glacial cross section. This wide valley, with steps in the long profile, is diffusely covered by glacial sediments.

4.2. The Quaternary cover

The Aosta Valley was extensively affected by alpine glacial modeling during all of the Quaternary glaciations. The Dora Baltea Glacier repeatedly covered the main valley was for its entire length. These events are recorded in the Ivrea Morainic Amphitheatre at the valley outlet, ranging from the end of the Early Pleistocene (Carraro et al., 1991) to the end of the Late Pleistocene (Arobba et al., 1997; Gianotti et al, 2008).

Most of studies about the Aosta Valley Quaternary regard the glacial stratigraphy. Glacial sediments were at first connected with a single major glaciation (Gastaldi & Martins, 1850; Baretti, 1866; 1877; 1879; Bruno, 1897). Only Baretti (1893) has described the post-glacial formations signaling the Becca France landslide. Subsequently, some authors focused on the "Würm" glacial expansion of the Dora Baltea Glacier, probably reaching a thickness of about 1000 m (Novarese, 1915) or 1200 m (Sacco, 1927) in the middle Aosta Valley. Six glacial stadials in the Ivrea Morainic Amphitheatre and six glacial stadials in the Dora Baltea Valley have been identified, referred to the Last Glacial Maximum and the Lateglacial (Gianotti, 2007; Gianotti et al., 2008), taking into account the previous works about the mountain sector (Novarese, 1915; Sacco, 1927; Porter & Orombelli, 1982; Carraro, 1992). Relicts of a frontal moraine in the main valley floor, 3 km upstream Sarre (680 m) prove a glacier halt in the investigated area (Saint-Pierre stadial), probably correlated with the Gschnitz stadial (Gianotti, 2007).

This area (Fig. 6) extends 30 km downstream from the head of the Dora Baltea Valley, where the Mont Blanc glacial alimentation center developed. Glacial sediments discontinuously cover the left slope of the main valley in an altimetric band of 1200 m, between the valley floor (600 m) and approximately 1800 m. The highest kame terraces of a supposed LGM age reach 1925 m above the Saint Nicolas village, about 6 km upstream on the left side of the main valley. Morehover, till bodies and erratic boulders are widely found up to 1710 m (Plan de Golette) on the Bellon watershed ridge, between the Dora Baltea Valley and the Clusellaz Valley. On the contrary, they are not observed at greater altitudes on the same ridge. This distribution confirms that the Dora Baltea Glacier during the Last Glacial Maximum (LGM) did not exceed 1800 m along the Sarre cross section.

Subglacial sediments, mainly melt-out till and lodgement till, are the facies most widely represented. These sediments cover the bedrock with discontinuous and thin bodies. They consist of very packed silty sands with faceted and striated pebbles, cobbles and boulders, markedly matrix supported, often weakly bedded. Marginal glacial sediments (flow till and glaciolacustrine deposits) cover the bedrock or the subglacial till with thin restricted bodies. They consist of coarse gravel a silty-sandy matrix, with a clast-supported to matrix-supported texture and a poorly defined massive stratification. The-

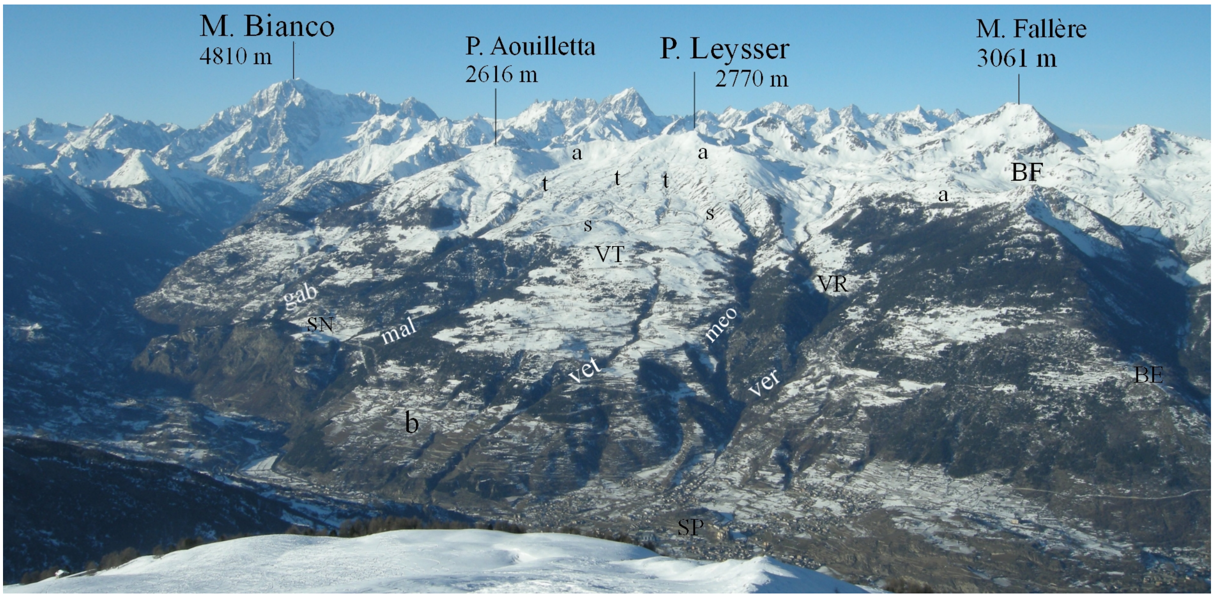

Fig. 8 - The P. Leysser DSGSD shows a remarkable main scarp, arched in plan, just below the crest (a). Its a distal sector (b), expanded in the Aosta Valley floor, is incised by several watercourses: T. Gaboé (gab), T. Mallaley (mal), T. de Vetan (vet), T. de Meod (meo) and T. de Verrogne (ver). The gravitational landforms, as minor scarp (s) and longitudinal trenches (t), are underlain by the snow. The location of Becca France (BF) and of the villages of Vetan (VT), Verrogne (VR), Saint Nicolas (SN), Saint Pierre (SP) and Bellon (BE) are also indicated.

se sediments generally form small kame terraces, involved in the remodeling, that are well-preserved east of Combelin (1550-1620 m).

In the lateral valleys, the glacial cover is linked to the Clusellaz and Verrogne glaciers and to their tributaries (Fig. 7). The distribution of sediments suggests their reference to the LGM and to subsequent Lateglacial stadials. In detail, the marginal glacial deposits are diffused especially above Combroz. They are matrix supported and rich in angular clasts supplied by the calc-schist overhanging walls. These sediments form moraines or small kame terraces. The lateral moraines in the upper Clusellaz Valley and the lateral and terminal moraines in the Verrogne Valley, between Or and Vulmian, are particularly significant.

Remnants of ancient glacial deposits (pre-LGM) are locally observed at a high elevation. The Dora Baltea Glacier ancient sediments consist only in their derived remains.

4.3. The P. Leysser deep-seated gravitational slope deformation

The deep-seated gravitational slope deformations (DSGSDs) are common in the main Dora Baltea Valley

Fig. 9 - The remarkable doubled ridge (700 m long, average 50 m wide and 25 m deep) on the Becca France crest, observed from the south slope of the M. Fallère. The Tsa de la Comba pasture is shown in the lower left corner.

Fig. 10 - The extension of the doubled ridge of Fig. 9 toward the E, observed from the Becca France ridge. M. Emilius and P. Garin are in the background.

and in its tributaries. These phenomena are currently interpreted as the product of the gravitational spreading of the slopes (Crosta, 1996), usually affecting the steep sides of the deep glacial valleys. In the Aosta Valley 230 DSGSDs have been recognized (IFFI Catalogue of landslides and sheets of the Geological Map of Italy at 1:50,000 scale) covering a total area of about 460 km^2 (14% of the basin). They involve all kinds of metamorphic lithotypes without significant differences. This evidence supports that DSGSDs are favored and driven by tectonic discontinuities (fractures, faults and thrusts) and, on the contrary, they are less dependent on lithological features (mechanical and chemical properties and foliations).

The Becca France ridge is comprised in the 23 km^2 wide P. Leysser DSGSD, occurring in the left side of the Dora Baltea Valley (Fig. 1). This large phenomenon has not been reported in the first Italian Alps DSGSDs Catalogue (Mortara & Sorzana, 1987). It has been only partially mapped in the Aosta Valley geological map (Elter, 1987) as a landslide, limited to a less extended area not including the Becca France.

The Pointe Leysser mountain ridge bounds the DSGSD (Pointe Aouilletta, 2616 m; Pointe Leysser, 2770 m; Becca France, 2312 m), forming the watershed between the Dora Baltea and its tributary Vertosan and Clusellaz basins. This 8 km long watershed, only cut off by the T. Verrogne incision, shows an arched in plant scarp just below the crest (**a** in Fig. 8). It represents the very extended main scarp of the Punta Leysser DSGSD. The gravitational phenomenon affects the Piedmont calcschist, with rare slices of prasinite and serpentinite. Several minor scarps (**s** in Fig. 8) occur in the whole area. The general extension of the collapsed rocky mass caused the opening of several NW-SE longitudinal trenches (**t** in Fig. 8), re-used by the local watercourses (Gaboè, Mallaley, de Vetan, de Meod and lower Verrogne torrents) and others ephemeral streams.

The DSGSD 9 km^2 central sector, laterally delimited by the T. Mallaley and T. de Meod incisions, represents the most deformed area. Its distal sector (**b** in Fig. 8) is expanded in the Aosta Valley floor.

The investigated sector represents the DSGSD northeastern edge (Fig. 1), where a set of WNW-ESE doubled ridges near the watershed (Figs. 9, 10) is the more remarkable of the gravitational landforms. This evidence, with an overall length of 2 km, an average width

Fig. 11 - Extended area with very fractured rocks (r), connected to the P. Leysser DSGSD developed in the southern slope of the Becca France above the Or pasture. They may be confused with areas covered by debris sediments. A longitudinal trench, on the right, is deepened and enlarged by an ephemeral watercourse (t).

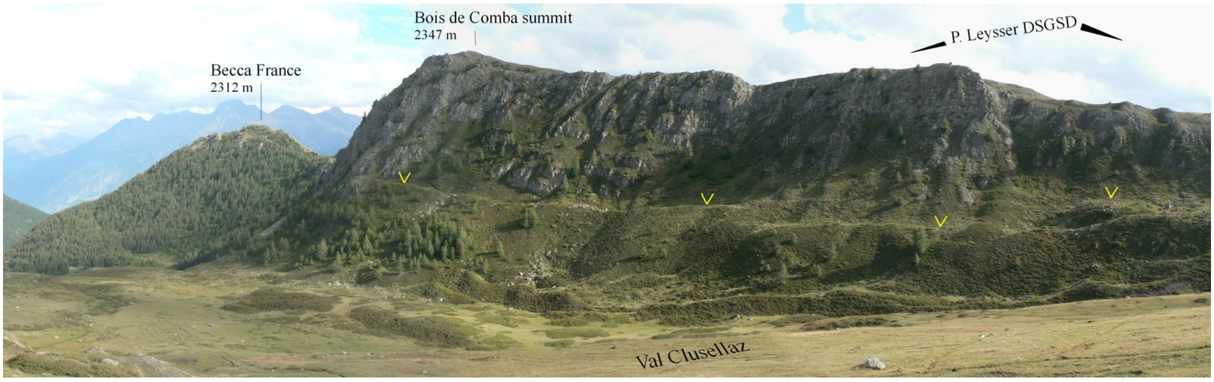

Fig. 12 - In the northern slope of the Becca France ridge, a uphill-facing scarp (arrows) develops, linked to the DSGSD phenomenon.

of 50 m and a depth of 25 m, is abruptly interrupted, on its eastern edge, by the wide detachment niche of the historical described landslide (Fig. 4). The summit doubled ridge set is not reported in the geological map (Fig. 6) to permit the mapping of other gravitational evidence.

A succession of minor scarps (100-500 m long, 5-50 m wide and 2-10 m deep) involves the upper band of the Becca France SW side. Several WNW-ESE trenches (transversal trenches), orthogonal to the DSGSD movement, also develop in the whole slope and locally form small closed depressions. They are several tens of meters extended and a few meters deep.

In the watershed sector the various fractures are only slightly open (from a millimeter to some centimeters). In the lower band of the SW slope, the fractures (§4.1) are generally up to some decimeters open. Locally wide bedrock outcrops simulate the presence of debris sediments: here the very pervasive and partially open fractures favor a strong erosion of the bedrock and many secondary surficial landslides. Some concave pluri-decametric niches locally develop with badland morphology (**r** in Fig. 11). They are probably related to accelerated erosion rather than to a landslide. These niches open at the head of a flat-bottomed deep incision, likely corresponding to longitudinal trenches used and remodeled by debris flow and alluvial processes (**t** in Fig. 11). An ensemble of similar longitudinal trenches, variously re-used by avalanches and minor watercourses, was recently described in the Western Alps along the Germanasca Valley (Forno et al., 2011).

Some gravitational discontinuities are also visible in the Becca France landslide niche, being a wide outcrop of bedrock involved in a DSGSD (Fig. 4). These

Fig. 13 - The greatest rise of the landslide accumulation on the left side of the Clusellaz Valley (dashed line) is noticeable by the different colors of the trees (view from the niche crown).

discontinuities are difficult to identify into the very fractured bedrock. Some sliding surfaces are suggested by the rocky layers displacements. In detail, a sliding surface has lowered the gypsum-cargneule layer of more than 50 m in a SW direction, forming the double ridge morphology visible in the niche crown.

Other gravitational elements are observed on the NNE side of the Becca France ridge. Here a main continuous low angle uphill-facing scarp forms a 500 m long ledge (2220-2230 m, 50 m above the Clusellaz Valley floor) (arrows in Fig. 12). It marks the boundary between differently fractured calcschist. This discontinuity can be likely interpreted as a slipping plane dipping southwards. Therefore this scarp, apparently outside the P. Leysser DSGSD, is probably the lower visible evidence of the gravitational deformation.

Fig. 14 - The facies of the landslide accumulation consists in angular clasts of very different sizes, mixed to a poor, slightly packed, sandy and silty matrix.

Doubled ridges, slide scarps and trenches show various relationships with the Last Glacial Maximum-Lateglacial cover.

The gravitational evidence frequently cuts the glacial evidence (Tsa de la Comba): in these sites, the DSGSD dislocates the glacial cover (forming scarps in which the sediments outcrop) and cuts through the glacial and outwash landforms.

Glacial evidence elsewhere modifies the gravitational landscape (Plan di Modzon). The ancient Verrogne Glacier, entering into trenches, probably enlarged them and partly deprived them of their primary typical shapes.

The lower Verrogne Valley is the most notable result of the interaction between the glacial and deep gravitational processes. This wide and U-shaped incision, with a NNW-SSE direction perpendicular to the contour lines, is probably linked to a longitudinal trench enlarged by the Verrogne Glacier, during the Lateglacial (Fig. 7). Other similar longitudinal trenches W of the Verrogne Valley, with a broken line trend and a V-shaped cross section, have been instead re-used by watercourses (**t** in Fig. 8).

The different relationship between glacial and gravitational morphology suggests a long evolution of the P. Leysser DSGSD from the LGM to the present.

5. THE BECCA FRANCE LANDSLIDE

The historical phenomenon of the Becca France landslide (July 6, 1564) produced a wide scarp on the eastern slope of the Becca France ridge (2312 m) and a huge accumulation within the lower Clusellaz Valley, 6 km NW of the town of Aosta (Fig. 2).

The Becca France landslide, historically already well-known (§1), has been reported in an ancient geological investigation of the Aosta Valley (Baretti, 1893). In the "Aosta" 1:100,000 Geological Map of Italy (Mattirolo et al., 1912), in which the landslides were not indicated, a morainic cover and, subordinately, debris sediments were represented instead of the Becca France accumulation. The priest and naturalist Abbé Henry (1917), on a day trip, first observed some deep fissures on the Becca France crest and the morphology with ridges of the landslide accumulation. This evidence has suggested to the author an important rule of the water in the gravitational event, linked to heavy rains. No detailed cartographies of the accumulation are reported in the overall Aosta Valley geological map at the 1:100,000 scale (Elter, 1987; De Giusti et al., 2004). A first brief geological description of the Becca France landslide is, finally, reported in Forno et al. (2004).

5.1. Geomorphic features

Geological and morphological features of the Becca France landslide have been mapped (Fig. 6). The lithology of the detachment niche, the morphology and the petrographic composition of the landslide body have been analyzed in detail.

The evident detachment niche corresponds to a steep concave scarp, approximately 500 m high (2300-1800 m), 850 m wide and 700 m long, without vegetation cover (Fig. 4). The niche crown, arched in plan, comprises two main stretches trending NNW-SSE and WNW-ESE. The two niche stretches follow the fracture systems of the bedrock. The niche cuts the Becca France crest and, in detail, breaks off the main WNW-ESE doubled ridge developed on the watershed (Fig. 4) (§4.3).

The lithological constitution of the niche consists of two overlapping units (§4.1), separated by a tectonic contact underlain by a cargneule and gypsum level, some tens of meters thick (**b** in Fig. 4). At the base of the niche, the Lower TMU outcrops, composed of a 150 m thick prasinite body, covered by an approximately 170 m thick calcschist body (**a** in Fig. 4). At the top of the niche, the Upper TMU is instead composed only of a 150 m thick calcschist body (**c** in Fig. 4).

The niche is widely covered by debris and local rockfall deposits, forming a 35°-36° slope. The bedrock diffusely outcrops only in the higher band (1950-2300 m). The debris sediments, with an open-work texture, are made of angular clasts, from some centimeters to a few decimeters in size. Obviously their petrographical constitution (90% calcschist and grafitic calcschist, 10% prasinite with rare cargneule clasts) strictly reflects the niche lithology. These sediments locally contain rounded clasts, related to the reworking of ancient glacial sediments.

The landslide accumulation, located in the glacial Clusellaz Valley, is 3.2 km long and 300-940 m wide. It shows a total extent of 1.26 km^2, covering the elevation range between 1800 m and 800 m. In detail, the landslide body partly (18%) extends on the right side of the valley, immediately below the detachment niche (proximal sector) and partly (82%) appears lengthened into the valley floor, covering the lower band of both the valley sides (for over 3 km) (middle-distal sector) (Fig. 13). Between these two accumulation sectors, a gentle NNW-SSE depression is partly buried by debris flow deposits, coming from the detachment niche.

The upper sector shows a cone landform, now partially covered by debris sediments. The lower landslide body rises on the opposite (left) side of the valley, in front of the niche, for approximately 80 m of elevation, where a typical blocky ridge occurs at the culmination (*brandung* in Heim, 1932). The accumulation toe overlooks the Dora Baltea Valley and reaches the main valley floor at 800 m.

The landslide accumulation shows a different slope, high immediately below the detachment niche (average 23°) and slight in the lower sector (average 15°). The lower sector, entrenched into the Clusellaz Valley floor, shows some remarkable lengthened ridges parallel to the valley trend (flowbands), a ten of meters high, separated by depressions (Fig. 13). The main ridges, linear or arched in plan, are alternately distributed on the opposite sides of the valley. Five main ridges develop (550÷200 m length), relatively continuous for a few hundreds of meters in the valley floor (Fig. 6). Several changes in the slope of the landslide body are likely related to the presence of buried rocky scarps shaped by subglacial erosion (buried thresholds in Fig. 6). The ridges break off on these thresholds and begin again downstream.

The landslide deposits show a visible thickness of approximately ten meters, as calculated by the height difference between the ridge crests and the depressions; the lack of wide outcrops prevents the observation of the entire sedimentary body. They consist of a chaotic pile of rock angular clasts, some tens of centimeters to a few thousand of m^3 in size (Fig. 14). Several lengthened blocks are prevalently arranged parallel to the ridges. The subordinate sand-gravelly matrix is poorly consolidated in the surficial layer. Coarse-grained sediments with an open texture develop on the ridges, probably related to the removal of an original scanty matrix.

The petrographic constitution of the ridges is partially different. Prasinite and prasinite-gneiss blocks constitute the external ridges. Prasinite, prasinite-gneiss, calcschist, grafitic calcschist and marble schist blocks form the intermediate ridges. Calcschist, grafitic calcschist and marble schist clasts, with locally abundant cargneule, constitute the internal ridges. A gently-dipping and some meters thick band of crushed and pulverized cargneule discontinuously outcrops in the middle sector of the accumulation, probably separating two bodies of calcschist blocks. The entire distal sector, below 1300 m, consists only of prasinite blocks.

A total drop height of 1500 m, a runout distance of 4150 m and an accumulation thickness of 10 m on average and a 30 m maximum are the main geometrical parameters of the landslide. The volume of 15-25 million m^3 has been assessed using the accumulation area and the estimated average thickness, based on a preliminary geophysical cross section.

5.2. The landslide remodeling

The T. Clusellaz, in spite of the recent age of the landslide dissects the accumulation. Lengthened debris flow bodies develop, confined in the watercourse incision, entrenched into the landslide accumulation and further terraced (Fig. 6). These debris flow bodies, composed of calcschist, graphitic schist and cargneule clasts, form two terraces parallel to the watercourse. A thin band of present torrential sediments develops into the riverbed.

In addition, on the left slope, two secondary landslide accumulations develop, 50,000 and 300,000 m^3, respectively. Their detachment niches occur into the main landslide body, cutting its parallel ridges. In the Clusellaz Valley floor, under the detachment niche, debris flow sediments bury a wide sector of the landslide accumulation. They have been derived from the reworking of the debris that diffusely covers the niche. Here the loosened bedrock outcropping into the niche favours the progressive detachment of rocky bodies of various sizes.

The landslide body is covered by a continuous larch and pine wood (*Larix decidua* and *Pinus nigra*). The plant cover differs from the woods without pines on the adjacent sectors (dotted line in Fig. 13). Some springs (Sources du Ruet) arise on the landslide body, into a relict channel in the next of the T. Clusellaz incision. They are linked to the high permeability of the deposits and suggest a low permeable substratum in the immediate subsoil (bedrock or subglacial till) and consequently a local weak thickness of the landslide body.

6. DISCUSSIONS AND CONCLUSION

The geological survey allows the detection of two superposed calcschist units, separated by a deformation zone (Fig. 6), and to the contrary of the unique Aouilletta Unit reported in the geological literature. This zone, a few tens of meters thick, prevalently consists of cargneule, gypsum and very subordinate quartzite. The regional foliation dips below 30-35° towards the S-SW.

This survey allows the description of the gravitational evidence connected to the P. Leysser DSGSD (Fig. 8), as remarkable doubled ridges (Fig. 1), several minor scarps as well as longitudinal and transversal trenches. Their trend suggests that the regional foliation and lithostratigraphical setting favor the gravitational landforms. The gravitational movements prevalently reuse the previous tectonic systems surfaces.

The wide Becca France landslide is also mapped with greater extension and detail than in the previous maps. The detachment niche is particularly remarkable, corresponding to a 500 m high and 850 m wide scarp, arched in plan. It shows a cirque-like morphology (Turnbull & Davies, 2006).

The accumulation is of approximately 1.26 km^2 wide and up to about 30 meters thick, covering an elevation range of 1000 meters. It consists of an incoherent ensemble of angular rock fragments of various sizes. Its varied, but very sorted, petrographical composition is a good example of "remnant stratigraphy" (Heim, 1932).

The upper (proximal) sector of the landslide accumulation is immediately below the detachment niche, with a cone landform typical of a rockfall.

The lower (middle-distal) sector is entrenched in the Clusellaz Valley floor and shows instead a wide distribution and some parallel ridges typical of a rock avalanche.

> Rock avalanches (RA) are catastrophic gravitational events occurring suddenly, with very high rates of movement (100-250 km/h) and great sizes (>10^6 m^3). They have a rapid runout and emplacement of crushed and dry rock for distance of several kilometers (Hewitt et al., 2008).
>
> Many RA are listed into the Alps (Heim, 1932; Abele, 1974; Eisbacher & Clague, 1984; von Poschinger, 2002). In the Aosta Valley they are the prehistoric Courmayeur (about 600 BC; Porter & Orombelli, 1981) and Cervino landslides (> 1000 AD; Porter & Orombelli, 1981), the historical Triolet RA (1717 AD; Porter and Orombelli, 1980; Deline & Kirkbride, 2009), the two Brenva events from the Mont Blanc Massif (1920 and 1997 AD; Dutto & Mortara, 1991; Barla et al., 2000; Deline, 2001; Bottino et al., 2002) and the recent Luseney RA in Valpelline (1952 AD; Dutto & Mortara, 1991). They have prevalently runout onto glaciers, with the likely exception of the Courmayeur RA, because of its unknown source, and of the Luseney RA only slipped onto a suspended glacieret. On the contrary, the Becca France landslide is the only known event in the Aosta Valley occurred in a completely free of glaciers basin.

The magnitudo of the Becca France accumulation (estimated volume of 15-25 x 10^6 m^3) is in agreement with the minimum values requires for rock avalanches. Its maximum runout distance (L = 4100 m) is 2,7 times the total fall height (H = 1500 m). The L/H ratio is significantly lower than the characteristic values of 5-10 times often assigned for rock avalanches. It is instead consistent with the L/H ratios between 0,6 and 8,3 assigned for 36 rock avalanches (Hewitt et al., 2008), although below their average (4,0).

The Becca France landslide is, according to the few cases reported in the literature, a rather rare example of rock avalanche with longitudinal ridges. The Flims landslide in the Swiss Alps (Abele, 1997), the Mutzogata RA in the eastern Pamir (Fort & Peulvast, 1995) and the Ghoro Choh I in Karakoram Himalaya (Hewitt et al., 2008) have similar features (eg the Ghoro Choh I RA shows five longitudinal ridges up to 3 km long and 10-30 m high). The Slide Lake RA in Montana (Butler et al., 1986), with a longitudinal ridge 1.25 km long and 15 m high, seems the more comparable event. The rock avalanche bodies with transversal ridges are, instead, more common.

The morphology of the distal sector of the accumulation (overall homogeneity and lack of intersections) allows the attribution to a unique rock avalanche event. This event involved the calcschist of the Lower TMU, the cargneule of the deformation zone and partly the overlying calcschist of the Upper TMU (Fig. 6).

The genesis of the proximal sector is, instead, more questionable. It is probably linked to a rockfall phenomenon with minor energy, simultaneous with the rock avalanche and involving only the calcschist of the Upper TMU (Fig. 6). Alternatively this proximal sector should be connected with another gravitational event after the rock avalanche, covering partially the empty space between the niche and the lower body.

The predisposing factors of the landslide occurrence are then preliminarily specified.

- The strong relief energy, with high mountains up to over 3000 m (M. Fallère, 3061 m; P. Leysser, 2770 m) and relatively low valley floors, developed at about 600 m (Fig. 2). In detail, the sufficiently high gradient of the right slope of the Becca France ridge (average slope of 32°) is to be considered.
- The overall geological context. The outcropping calcschist, with poor geomechanical properties, is defined among the more frequent causes of the NW Alpine large landslide (Mortara & Sorzana, 1987; Forno, 1989; Forno & Massazza, 1983; 1987). The high grade of rock fracturing, linked to the tectonic setting, favored the detachment. Cargneule and gypsum, along the tectonic contact between the two calcschist units, subjected to chemical dissolution, cause sinking and gravitational collapse of the overlying rock mass. The filling of fractures by cargneule, sometimes successively affected by dissolution, is also a possible aid to the landslide movement. The most obvious example is the evident sub-vertical fault observed in the detachment niche, encrusted with cargneule, simulating a thick cargneule body (Fig. 4). This surface before had been an open fracture, with carbonate fluids circulating, and successively probably became one of the main surfaces responsible for the detachment phenomenon.
- The wide P. Leysser DSGSD. This gravitational deformation multiplies and enlarges the tectonic fractures, creates new sliding surfaces and promotes scarps and uphill-facing scarps. The continuous summit doubled ridge, cut by the landslide niche, is the more remarkable evidence of the importance of the gravitational factors.

The rock avalanches are statistically slightly linked to the DSGSDs, although these latter are very common in the mountain areas (Hewitt et al., 2008). This scarce connection between rock avalanches and DSGSDs is related to the rheology of the very jointed involved rocks. The dilated bedrock is unsuitable to forming high scarps and to trigger large slope failures, both necessary for the RA runout. Nevertheless, some rock avalanches triggered by DSGSDs are reported, as numerous events in Norway (Blikra et al., 2006), the Nomal RA (Hewitt, 2001) and the Gol Ghone I RA in Karakoram (Hewitt, 2002) and the Hope RA and Frank RA in western Canada (Cruden & Krahn, 1978). In the Becca France RA the slope failure occurred at the edge of the P. Leysser DSGSD, from the opposite side of the rocky divide forming the DSGSD main scarp, where a relatively high-energy relief occur and the bedrock is not totally crushed.

The trigger factors of the Becca France landslide are not historically well-known. Both a seismic source (reference in Fenoil, 1883) and an interval of extremely heavy rainfall (Henry, 1917; Colliard, 1970; Rampolla, 1981) have been reported in the past, although without evidence. This rainfall may be responsible for an increase in the interstitial pressure of the water in the rocks, producing their collapse. A possible seismic event is instead described in an administrative act, written only a year after the landslide. However, the shock felt could have been a consequence of the landslide, but not necessarily its cause.

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