Large sackung along major tectonic features in the Central Italian Alps

C. Ambrosi*, G.B. Crosta

Dipartimento di Scienze Geologiche e Geotecnologie, Università degli Studi di Milano Bicocca, Piazza della Scienza 4, 20126 Milano, Italy

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Abstract

Deep-seated gravitational slope deformation (sackung) is common in alpine mountain belts. It is controlled by lithological, geomorphological, and structural features. We describe and discuss five examples of DSGSD along the Insubric Line (Periadriatic Fault) in the Central Italian Alps. The five examples are different in morphology, size, state of activity, and distribution, and are located along both primary and secondary valleys. We demonstrate relations between structural and gravitational features and discuss the possibility that structural has both passive and active roles in sackung development. Analysis of PS–SAR data shows that the studied examples are not active today. Numerical modelling demonstrates the importance of lithological and structural constraints, postglacial debuttressing, groundwater fluctuations, and weathering on sackung triggering and development.

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1. Introduction

Large, deep-seated, slow slope movements are common in areas of high relief energy. The movements produce conspicuous geomorphic features, including double ridges, scarps, counterrscarps or up-hill facing scarps, trenches, and toe bulging. They induce secondary slope failures, and they may damage buildings, roads, hydroelectric power stations, dams, underground caverns, penstocks, and tunnels. The movements, although slow, can continue for long periods, producing large cumulative displacements (Cruden and Hu, 1993; Ballantyne, 2002). Reactivation can also happen after long periods of quiescence or inactivity. Surface displacements typically range from a few millimetres to several centimetres per year, and are commonly close to the detection limit of monitoring equipment (Bovis, 1990). Secondary landslides, in contrast, may be sudden and rapid. They range from a few cubic metres to thousands of cubic metres (rock falls, toppling, rock-slides) to tens of millions of cubic metres (debris avalanches, debris flows, rock slides, and rock avalanches). The subsurface geometrical and physical characteristics of slow, deep-seated slope movements are commonly unknown, making it difficult to distinguish these phenomena from simpler landslides.

Joints, faults, shear zones, and other structural lineaments are important in deep-seated slope movements (Crosta and Zanchi, 2000; Agliardi et al., 2001), consequently the movements commonly cluster around major tectonic features. It is not clear whether the structural features play an active or passive role in the slope movements, i.e. they coincide with a zone of stress concentration or are simply a zone of weak rock.
Deep-seated slope gravitational deformation (sackung) has been described worldwide, although it has been defined differently by different authors (Zischinsky, 1966, 1969; Mahr, 1977; Radbruch-Hall, 1978; Bovis, 1982, 1990; Savage et al., 1985; Savage and Varnes, 1987; Varnes et al., 1989; Chigira, 1992; Crosta, 1996; Agliardi et al., 2001). Sackung described in this paper are characterised by scarps, including uphill-facing or antislope scarps, trenches, troughs, ridge-top depressions, double or multiple ridges, ridge-crossing depressions, and toe bulging. Slopes are steep and have high relief (>500 m). The features have ill-defined margins, but are large (areas >0.25 km², volumes >0.5 km³, thickness >100 m). Movement rates are low, commonly a few millimetres per year. The distribution of sackung can be related not only to relief but also to glaciation and deglaciation (e.g. glacial debuttressing), weathering, groundwater flow (Ballantyne, 2002), tectonic and locked-in stresses (Miller and Dunne, 1996), structural fabric, tectonic uplift, and fluvial erosion of the toe of the slope.

Sackung are common in the Central Italian Alps (Forcella et al., 1982, Forcella, 1984a,b), and in the last decade many have been described in detail (Fig. 1; Crosta and Berto, 1996; Crosta and Zanchi, 2000; Agliardi et al., 2001; Colesanti et al., 2004). Many sackung occur within the Metamorphic Basement south of the Insbruc Line in the Orobie Alps (northern Italy, Southern Alps; Figs. 1 and 2). Field surveys and aerial photographic interpretations have allowed us to recognize and map these sackung. In this paper, we present geologic, geomorphic, and geomechanical data for the five areas of deep-seated gravitational slope deformation. We discuss possible reasons for the clustering of large instabilities along major tectonic lineaments and the role of the lineaments in the initiation and evolution of the instabilities. We chose these examples for presentation because of their size, conspicuous surface features, distribution along the entire length of the Insbruc Line in the Lombardy Central Alps, and locations in both primary and secondary valleys with different characteristics (e.g. presence of glacial or alluvial deposits, presence of submerged slopes, position with respect to tectonic features, and topographic relief).

Engineering geology surveys were conducted both within and outside sackung to characterize the rock mass. PS–SAR (permanent scatterers–synthetic aperture radar; Ferretti et al., 1999, 2000, 2001a,b; Colesanti et al., 2004) data were used to assess the activity of the sackung and to estimate displacement rates. Two-dimensional and three-dimensional numerical modeling provided an understanding of the factors controlling slope movements, the kinematic and dynamic...
behaviour of the sackung, and the significance of displacement rates measured at two sites.

2. Geologic setting

The study area lies south of the Insubric Line (also known as Periadriatic Fault) in the central Orobie Alps of northern Italy, which are part of the Southern Alps (Fig. 1). The Alpine nappe in this region was transported to the south (Fig. 1) and metamorphism is low grade, in contrast to the situation in the Central Alps (Laubscher, 1985). A basement consisting of orthogneiss and meta-sedimentary rocks was deformed and metamorphosed to amphibolite facies during the Variscan orogeny. The basement rocks are unconformably overlain by a Permian–Triassic volcano-sedimentary sequence deposited in small fault-controlled basins.

The central Southern Alps is a fold-and-thrust system. The South Alpine thrust belt represents the deformed margin of the Adria plate, comprising thick-skinned, pre-Alpine basement and Permian–Mesozoic cover slices. Three major thrust sheets were created by Alpine compressional tectonics and were successively imbricated from north to south (Fig. 1): the upper Orobie or San Marco nappe with the Orobie fault system at its base; the Mezzoldo-Varadega unit containing the Orobie, Trabuchello, and Cedegolo anticlines; and a frontal belt of east-trending regional folds.

The South Alpine basement, bordered to the north by the Insubric–Tonale tectonic line, is composed of three main lithostratigraphic units: Morbegno Gneiss, Stabiello Gneiss, and Edolo Schists, each of which is delineated by faults (Fig. 1). The Morbegno Gneiss unit comprises gneiss and micaschists with interlayered amphibolite, quartzite, marble, calcareous schist, metagranitoid rocks, and pegmatite (Spalla et al., 2002). In the Como Lake area, the basement has been subdivided into two tectono-metamorphic, south-verging thrust blocks, the Domaso–Cortafo zone (DCZ; Fig. 1) and the Dervio–Olgiasca and Mt. Muggio Zone (DOZ, MMZ), which are separated by cataclasites of the

![Geological map of the Middle Valtellina–upper Val Camonica area, showing the locations of the Livrio, Armisa, and Padrio–Varadega sackung.](image)
Musso Alpine fault zone. The boundary between the northern DOZ and southern MMZ units is the Lugano–Valgrande normal fault zone, a thick greenschist–facies mylonite belt.

Permian and Mesozoic sedimentary rocks (Verrucano Lombardo Formation) unconformably overlie the South Alpine basement. Fault-bounded slices of these rocks are present along the main tectonic lineaments.

The Periadriatic Fault is the main tectonic feature of the Alps and formed during successive stages of the collision of Africa with the European continent. The fault separates the Pennidic and Austroalpine nappes, which were reworked during Alpine orogenesis and which show no penetrative Alpine metamorphic or structural overprint. Along the western part of the Periadriatic Fault, northwestern-directed movement of the Adriatic sub-plate during the late Oligocene and early Miocene created a dextral transpressional tectonic environment in which the Lepontine nappes were back-thrust and uplifted about 15–17 km.

Vertical displacement is replaced by sub-horizontal dextral strike–slip fault movements in the San Iorio Pass area (Fig. 1). In the Valtellina sector, the Periadriatic Fault zone is characterized by a belt of subvertical to steeply north–northwest-dipping, greenschist–facies mylonites. The fault zone has a brittle overprint in the Valtellina area, evidenced by a cataclastic belt that separates the Eastern Alps from the Southern Alps. This cataclastic belt has been ascribed to the formation of the Tonale Fault, a regional master fault.

The Mortirolo Fault (Fig. 2) separates the Tonale and Campo Austroalpine units and is interpreted by Meier (2003) to be a regional Alpine trans-tensional strike–slip fault. It has a complex deformation history encompassing several episodes of Alpine shortening and extension of the crust.

The Morbegno Gneiss and Edolo Schists are separated by the east–northeast-trending Porcile Line. This structural lineament locally includes lenses of the sedimentary cover (Servino and Verrucano units).

The South Alpine basement is thrust over Permian–Mesozoic sedimentary cover along the Orobic Line during the Cretaceous. The south-verging Orobic Anticline formed during the Neogene, coincident with northward steepening of thrust planes.

The glaciation history of the area is complex and poorly documented. Early Wurm (74,000–59,000 year BP) glaciation in the Central Alps was followed by a period of climatic amelioration and deglaciation (van Husen, 1997; Florineth, 1998). Renewed cooling after about 30,000 year BP led to expansion of glaciers in the Alps, culminating between 20,000 and 18,000 year BP (Last Glacial Maximum, LGM). A mountain ice sheet with a maximum surface elevation of about 3000 m existed in the Central Alps at the LGM. The ice surface descended gradually from the Pizzo Bernina area to the southeast and west (Florineth, 1998). The ice surface in the Valtellina and Valchiavenna areas and in the Orobic Prealps was between 2000 and 2600 m asl, with ice thicknesses of between 700 and 1400 m.

3. Case studies

We identified and mapped about 200 large (>0.25 km²) rock slope instabilities over an area of 750 km² in the Lombardy region of the Central Alps. Fifteen of the rock slope instabilities show evidence of deep-seated gravitational slope deformation. We have selected five examples to along the above-mentioned structural linear elements to illustrate the range of sackung present in the study area (Figs. 1 and 2). The five examples, from west to east, are Mt. Cortafö, Mt. Legnoncino, the Livrio–Pizzo Campaggio–Pizzo Meriggio area, Armisa–Pizzo di Faila Pesciola area, and Mt. Padrio–Mt. Varadega area. All five are located along the Insubric Line or between it and secondary regional tectonic lineaments (Musso Line, Porcile Line, Mortirolo Fault). Four of the sackung are within the San Marco Unit; the other is in the Tonale unit.

3.1. Mt. Cortafö

A huge sackung covers an area of about 10 km² on the northern flank of Mt. Cortafö (Fig. 3). The east-trending Insubric Line extends along the Liro valley bottom and it is marked by mylonites. Micaschists with lenses of amphibolite also crop out in the area, and paragneisses is exposed on the upper slope west of Motto Paraone. The main schistosity planes along the Mt. Cortafö slopes dip, on average, 40° to the east and northeast. The maximum ice thickness during the LGM, ranges from 700 to 1050 m (Florineth, 1998).

A ridge between 1200 and 1800 m asl is characterised by a series of counterscarps and trenches (Table 1) that have an oblique trend with respect to the Mt. Cortafö slope. Three sectors are recognized within the area of the sackung, based on the geomorphic evidence (letters A, B, and C in Fig. 3). Sector A, north of Motto di Paraone, is limited uphill by rock scarps and trenches trending west–northwest and is laterally delimited by two small incisions. Sector B, which is close to Mt Cortafö, is characterised by a 1100-m-long head scarp with a maximum relief of about 20 m. East-trending secondary scarps join the
main scarp to the west, creating a terraced surface. Northeast-trending counterscarps are present between 1500 and 1600 m asl. The presence of a deep failure surface in this sector is suggested by two deeply incised, north–northeast-trending valleys in fractured bedrock and debris. The upper part of sector C, to the east, is characterised by numerous west–northwest-trending trenches up to 1 m wide, oriented slightly oblique to an east-trending 700-m-long scarp associated with the double ridge of Mt Cortafo. West–northwest-trending secondary scarps and counterscarps lie below the main scarp, between 1300 and 1600 m asl. They delimit small graben-like structures. Glacial and periglacial deposits on the upper slopes of all three sectors are dislocated, suggesting postglacial activity. The lower slopes bulge and are characterised by blocky accumulations from rotational and translational landslides. Statistical analysis of the lineaments suggests preferential north–northeast and west orientations, parallel to the Insubric and Musso lines. Results of structural measurements and laboratory tests that were made to characterize the rock masses are presented in Table 2.

3.2. Mt. Legnoncino

The Mt. Legnoncino study area is located on the east side, and at the north end, of Lake Como (190 m asl; Figs. 1 and 4) at the confluence of the Valchiavenna and Valtellina valleys. The north flank of Mt. Legnoncino (1711 m asl, Fig. 4) is affected by a 7 km² sackung inclined toward the lake, which in this area is about 200 m deep. Sillimanite–biotite-bearing micaschists crop out north of Dorio, whereas garnet-bearing micaschists and chlorite–albite-bearing gneisses with lenses of amphibolite and marble dominate south of Dorio. The upper limit of ice surface in this area at the LGM ranged from 1050 to 1400 m asl.

Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Number</th>
<th>Average</th>
<th>S.D.</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
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<td>Mt. Cortafo</td>
<td></td>
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<td></td>
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<tr>
<td>Scarps</td>
<td>58</td>
<td>123</td>
<td>109</td>
<td>582</td>
<td>4</td>
</tr>
<tr>
<td>Counterscarps</td>
<td>46</td>
<td>77</td>
<td>44</td>
<td>244</td>
<td>23</td>
</tr>
<tr>
<td>Mt. Legnoncino</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Scarps</td>
<td>114</td>
<td>203</td>
<td>175</td>
<td>1269</td>
<td>12</td>
</tr>
<tr>
<td>Counterscarps</td>
<td>28</td>
<td>171</td>
<td>106</td>
<td>555</td>
<td>72</td>
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<tr>
<td>Livrio–Pizzo Campaggio–Pizzo Meriggio</td>
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<td></td>
<td></td>
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<tr>
<td>Scarps</td>
<td>146</td>
<td>204</td>
<td>324</td>
<td>3362</td>
<td>31</td>
</tr>
<tr>
<td>Counterscarps</td>
<td>46</td>
<td>76</td>
<td>44</td>
<td>244</td>
<td>23</td>
</tr>
<tr>
<td>Armisa–Pizzo di Faila–Pesciola</td>
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<td></td>
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<tr>
<td>Scarps</td>
<td>37</td>
<td>241</td>
<td>343</td>
<td>1589</td>
<td>42</td>
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<td>98</td>
<td>143</td>
<td>116</td>
<td>805</td>
<td>34</td>
</tr>
<tr>
<td>Mt. Padrio–Mt. Varadega</td>
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<tr>
<td>Scarps</td>
<td>897</td>
<td>184</td>
<td>202</td>
<td>1523</td>
<td>6</td>
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<tr>
<td>Counterscarps</td>
<td>262</td>
<td>203</td>
<td>191</td>
<td>1231</td>
<td>4</td>
</tr>
</tbody>
</table>
Surface features indicative of deep-seated gravitational slope deformation (Table 1) include a swarm of scarps and counterscarps in the middle and upper part of the slope, between 700 and 1300 m asl, east of the village of Sommafiume (1070 m asl). These features are truncated on the east by a large complex paleo-landslide extending eastward to the Perlino torrent. The slope west of Sommafiume is characterised by large northeast-trending master joints dipping 70° to 80° towards 10° to 30°. This orientation is comparable to that of the main foliation, which dips 60–90° to the northwest and southeast. The western side of Mt Legnoncino has a number of long fractures that reach the scarp of the Mt. Leté landslide. Below Mt. Legnoncino ridge are steep

Table 2
Geomechanical parameters adopted for analysis and modelling

<table>
<thead>
<tr>
<th>Site</th>
<th>Intact rock</th>
<th>Rock mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_c$ (MPa)</td>
<td>$\gamma$ (g/cm³)</td>
</tr>
<tr>
<td>Cortafò</td>
<td>48–90</td>
<td>2.8–3</td>
</tr>
<tr>
<td>Legnoncino</td>
<td>45</td>
<td>2.7</td>
</tr>
<tr>
<td>Livrio</td>
<td>67–87</td>
<td>2.7</td>
</tr>
<tr>
<td>Armisa</td>
<td>67</td>
<td>2.6</td>
</tr>
<tr>
<td>Padrio Varadega</td>
<td>70</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Fig. 4. Geomorphic map of the Mt. Legnoncino area (site 2 in Fig. 1). Rose diagrams show orientations of structural lineaments. Main structures affected by slope deformation are indicated.
rocky cliffs that dip slightly downslope and are probably associated with steep failure planes. The head scarp of the landslide has up to 80 m of relief and the same northeast trend as the other scarps. It is interpreted to be the daylighted portion of the main sackung failure surface. Three secondary scarps are present beyond the major scarp. They dislocate the Mt. Legnoncino ridge.

At lower elevations, close to Sommafiore, numerous minor scarps connect the northeast-striking schistosity to the northwest-trending structures on Mt. Letè. Some trenches in this area control the local drainage, which is here transverse to the slope (Val Rossello in Fig. 4).

The northwest-trending ridge between Mt. Piazzo and the Dorio–Mt Letè sector is dissected by a series of sharp northeast-trending scarps, counterscarps, and trenches. The slope is convex in profile below 650 m asl and is locally affected by landslides of different styles and states of activity. This morphology changes abruptly in the Rossello–Garavina area (Piona Sound), where a vertical rocky cliff up to 100 m high rises above a large talus slope supplied by rockfalls.

Statistical analysis of mapped scarps and other lineations reveals a dominant northeast trend, coincident with the strike of foliation. Results of laboratory tests on rock samples from the Mt. Legnoncino study area are summarized in Table 1.

Monitoring with distometers and extensometers located in the Mt. Letè area indicates slope displacements and fracture opening of the order of a few millimetres per year. Slow but continuous movements are further suggested by the gradual sinking of a paved road crossing a major fracture at 1141 m asl.

Roches moutonnées, parallel to and partially coincident with sackung lineaments, suggest that some slope deformation predates the LGM. Indications of ongoing activity include rockfall along the toe of the slope, large open fractures on the middle and lower slope, and railway and highway tunnel instabilities during severe rainstorms.

3.2.1. PS–SAR measurements

Satellite radar interferometry involves phase comparison of synthetic aperture radar (SAR) images, gathered at different times with slightly different angles of view (Curlander and McDonough, 1991; Ferretti et al., 1999, 2000, 2001a,b; Dehs et al., 2002). SAR is an active microwave device that records electromagnetic echoes back-scattered from the earth’s surface. If the dominant scatterers correspond to objects whose reflectivity does not vary through time, temporal decorrelation is negligible and changes in surface elevation can be determined with precision of 0.1–1.0 mm a\(^{-1}\). The point scatterer approach used with Differential SAR Interferometry (DinSAR) allows time histories of displacements since 1991–1992 to be determined, which is often not possible with more traditional methods such as levelling and GPS surveys.

Fig. 5 summarizes the results of a PS–SAR survey of the Dorio–Piona Sound area. PS locations and their average annual displacement rates (mm a\(^{-1}\)) are shown in this figure. The measured displacement rates range from \(-2\) to \(-20\) mm a\(^{-1}\) and are in good agreement with mapped lineations and recently (November 2002) reactivated landslides. The agreement is especially good for the Mt. Piazzo–Rossello and Sommafiore areas. Fig. 6 shows time–displacement histories for three different points (A, B, and C in Fig. 5) along the north flank of Mt. Legnoncino. Noteworthy is the response of the slope to the November 2002 rainstorm, when about 200 m of the roof of a highway tunnel in the Mt. Piazzo–Rossello–Sparese sector collapsed. The displacement rate along the Mt. Letè–Olgiasca–Piona peninsula progressively decreases in a downhill direction.

3.2.2. Numerical modelling

Two-dimensional and three-dimensional numerical models (Flac and Flac3D) have been prepared to better understand the postglacial evolution of the Mt. Legnoncino slopes. Two-dimensional models were initially run to evaluate the sensitivity of the models to boundary conditions, including glacial unloading and reloading and groundwater level. Data used in the 2D models included the initial slope profile and internal anisotropy (subvertical pervasive foliation planes). Below, we discuss only the results obtained from 3D modelling.

Slope geometry was obtained from a DEM of the area (5 m cell size). The limit of glaciation was estimated from field surveys and aerial photographic interpretation. We assumed Mohr–Coulomb behaviour associated with ubiquitous joints to simulate the northeast-trending foliation. Groundwater conditions were imposed by starting with present-day piezometric levels and increasing them during deglaciation, when, it is assumed, water availability was greater.

The model results indicate that plastic deformation initiates near the highest ridge just after deglaciation commences. A shear zone develops at this time and propagates toward the toe of the slope and then below lake level (190 m asl). The thickness of the failing mass increases from 50 m to more than 100 m during glacier retreat. Sections of the slope affected by tension are aligned in a northeast direction parallel to the foliation.
Fig. 7 shows displacements and shear strain in 2D and 3D revealing two maxima, one near Mt. Legnoncino and the other in the Mt. Piazzo–Sparèsè area. The latter was activated when the upper limit of ice was at 400 m asl. Maximum displacement rates are in the middle and lower parts of the slope; they decrease after deglaciation.

Fig. 6. Plots of displacement rate vs. time for sites A, B, and C in Fig. 5. Note the rate increases during periods of intense rainfall in 2001 and 2002.
but fall to zero only when the groundwater table becomes very low. We verified the sensitivity of the slope to changes in the groundwater table using data obtained during the November 2002 rainstorm. Under these conditions, the Piazzo–Sparise area and the Mt. Letè landslide scarp become the most active sectors.

At the end of the model run, three shear surfaces develop: one extending from Sommafiume to Mt. Legnoncino ridge; another beneath the entire slope at an average depth of 70–100 m; and a third from the Rossello deep trench to the toe of the slope (Fig. 7). The maximum displacements are near the Mt. Letè scarp. This pattern of displacements compares well with the observed dislocations and fractures, and with displacements measured by the PS–SAR technique (Figs. 5 and 6). The agreement suggests that the model is reliable and that the assumed material properties and boundary conditions are reasonable.

3.3. Livrio–Pizzo Campaggio–Pizzo Meriglio

The Livrio–Pizzo Campaggio–Pizzo Meriglio sackung (no. 3 in Figs. 1 and 8; Table 1) extends over an area of about 12 km². It is crossed in a north–north–
west direction by the Porcile Line (Fig. 2), which in this area dips steeply to the northwest. Garnet–biotite micaschists crop out southeast of the Porcile Line, and biotite paragneisses and quartz schists occur northwest of the line. Arenites and conglomerates of the sedimentary cover occur locally as fault slices along the Porcile Line. The Porcile Line converges obliquely with the Insubric Line. The sackung is located in a structurally complex zone in the area of convergence. Ice thicknesses at the LGM ranged from 700 to 1050 m in this area.

A large continuous head scarp delimits the sackung between Pizzo Campaggio and Punta della Piada (2120 m asl, Fig. 8). Smaller scarps, up to 5 m high and 300 m long, occur along the upper part of the slope, decreasing in frequency downslope. Scarps are common and up to 250–300 m long adjacent the Porcile Line, suggesting a brittle reactivation of the fault. Similar north–northwest-trending scarps and counterscarps occur near the northernmost limit of the sackung. They have maximum lengths of about 150 m and heights of 2 m, and intersect one another, creating a lozenge-like pattern.

Structures above 2000 m asl are partially masked by glacial deposits, and rockfall and large old slump deposits dominate below 1750–1950 m asl as far as the Livrio torrent, with only rare rock outcrops. More active, small- to medium-size landslides occur at the toe of the slope along the Livrio torrent.

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**Fig. 8. Geomorphic map of the Livrio–Pizzo Campaggio–Pizzo Meriggio area (site 3 in Fig. 1). Rose diagrams show orientations of structural and gravitational lineaments.**
Four main joint sets, striking east and northeast, were recognized through field surveys (Table 1). Lineaments parallel to the Porcile Line appear to control the morphology of the sackung.

The sackung dislocates glacial deposits (Fig. 8), suggesting a postglacial phase of activity. We cannot, however, preclude the possibility that the sackung has a longer history. Periglacial features (e.g., rock glaciers) are not dislocated; therefore, the sackung seems to be presently inactive. No monitoring data, however, are available to confirm this conclusion.

3.4. Armisa–Pizzo di Faila–Pesciola

The Armisa–Pizzo di Faila–Pesciola sackung (no. 4 in Figs. 1 and 9; Table 1) covers an area of 4 km² between Pizzo di Faila (2456 m asl) and Armisa. Garnet–biotite micaschists with lenses of amphibolite and quartzite are the prevalent lithologies in the area. Ice thicknesses during the LGM ranged from 700 to 1050 m. Conspicuous features at this site include a 100- to 150-m-wide valley (talzuschub) and a double ridge extending from Pesciola to the summit of Pizzo di Faila. A series of northwest-trending counterscarps extend north of Pesciola (1969 m asl) at a slightly oblique angle with respect to the downslope direction. The counterscarps are 50–150 m long and have a few metres of relief. They trend north across a disarticulated rock mass and then shift to the north–northwest.

Scars and counterscarps in the Pesciola area trend north–northeast before gradually rotating southward, becoming concave to the northwest, where the head

Fig. 9. Geomorphic map of the Armisa–Pizzo di Faila Pesciola area (site 4 in Fig. 1). Rose diagrams show orientations of structural and gravitational lineaments.
scarp follows the ridge to Pizzo di Faila. The double ridge at Pizzo di Faila trends north–northwest, is up to 30 m wide, has walls 5–8 m wide, and is delimited by foliation-parallel scarps sloping 40°–60°. Trenches between the ridges are partially filled with colluvium. This structure is associated with a deep failure surface with up to 70–80 m of dip-slip displacement, increasing toward Pizzo di Faila.

The lower half of the slope, below 1750 m asl, has a strongly convex profile resulting from large rotational landslides that overlap one another at different levels. A rock glacier at 1780 m asl in the central sector is cut by a series of northeast-trending counterscarps.

Most of the lineaments trend north–northeast trend, sub-parallel to the foliation, which dips 40°–50°. The foliation also controls the position and orientation of the head scarp.

The sackung is known to be postglacial in age because some rock glaciers are cut by scarps, counterscarps, and trenches. Most of the rock glaciers are vegetated and probably inactive. One rock glacier just west of Pizzo di Faila, however, is probably active; it too is crossed by scarps (Fig. 9), suggesting that slope deformation is continuing, at least in that area. The lower part of the sackung has a low level of activity, but some engineered structures along the torrent and subsurface hydroelectric tunnels have been damaged by slope movements.

3.5. Mt Padrio–Mt Varadega

The Mt. Padrio–Cima Verda–Mt. Varadega sackung is the largest of the five deep-seated slope movements reported in this paper, with an area of over 30 km² (no. 5 in Figs. 1, 2 and 10; Table 1). It is located on the south-eastern flank of Valtellina, between Tirano and Grocio, where the valley shifts from the north to the east. The maximum ice thickness in this area during the LGM ranged from 1400 to 1750 m, with nunataks above 2200–2400 m asl.

The site is structurally complex, because the west–southwest-trending Insubric Line approaches the Mortirolo Fault. The Insubric Line in this area is characterised by a zone of cataclastic rocks hundreds of metres thick. The Mortirolo Fault is an 800-m-thick mylonite shear zone located on the southern limb of the east-striking Mortirolo antiform. Low- to medium-grade gneisses and micaschists with interlayered amphibolite, marble, quartzite and pegmatite crop out north of the Mortirolo Fault, whereas higher-grade gneisses and micaschists are present to the south. The Mortirolo antiform has an east-plunging axis and is responsible for the repetition of mylonites in the study area (Figs. 2 and 10). The Mortirolo Fault was originally interpreted as a thrust, but Meier (2003) suggests that it formed by sinistral trans-tensional shearing during the late Cretaceous, followed by north-directed thrusting in the Eocene.

Mt. Varadega and Cima Verda are located on the hinge of the Mortirolo antiform. The axial plane of the antiform in that area dips 40° west–northwest. Statistical analysis of more than 2200 lineaments measured on aerial photographs (Fig. 10) shows that the dominant structures in the southern part of the study area trend northeast, parallel to the Insubric Line. In contrast, the dominant east–northeast-trending features in the northern part of the area are parallel to the Mortirolo Fault. The most conspicuous structures are located along the northeast-trending ridge between Cima Verda and Mt. Varadega. Head scarps more than 100 m high closely follow the ridge and the Mortirolo Fault.

Two deep ravines delimit the northern part of the sackung, which is characterised by longitudinal and transverse convexity. Here, close to Grosio, the valley floor is very narrow, due slope movements. The valley may be completely closed below the alluvial deposits of Adda River. Hydroelectric facilities, including a building, 382-m-long penstock (Figs. 10, 11 and 13), small storage reservoir, and long tunnel, have been deformed, with the deformation monitored since 1970.

Scarp, counterscarp, and grabens occur south of Grosio (A in Fig. 10). These features trend northeast and range from a few tens of metres to hundreds of metres in length, and 1 to 4 m high. Some of the scarps are superimposed on pre-existing brittle structures. The 2-km-long scarp crossing the slope in a northeast direction south of Mazzo (B in Fig. 1) is one such feature. It probably reactivated one of the late Eocene thrusts that are present in this area.

Middle and lower slopes, below 1500 m asl, are marked by numerous slumps and complex slides that collectively cover an area of more than 2 km² north of Mazzo, and by alluvial and debris flow fans.

3.5.1. PS–SAR measurements

About 300 point scatterers on the middle and lower slopes of the sackung were analyzed, yielding a consistent pattern of displacement (Fig. 11; Colesanti et al., 2004). The point scatterers correspond to both natural and artificial features, including bedrock outcrops, iron roofs, and metallic pylons. The vertical displacement rate decreases progressively downslope. Comparison of the data with mapped landslides reveals good agreement. Point scatterers with similar average rates of
displacement were associated with specific landslides or with different areas of the same landslide. We tried to define relations among measured rates of displacement, positions of point scatterers along the slope, and the inferred failure surface. We conclude that the progressive downslope decrease in the vertical displacement rate (Fig. 12) is linked to the presence of a semicircular or compound failure plane. The plane is steep in the upper slope sector and sub-horizontal or dips gently into the slope at the toe where small negative and positive values were measured. The interpretation, however, is difficult in the toe sector because thick alluvial sediments fill the valley bottom and mask the sackung. Nevertheless, topographic measurements were made between 1970 and 1985 along a penstock and at the hydroelectric power station mentioned above (Fig. 13). The time intervals during which the two different techniques were used are not the same, but we assume that the deformation was continuous and of similar magnitude over the period of measurement. At any rate, downslope movements are recorded at many points, with a rapid decrease in the rate of displacement in a downslope direction along the penstock. At the power station building, both the point scatterers and the levelling data show an upward movement, with similar values (0.75 and 1.0 mm a\(^{-1}\)).

The results indicate a roughly semicircular failure plane geometry, with localized active sectors and pos-
sible bulking of the slope close to or below the aluvial plain.

4. Discussion and conclusions

Sackung are complex mass movements controlled by many different factors: recent geological history (e.g. glaciation and deglaciation, periglacial conditions, erosion and valley deepening, tectonic stress, uplift, seismicity, and landsliding); structural features (joints, faults, foliations); slope materials (lithology, weathering, and metamorphism); topographic factors (slope length and gradient); and groundwater conditions. The five sackung discussed in this paper are located along a major tectonic feature, the Periadriatic Fault, and are developed in metamorphic rocks, mainly paragneisses, micaschists, and gneisses. All five of the sackung show evidence of early postglacial activity, suggesting that glacial debuttressing triggered, or set up the slope, for the initiation of the instability. Earthquakes may also play a role. Vertical crustal movements increase progressively towards the east, from about 0.95 mm a\(^{-1}\) in the Cortafo–Como Lake area to about 1.55 mm a\(^{-1}\) in the Padriro Varadega area (Schlatter and Marti, 2002). This distribution agrees with that of the seismic activity. Seismicity is low along the Lower and Middle Valtellina valley, but increases in the Upper Valtellina valley and the Chur area.

Fig. 14 summarizes the main results of this study, namely the measured displacements, high relief (950–2100 m), the frequency and geometry of mapped lineations, the deep failure planes and shear zones determined by 2D and 3D numerical modelling, and the favourable dip of the foliation with respect to sliding, flexural toppling, and shearing. Analysis of slope profiles shows that the average slope angles for the five
sackung are similar, ranging from 21° to 27°, with no difference between sackung in main valleys and those in tributary valleys. These angles are generally less than those of fresh deglaciated slopes and may represent values for slopes that are in dynamic equilibrium in these geological environments.

Fig. 14 also shows the spatial and geometric relations between the sackung and regional tectonic features. The Insubric Line and Mortirolo Fault are marked by swarms of primary and secondary faults and master joint sets associated with mylonitic and cataclastic rocks. We observed a strong relation between tectonic and gravitational features, suggesting a strong interplay between the two. This relation is evident, for example, in the cases of the Mt Cortafò and Legnoncino sackung, which are close to the Insubric and Musso lines, and the Mt Padrio–Mt Varadega sackung, located between the Insubric Line and the Mortirolo Fault. It is less evident for the Livrio–Pizzo Campaggio–Pizzo Meriggio sackung, probably because it occurs where the Insubric Line and the Porcile Line converge, and the north-northeast orientation of the Porcile Line is more favourable to slope instability following the trend of secondary valleys. The relation between tectonic and gravitational features is even less clear in the Armisa–Pizzo di Faila area, where the two are orthogonal to one another. The lack of an obvious relation between tectonic and gravitational features in this area could be due to proximity to the east-trending Orobic Fault and the presence of secondary discontinuities parallel to the maximum stress direction and to the direction of the valley.

Fig. 12. Plots of displacement rate vs. time for sites A–G in Fig. 11.

Fig. 13. Annual displacements measured along a penstock and at a hydroelectric power station at the toe of the Mt. Varadega slope (see Figs. 10 and 11 for location). Displacements were determined using geodetic and PS–SAR techniques. Cumulative displacements vs. time for the penstock and the main power station building are shown at the upper right.
The sackung exploit existing weaknesses in rock masses. Rock fabric thus, according to the numerical modelling results, can control the propagation of deep-seated gravitational slope deformation failures. Furthermore, the major tectonic features described in this study control the degree of fracturing, strength, and permeability. Figure 14 shows cross-sections of the five sackung described in this paper, highlighting the main gravitational features, inferred failure surface, apparent dip of foliation or schistosity, and the geometry of the main fault zone. Circles with arrows indicate average displacement rates determined by PS–SAR.
ability of the surrounding rock masses and facilitate the development of a quasi-continuous or continuous failure zone.

The PS–SAR results demonstrate that at least two of the sackung are moving under present climatic conditions and can accelerate during extreme rainfall events. The observed displacement rates range from a few millimetres to tens of millimetres per year (Table 3).

Analysis of the data allows us to discuss some of the conclusions about landscape adjustment to nonglacial conditions found in the literature (Bovis, 1990; Cruden and Hu, 1993; Ballantyne, 2002). Some authors suggest that the paraglacial period of landscape adjustment is limited to few thousand years. Total displacements on the slopes since the LGM ranges from about 100 to 500 m. These values can be divided by the time since the LGM (about 18,000 years) to determine average displacement rates (Table 2). The average displacement rates calculated in this manner are similar to those measured using the PS–SAR technique. Thus, the long-term rates can explain the total observed slope displacements, which suggests that, after triggering and acceleration, the sackung may have moved at a relatively constant rate. If so, the duration of the paraglacial interval could span tens of thousands of years, in agreement with the conclusions of Cruden and Hu (1993; duration of about 25,000 years) and Ballantyne (2002). These displacement rates and their distribution along the slopes also agree with the results of numerical modelling, showing a condition of continuous dynamic equilibrium with slow displacement rates after initial paroxistic phase. Numerical modelling also shows the importance of pervasive anisotropies, such as cleavage and foliation, major structural features, and groundwater in predisposing slopes to failure. Large displacements could not be generated on slopes with exceptional rocks without major structural discontinuities and without groundwater.

Our study suggests that sackung, which are generally considered as relicts on landslide inventory maps, must be reassessed. These slow, deep-seated gravitational movements can damage or destroy infrastructure, and sections of individual sackung may accelerate during rainstorms or with climate change.

A substantial improvement in understanding sackung can be obtained by evaluating the pattern of measured displacement rates in terms of possible geometries of the failure surface and by comparing the geometries with data acquired from drilling and seismic surveys. Remote sensing and numerical modelling can provide additional insights into the geometry of the failed mass and the future evolution of sackung.

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References


Table 3
Average displacement rates computed from observed total displacements since the LGM, and displacement rates measured by the PS–SAR technique for the Mt. Legnoncino and Mt. Padrio Varadega sackung

<table>
<thead>
<tr>
<th>Site</th>
<th>Observed displacement</th>
<th>Average computed displacement rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta x$ (m)</td>
<td>$\Delta y$ (m)</td>
</tr>
<tr>
<td>Mt. Legnoncino</td>
<td>439</td>
<td>219</td>
</tr>
<tr>
<td>Mt. Padrio–Varadega</td>
<td>228–355</td>
<td>135–220</td>
</tr>
</tbody>
</table>


