



# Inversion kinematics at deep-seated gravity slope deformations revealed by trenching techniques

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Received: 18 June 2015 – Published in Nat. Hazards Earth Syst. Sci. Discuss.: 5 August 2015

Revised: 8 February 2016 – Accepted: 25 February 2016 – Published: 9 March 2016

**Abstract.** We compare data from three deep-seated gravitational slope deformations (DSGSDs) where palaeoseismological techniques were applied in artificial trenches. At all trenches, located in metamorphic rocks of the Italian Alps, there is evidence of extensional deformation given by normal movements along slip planes dipping downhill or uphill, and/or fissures, as expected in gravitational failure. However, we document and illustrate – with the aid of trenching – evidence of reverse movements. The reverse slips occurred mostly along the same planes along which normal slip occurred, and they produced drag folds in unconsolidated Holocene sediments as well as the superimposition of substrate rocks on Holocene sediments. The studied trenches indicate that reverse slip might occur not only at the toe portions of DSGSDs but also in their central-upper portions. When the age relationships between the two deformation kinematics can be determined, they clearly indicate that reverse slips postdate normal ones. Our data suggest that, during the development of long-lived DSGSDs, inversion kinematics may occur in different sectors of the unstable rock mass. The inversion is interpreted as due either to locking of the frontal blocks of a DSGSD or to the relative decrease in the rate of downward movement in the frontal blocks with respect to the rear blocks.

## 1 Introduction

Deep-seated gravitational slope deformations (DSGSDs) consist of 10–100 m thick rock masses, which can involve the whole slope of a mountain and are affected by gravitational instability (Zischinsky, 1966; Nemcok, 1972; Radbruch-Hall

et al., 1977; Savage and Varnes, 1987). These phenomena have been intensively studied by several authors in terms of their geomorphological features (Mahr, 1977; Dramis and Sorriso-Valvo, 1994; Tibaldi and Viviani, 1999; Rohn et al., 2004) and geotechnical properties (Braathen et al., 2004; Pellegrino and Prestininzi, 2007), through numerical modelling (Forlati et al., 2001; Baron et al., 2005; Hürlimann et al., 2006; Ambrosi and Crosta, 2011; Apuani et al., 2013), analogue modelling (Chemenda et al., 2005; Bachmann et al., 2009), radar interferometry (Tarchi et al., 2003; Antonello et al., 2004; Saroli et al., 2005), structural methods (review in Stead and Wolter, 2015), and geophysical methods (Ferrucci et al., 2000; Meric et al., 2005; Pánek et al., 2009). In order to improve the hazard assessment of DSGSDs, the reconstruction of their kinematics is of paramount importance to gain a better knowledge of their evolution and expected ground deformation. This is usually achieved thanks to in situ instrumentation and radar interferometric techniques designed to analyse active structures. However, the above types of approach are applicable to slopes subjected to medium-to-high deformation rates (in the order of  $\text{mm yr}^{-1}$  to  $\text{cm yr}^{-1}$ ), whereas in the case of extremely slow to inactive DSGSDs, radar interferometric techniques are not a suitable option. At presently inactive DSGSDs, only trenching methods can be used to assess the age of the latest movements. Above all, it has been proven that DSGSD deformations develop not only as a consequence of creeping and progressive deformation (Genevois and Tecca, 1984; McCalpin and Irvine, 1995; Evans and Clague, 2003) but also through episodic movements (Beget, 1985; Thompson et al., 1997; McCalpin, 1999; McCalpin and Hart, 2003; Tibaldi et al., 2004; Gutiérrez-Santolalla et al., 2005). Since some DSGSDs can move

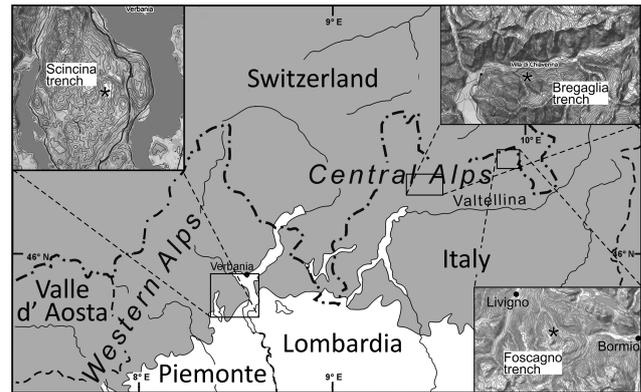
episodically separated by periods marked by very low activity or even inactivity, an approach based only upon in situ instruments or radar interferometric techniques is not always reliable enough to look into this type of DSGSD.

In recent years, palaeoseismological techniques such as artificial trenching have begun to be applied to DSGSDs (McCalpin and Irvine, 1995; Tibaldi et al., 1998, 2004; Onida et al., 2000; McCalpin and Hart, 2003; Gutiérrez-Santolalla et al., 2005; Tibaldi and Pasquaré, 2007; Gutiérrez et al., 2008, 2010, 2015; Agliardi et al., 2009; McCalpin et al., 2011; Pánek et al., 2011; Moro et al., 2012; Gori et al., 2014). By trenching methods, it is possible to reveal the presence of shallow deformation structures, measure their geometry and kinematics, and define their spatial and chronological characteristics. These data are fundamental to better constrain the structure of a DSGSD and to carry out numerical and analogue modelling with a more robust set of data inputs. Trenching also allows better understanding the significance of surface landforms produced by slope deformation. This methodology also enables assessing the age of the main past deformations, which is paramount to define the long-term behaviour of a DSGSD. Dating the main slope deformations, in turn, allows the comparison with other long-term possible influencing factors, such as climate changes, past extreme meteorological events, and earthquake-induced ground shaking. Since DSGSDs usually have a very long history, in the order of thousands of years, trenching is the only method that enables their behaviour to be reconstructed in a realistic time perspective. In view of the above-highlighted relevance of this methodology, in this work we combine and reinterpret our data coming from trenches excavated across gravitational structures in the Alps (Fig. 1). Such trenches have been selected because they show intriguing similarities to each other. The most striking similarity is represented by the presence of slip planes that have moved under different kinematics over time; we called this phenomenon “inversion kinematics” because it resembles the change from normal to reverse motions that may occur along fault planes during a change of the regional tectonic state of stress. Of course, at DSGSDs the reason behind the inversion of kinematics is different and will be widely discussed in the present paper. Moreover, the trenches illustrated here are located in different parts of DSGSDs, whereas most published works focus on trenches opened at the head scarp. Our data and interpretations might help shed light onto the workings of gravitational structures and contribute to understanding how DSGSDs may develop over time.

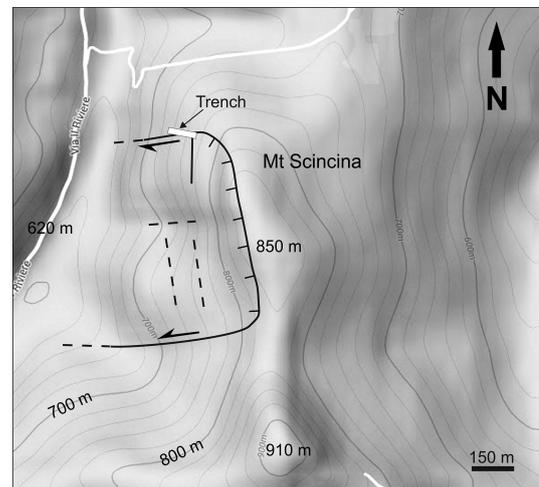
## 2 Case studies

### 2.1 Mt Scincina, western Alps

Tibaldi et al. (2004) documented the occurrence of a series of DSGSDs in a hilly region in Piedmont, in the western Italian Alps (Fig. 1). The DSGSD described here is lo-



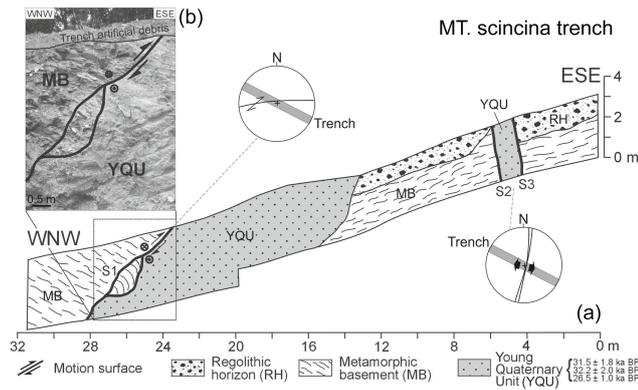
**Figure 1.** Location of the study areas in the context of the western and central Italian Alps.



**Figure 2.** Digital elevation model of the area of the deep-seated gravitational slope deformation (DSGSD) at Mt Scincina (western Alps, Italy), with location of the trench studied by way of palaeoseismological techniques, and trace of the main morphostructures identified at the DSGSD.

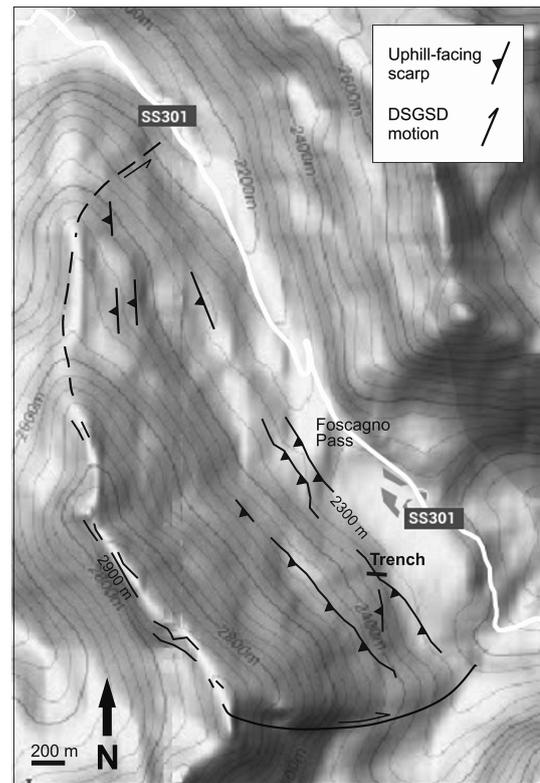
cated near Mt Scincina and affects a slope extending from 860 m a.s.l. down to 625 m in altitude (Fig. 2). The slope is characterised by slight changes in dip that reveal remnants of NNW–SSE-striking, uphill-facing scarps; these scarps were filled by sediments that smoothed out the morphology. The uppermost part of the slope terminates against a gently dipping downhill-facing scarp (i.e. to the WSW), mostly trending NNW–SSE, with an arcuate shape in plan view. The presence of this scarp is suggested by the fact that the slope facing towards the west, with respect to the Mt Scincina ridge, is much steeper than the slope facing to the east.

In order to better evaluate the age and kinematics of this DSGSD, an artificial trench located in the northern part of the slope is described here. The trench is about 35 m long and up to 4 m deep, and was opened during the construction of a gas pipeline. It is located at an altitude of 750–760 m



**Figure 3.** (a) Log of the northern trench wall excavated across the central-upper part of the DSGSD at Mt Scincina (western Alps, Italy; for location see Fig. 2). Note the superimposition of the substratum metamorphic rocks (MB) onto late Quaternary deposits (YQU) along reverse oblique slip plane S1. S2 and S3 are extensional fractures filled by YQU deposits. Stereograms (Schmidt's projection, lower hemisphere) show the geometry of slip planes and orientation of the trench. (b) Photo of the reverse oblique fault that puts into contact MB in the hanging-wall block with YQU in the footwall block (modified after Tibaldi et al., 2004).

and is trending  $117^\circ\text{N}$  (Figs. 2 and 3); the trench reveals three main fracture planes that correspond with the contacts between the metamorphic basement (MB) and Quaternary glacial deposits (younger Quaternary unit, YQU). The local basement is composed of micaschists belonging to the Scisti dei Laghi unit (Boriani et al., 1990). In the stratigraphic profile performed on the northern trench wall (Fig. 3a), starting from the left (i.e. west) there is a main slip plane (S1) dipping  $80^\circ$  downhill (in the log section the dip is apparent) with well-defined wall contacts and striae. The slip plane strikes  $85^\circ\text{N}$ , and the striae have a pitch of  $47\text{--}49^\circ\text{W}$  (see also the stereograms in Fig. 3). The plane puts basement metamorphic rocks in the hanging wall block on the northern side of the fracture into contact with glacial deposits from the Late Glacial Maximum (YQU, dated at  $26.5\text{--}32.2\text{ ky BP}$  through  $C_{14}$  methods; Tibaldi et al., 2004) in the footwall block. This geometry and the striae indicate transpressional kinematics with a subordinate right-lateral component. The right-lateral, strike-slip component is quite obvious due to the location of the trench at the northern side of the deforming slope, whereas the reverse-motion component is quite uncommon. A fish-eye structure (Fig. 3b) in the metamorphic rocks shows the bending of schistosity along the plane at the contact with YQU, consistent with the component of reverse motion. Close to the slip plane, the metamorphic rocks are intensely folded. A few metres away from the plane, the metamorphic rocks are marked by more open folds with axial surfaces dipping at low angles ( $10\text{--}15^\circ$ ) to the NNE. Further east, two  $20^\circ\text{N}$ -striking parallel vertical fractures are observed, 1.5 m apart from one another. They put YQU deposits



**Figure 4.** Digital elevation model of the area of the DSGSD near the Foscagno Pass (central Alps, Italy), with location of the trench studied by palaeoseismological techniques, and trace of the main Holocene morphostructures of the DSGSD.

into contact with metamorphic rocks in the form of a fissural structure that suggests an about E–W-trending dilation.

The remaining portions of the DSGSD are characterised by downhill-facing scarps in the upper section of the slope that suggest extensional deformations, and by a bulging of the slope toe.

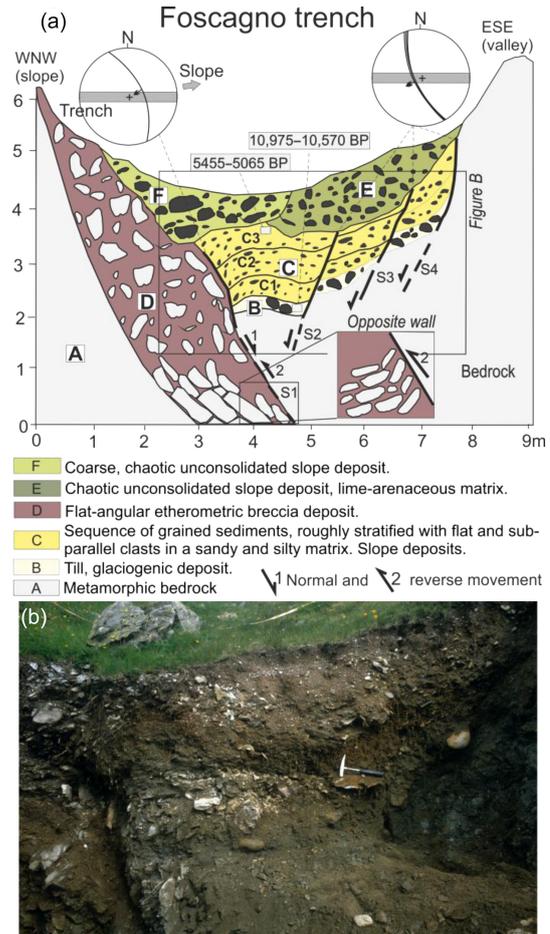
## 2.2 Foscagno Pass, central Alps

In the upper Valtellina region, central Alps (Italy), near the Foscagno Pass (Figs. 1 and 4), several indications of recent deformation can be observed. Such morphostructures mostly consist of downhill- and uphill-facing scarps, linear troughs, and double-crested ridges, regarded as the surface expressions of a DSGSD. The slope affected by the DSGSD extends from the mountain crest at about 2900 m a.s.l. down to 2260 m at the valley bottom. The total potential volume of the DSGSD is about  $1.5\text{ km}^3$ . Most of the mountain top is affected by a trench several metres to tens of metres wide. The trenches are parallel to the local slope and are bounded by two sub-parallel to parallel mountain crests, up to several metres in height. These structures indicate extensional deformation of the uppermost part of the unstable slope with a NE–SW to ENE–WSW direction of elongation. The cen-

tral and lower parts of the slope are characterised by several main, well-defined, uphill-facing scarps that strike NW–SE to NNW–SSE and are from a few tens of metres to 1 km long. These scarps are sub-parallel to the slope contour lines but have a more rectilinear trace in plan view (Fig. 4). This geometry suggests that the planes along which the motions took place are steeply dipping or sub-vertical. They cut the metamorphic bedrock as well as some of the surface deposits and glacial landforms attributed to LGM and post-LGM phases by means of radiometric dating (Calderoni et al., 1998) and field evidence (Forcella et al., 1998). The local basement is composed of dominant micaschists. The observed uphill-facing scarps do not show, in general, any correlation with rock fabric. Below we describe a trench dug across one of the uphill-facing scarps. The trench location was selected because it can reveal the subsurface structures that form near the toe of a DSGSD.

The trench was excavated into the lower part of the slope, at an altitude of 2320 m (Fig. 4). An analysis of the trench log reveals layers of poorly aggregated sedimentary deposits that rest on the metamorphic basement and are bounded by erosive or slip surfaces (Fig. 5). The lower units (marked as B–C in Fig. 5a), limited by a graben-like structure, rest in direct contact with the basement. The older units were dated through  $C_{14}$  methods at 10 975 yr BP, and the younger units at 5065 yr BP. They are intensely affected by slip planes, revealing a late Holocene age of deformation. In units B–C, the bedding is accentuated by textural features and the preferential elongation of pebbles. The alignment of pebbles shows a local bending, which can be correlated with slip planes having different size and kinematics. Downslope (i.e. eastward), three minor slip surfaces occur (S2, S3 and S4), which caused decimetre-sized normal dislocations through the basement–cover boundary and in the sedimentary layers (see also stereograms in Fig. 5). Upslope (i.e. westward), layers B–C are bent against the main slip plane (S1) that dips steeply in a downhill direction. Further westward (on the left-hand side of Fig. 5a), the deposit labelled D can be observed, the lowest portion of which is composed of in situ fractured basement rock that transitions up into a poorly organised deposit of boulders and pebbles encased in a matrix of clay and fine sand. Deposit D can be interpreted as the accumulation of scree into an open fissure. Moreover, deposit D is bent along plane S1 with a geometry that is consistent with reverse kinematics, as can be noticed in the box of Fig. 5 that shows an enlargement of the lower part of S1. All the above-described deposits and slip planes are unconformably covered and sealed by two heterogeneous, lenticular and chaotic debris flow deposits (E and F in Fig. 5).

An interpretation of the above-illustrated data suggests three main phases of deformation: (1) after the emplacement of deposits B–C, a first extensional phase produced the activation of the steeply dipping slip plane (S1) and the secondary planes S2–S4, along which normal movements took place, which resulted in a small asymmetric graben-like



**Figure 5.** (a) Log of the southern trench wall excavated across the lower DSGSD structure near the Foscagno Pass (central Alps, Italy; see Fig. 4 for location). Inset shows a log of the southern trench wall where the dragging of layers and clasts along the slip plane S1 is consistent with reverse movements. Plane S1 was previously an extensional fracture. Stereograms (Schmidt's projection, lower hemisphere) show the geometry of slip planes and orientation of the trench. (b) Photo of the trench wall included in the box of Fig. 5a.

structure; (2) this phase was followed by the formation of a wide sub-vertical open fissure along the uphill side of the graben, which acted as a trap for the infilling of detritus D; and (3) an inversion of kinematics occurred along the valley side wall of the previous fissure, and reverse movements developed along surface S1 as suggested by the dragging of layers. Although we are aware that the dragging of the rock fragments at the lower part of S1 could also have been caused by differential compaction of the deposit D that filled the original fissure, we believe that the presence of dragging also at deposits B, C1, C2 and C3 (Fig. 5a), consistent with a reverse kinematics, cannot be a mere coincidence.

2.3 Bregaglia Valley, central Alps

The third DSGSD we examined is situated in the Bregaglia Valley (central Alps, Italy) (Fig. 1) along the tectonic Gruf Line (Tibaldi and Pasquaré, 2007). The latter is a zone of intense ductile shearing corresponding to the verticalised tectonic contact between the Tambo nappe–Chiavenna ophiolite complex to the N and the Gruf migmatite complex to the S (Schmid et al., 1996; Berger et al., 1996). The mountain affected by the slope deformation rises to an elevation of 2370 m, and the valley bottom lies at an elevation of 520–630 m (Fig. 6). The DSGSD affects the slope from the valley bottom to a maximum elevation of about 1600 m. The slope dips towards the north and is interrupted by several downhill- and uphill-facing scarps, each from a few metres to several hundred metres long. Most of the identified scarps strike E–W, but some strike also WNW–ESE, especially in the northeastern sector of the DSGSD. Two deeply incised gorges bound the sides of the DSGSD. The rocks cropping out along these valleys are pervasively crushed, with several vertical to sub-vertical planes striking N–S to NW–SE that should correspond to the side walls of the DSGSD. The head of the DSGSD is represented by a northward steeply dipping scarp that represents the zone of detachment and coincides with the trace of the Gruf Line (Fig. 7b). This area was affected by a strong N–S extensional gravity deformation. The whole DSGSD is broken down into four main blocks, separated by three slip planes dipping at a high angle towards the valley floor (i.e. towards the north, Fig. 7), which highlight local strong N–S-directed gravity extensional deformation. The blocks are internally dissected by pervasive, subsidiary, synthetic and antithetic slip planes that indicate more complex local kinematics. The toe of the slope is characterised by a major bulging area that might represent a sector subjected to contractional deformation. The studied DSGSD can be regarded as belonging to the “block slide” type (Varnes, 1978) in view of the fact that (a) the basal sliding surface is well defined; (b) the movement of the DSGSD has occurred in a mainly translatory fashion; (c) internal slip planes break the DSGSD into different blocks; and (d) “horst and graben” type structures are noted near the top of the gravitational deformation (Fig. 7b).

The trench site is characterised by an ENE-striking, uphill-facing scarp that cuts the bedrock (Figs. 6 and 7 for location). The log of the wall exposed by the artificial trench reveals a series of slide surfaces affecting the bedrock and the sedimentary infill of the depression induced by the uphill-facing scarp (Fig. 8). It is possible to highlight that the deformation of the DSGSD was a multistage one, which developed through decreasing incremental offsets (i.e. older layers were subjected to larger offsets), until very small offsets (a few decimetres) were produced in the later stages. Above the metamorphic substrate (A) there is a coarse deposit encased in a silty matrix (B) and containing several boulders up to 60 cm in diameter. This deposit, characterised by a regular

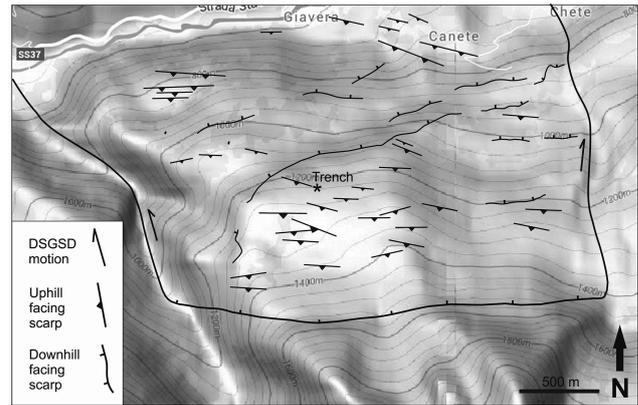


Figure 6. Digital elevation model of the area of the Bregaglia Valley DSGSD (central Alps, Italy), with location of the trench studied by way of palaeoseismological techniques, and trace of the main Holocene morphostructures of the DSGSD.

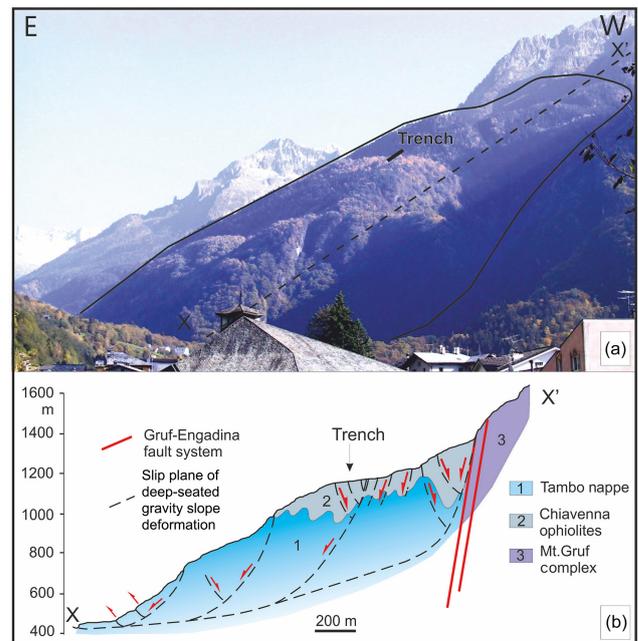
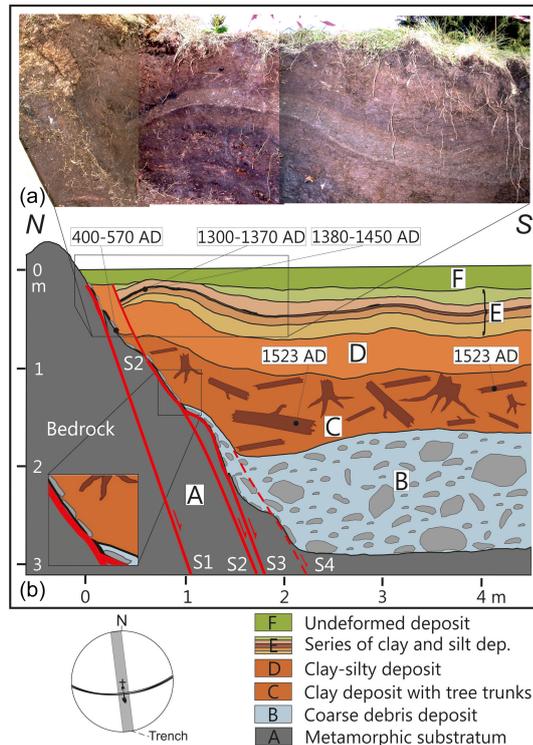


Figure 7. (a) Photo of the Bregaglia Valley DSGSD (central Alps, Italy) studied by palaeoseismological techniques and location of the artificial trench. The DSGSD is subdivided into four main blocks by three slip planes steeply dipping toward the valley floor. Arrows indicate the relative block movements. (b) Geological-structural section across the DSGSD. The location of the artificial trench of Fig. 8 is shown. Trace X–X’ of the section in Fig. 7a (modified after Tibaldi and Pasquaré, 2007).

thickness, abruptly abuts against slip plane S3 and is offset by slip plane S4 (see also the stereogram in Fig. 8). These slip planes are steeply dipping uphill (i.e. southward); moreover, S3 merges upward with slip plane S2. Quite a few fragments from deposit B are aligned along S1 and the upper sector of S2, all the way up to a few decimetres from the to-



**Figure 8.** (a) Photo of a portion of the wall exhumed during the excavation of the artificial trench at the Bregaglia Valley trench and (b) complete log of the same wall. A series of slide surfaces offset the bedrock and the sedimentary infill of the depression induced by the uphill-facing scarp. Note that offset increases with the age of the layers. Absolute dating was obtained by radiocarbon  $^{14}\text{C}$  and dendrochronology techniques. Note the dragging of strata along slip plane S2, compatible with a small uplift of the hanging wall block located uphill of the slip planes. Stereogram (Schmidt's projection, lower hemisphere) shows geometry of the slip planes and orientation of the trench (modified after Tibaldi and Pasquaré, 2007).

pographic surface (small box in Fig. 8b). Above B, deposit C is characterised by several tree fragments and is overlain by a series of thin silt and clay deposits (D and E). Layers D and E are folded against slip plane S2, indicating reverse motions. The undeformed and most recent clay–silt deposit F lies unconformably above deposit E. The lower stratigraphic unit (B), which was sampled along the slip plane, was dated to AD 400–570, whereas the upper unit (E) was dated to AD 1380–1450 and AD 1300–1370. Dendrochronology age determinations performed on two trunks of Alpine larch trees from unit C provided the same year: AD 1523 (Tibaldi and Pasquaré, 2007).

The above-illustrated data suggest the following evolution: (1) an extensional phase affected the studied sector of the DSGSD as proved by the emplacement of a series of sedimentary units in onlap against an uphill-facing scarp, starting with unit B, and the deformation was incremental with the larger offset at unit B along plane S3 and possibly along

plane S4; (2) deposit C partially filled the depression and was followed by deposition of units D and E in the interval AD 400–1523; (3) further normal movements occurred after AD 1523, as witnessed by small normal offsets affecting also deposits C and D, along some of the slip planes (however, it is problematic to quantify them); slip planes S3 and S4 locked; and (4) slip plane S2 inverted its kinematics, producing the dragging of layers D and E, compatible with reverse motions.

### 3 Discussion

#### 3.1 Extensional deformation

Before discussing our observations and results, a cautionary note is needed here: we are aware that trenches can provide insights into the age and kinematics of DSGSD structures, but only at the shallowest level. Despite this, trenches and palaeoseismological techniques have been widely used in recent times to shed light on the above characteristics of DSGSDs. It would always be advisable to dig more trenches in different positions of a DSGSD, in order to obtain a better spatial resolution; however, this is not always feasible mainly due to logistical reasons.

The palaeoseismological analyses illustrated in this work were performed on trenches excavated in different locations of three DSGSDs; the Foscagno trench is located in the toe section of the DSGSD, whereas the Scincina and Bregaglia trenches are located in the central-upper part of the slope, at about two-thirds of the length of the DSGSDs. All trenches show the presence of extensional deformations: at Bregaglia and Foscagno they are expressed in the form of slip planes dipping downhill or uphill, with normal kinematics. Within the Foscagno and Scincina trenches there is also evidence of formation of extensional fissures along vertical to sub-vertical planes striking normal to the general slope dip. At the Foscagno trench, it has been possible to establish that extensional fissuring developed only after the formation of the first normal slip planes. As a consequence, the Foscagno site suggests that activation of at least a part of a DSGSD can originate from progressive downslope movements of the unstable rock mass along discrete slip planes. Successively, slip locking can occur and extension is released by fissure deformation. The presence of these two types of deformation has been detected also at the Scincina site; however, here the exposure did not allow the establishment of the relative chronology of deformation. At other DSGSDs, especially in sedimentary rocks, it has been proposed that fissuring usually precedes the development of normal slip planes (e.g. Margielewski and Urban, 2003). We stress that caution should be taken in generalising the mode of deformation at DSGSDs because, as shown by our data, the steps of development of the rock mass instability may be more complex, depending on several different parameters.

Regarding the relations of fissuring vs. normal slip planes with respect to the presence of predisposing mechanical anisotropy, in the Bregaglia Valley study, the upper boundary of the DSGSD originated along the tectonic Gruf Line (Fig. 7b). Most of the slip planes of this DSGSD strike in the same trend as the Gruf Line, suggesting that, here, ancient tectonic deformation events produced a preferential rock anisotropy. Gravity reactivated part of these tectonic structures that correspond to the upper vertical to sub-vertical sections of the DSGSD slip planes. This situation seems to favour the inception and development of slip planes instead of extensional fissuring, as confirmed by the fact that the latter deformation type is not present at the Bregaglia trench site. The dominance of slip planes has also been documented at other trench sites within DSGSDs, such as at Mt Morrone (Appennines, Italy) (Gori et al., 2014), whose data revealed that the DSGSD initiated after the activation of a dip-slip fault. The activity of this fault resulted in increased local relief, while another close tectonic fault acted as a sliding plane in its surficial portion. The activity of both faults produced structural features and discontinuities that weakened the rock mass and provided preferential sliding zones. A similar situation has been observed also at another DSGSD studied by means of palaeoseismological techniques at Mt Serrone (central Italy) by Moro et al. (2012). Also in the Carpathian Mountains, Pánek et al. (2011) suggested that the spatial coincidence of gravitational morphostructures with an inherited structural anisotropy represents evidence of a strong predisposition of the initiation of DSGSDs to be controlled by pre-existing tectonic structures, a characteristic that has been more and more discussed lately (see Stead and Wolter, 2015, and references therein).

However, at the two other trench sites described in this work (Foscagno and Scincina), there are no geometric relations between gravity structures and regional tectonic structures. This means that pure gravity forces were able to induce rupture of the rocks along planes of shear concentration, independent of the pre-existing rock anisotropy. A possible explanation is that, at Foscagno and Scincina, local tectonic structures are not suitably oriented to develop into gravity slip planes, whereas at the Bregaglia site the Gruf tectonic line is sub-vertical and perpendicular to the slope dip.

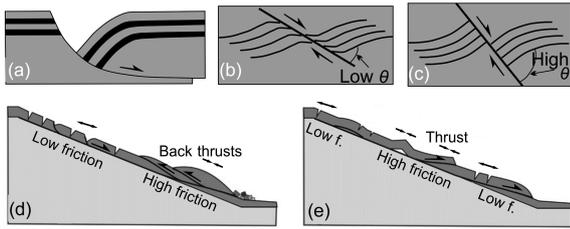
### 3.2 Inversion kinematics

At all the studied trench sites we documented the presence also of reverse kinematics. The reverse motions are expressed by drag folds of the recent sedimentary strata that infilled the previous depressions created by the DSGSD uphill-facing scarps or by extensional fractures. The recent sedimentary strata are folded against the slip planes with a unique geometry. Moreover, at the Foscagno and Scincina trench sites, the substratum rocks are displaced in the hanging wall block above the Holocene sedimentary strata, which compose the footwall block. Finally, also plate-like clasts are systemati-

cally re-oriented along slip planes (Fig. 5a), a geometry that is compatible with reverse kinematics.

Other different possible causes for these compressional deformations, such as neotectonics and glacioteconics, have to be ruled out. In fact, if the observed reverse motions had been induced by recent regional tectonics, they should be the expression of surface faulting. Since there is a well-established relationship between earthquake magnitude and the capability of a tectonic fault to reach the surface, it would be necessary to consider that an earthquake with at least a  $M > 5$  produced this surface tectonic faulting (Wells and Coppersmith, 1994; Anderson et al., 1996). Instead, the seismicity of the studied areas is very low, with most earthquakes having  $M < 3$  and very rare events with  $3 < M < 4$  (Akinci et al., 2004; Chiarabba et al., 2005). Moreover, if we consider the relationship between the length of surface tectonic faulting, surface offset and magnitude, the scarps along which the studied reverse kinematics occurred are too short. Also glacioteconics have to be ruled out because the studied drag folds occurred in the late Holocene when glaciers no longer covered the studied areas. Moreover, drag folds developed inside protected depressions carved in the slopes, or even at some metres of depth such as at the Foscagno trench. In any case, glacioteconics could not play any role whatsoever in the observed structural superimposition of metamorphic rocks above Holocene strata, documented at the Scincina trench.

Alternative interpretations in a more strictly structural sense might be (i) dragging along listric planes and (ii) reverse fault dragging. Regarding point (i), it is well known that movements along a fault which is not rectilinear in section view require adaptation of the rock volume in the hanging wall block as a consequence of changing fault dip (Wernicke and Burchfiel, 1982; Dula Jr., 1991; Higgs et al., 1991; Ruch et al., 2010). In the case of a fault plane whose dip decreases with depth, a roll-over anticline may develop (Fig. 9a). In this case, the bending of the hanging-wall layers develops in relation to the greater decrease in fault dip. However, in our case studies this possibility needs to be ruled out as there is no change in attitude of the slip planes along which the drag folds developed; hence, a geometric adaptation of the hanging-wall layers is not required. In regard to point (ii), as can be seen in Fig. 9b, usually a normal fault can show fault dragging which is compatible with the sense of shear. Instead, the phenomenon of reverse fault dragging is represented by the possibility that normal faulting was accompanied by an apparent dragging that suggests an opposite sense of slip, i.e. reverse movement (Fig. 9c) (Grasemann et al., 2005). These authors suggested that reverse dragging may stem from perturbation flow induced by fault slip. Material on both sides of the fault is displaced, and “opposing circulation cells” arise on opposite fault sides. This anomalous pattern may develop at the fault centre, depending on the angle  $\Theta$  between the layers and the fault: a correct dragging develops there for low angles ( $\Theta < 30\text{--}40^\circ$ ), and an “apparent”



**Figure 9.** (a) Bending of strata due to adaptation along a listric normal fault (rollover anticline); (b) normal fault with normal bending of layers, coherent with the sense of shear; (c) normal fault with reverse (apparent) sense of shear due to a high angle  $\Theta$  (b and c redrawn after Grasemann et al., 2005); (d) development of low-angle back thrusts at the toe of a DSGSD; (e) development of low-angle back thrusts and other contractional deformations in different parts of a DSGSD due to spatial changing in friction (d and e modified after Braathen et al., 2004).

reverse drag for higher angles. In our studied trenches, we do admit that the angle between the deformed layers and the slip plane is  $>40^\circ$ , and thus theoretically apparent reverse fault dragging might have occurred. However, the surface condition studied at the trenches is very different from the depth condition analysed in the work of Grasemann et al. (2005). Moreover, the studied bending of layers is observed in the uppermost part of the slip plane, near the tip, and not in the central part of a fault where reverse dragging may occur. We also emphasise that in our case we clearly observed also the superimposition of substrate rocks onto Holocene deposits, which indicate an unambiguous reverse kinematics.

We conclude that our field data suggest that slip planes inherited from a previous phase of extensional deformation, linked to the earlier development of the three studied DSGSDs, were re-activated in the form of reverse kinematics. As far as we know, these are the first artificial trenches that, by means of palaeoseismological observations, illustrate the presence of compressional deformations within DSGSDs. Moreover, since our trenches are placed in different positions within the DSGSDs, we also document the possible kinematic inversion with development of reverse slip planes in different parts of the unstable slopes.

At the Foscagno and Bregaglia trenches, since uphill-facing scarps are still present, the reverse offsets were not large enough to nullify the previous normal offsets. At the Scincina site, a morphological scarp is not present in the reverse slip plane. This may be due to deletion of previous normal offset by kinematic inversion, or because the latest offset is older than at the other trench sites and thus at Scincina the scarp was eroded away, or a combination of both. In agreement with the latter interpretation, the deformed deposits at Scincina have an age of 34.2–28.5 ky, whereas at the other trenches the deformed deposits are much younger (deformations younger than 7455 yr).

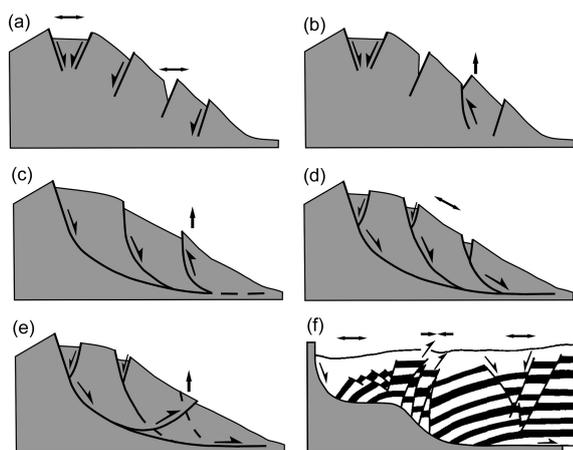
Compressional features have been recognised by Braathen et al. (2004) at the surface of slopes affected by large deep-seated instability, such as in the Norwegian mountains. Braathen et al. (2004) described the possibility of the development of extensional structures in the upper part of a DSGSD, linked to low basal friction, and contractional features at the toe expressed by a stacking of blocks by back thrusting. The contractional part may be due to high friction along the basal surface, or to “ploughing” due to blocking of the toe (Fig. 9d). Braathen et al. (2004) suggested also a more complex scenario with higher parts of the DSGSD under compression due to spatially changing basal friction (Fig. 9e). Finally, the change of the basal friction value can be associated with variation in the geometry of the basal slip plane. However we need to stress that, in the above cases, low-angle reverse faults have been consistently observed, different from what is seen in our trenches where slip planes subjected to reverse motions are steeply dipping. Low-angle reverse slip planes and other contractional structures such as folds have been recognised at the toe of DSGSDs by Mahr and Nemčok (1977), Savage and Varnes (1987), Chigira (1992), Hermann et al. (2000), Baron et al. (2004), and Hippolyte et al. (2006).

### 3.3 Mechanisms of overall deformation

The studied DSGSDs show different mechanisms of overall deformation. The Foscagno DSGSD is characterised by a series of parallel, uphill-facing scarps, rectilinear in plan view, and by the presence of a double crest at the mountain top (crest trench) (Fig. 4). These structures are typical of a sackung-type overall deformation mechanism, as illustrated in Fig. 10a. After normal slip and fissuring, reverse motions developed here along a slip plane steeply dipping downhill, suggesting a change in the kinematics and geometry of deformation, as shown in Fig. 10b.

The Scincina DSGSD is characterised by an overall amphitheatre morphology with a semicircular head scarp (Fig. 2) and narrowing of the valley bottom compatible with bulging at the foot of the DSGSD. These morphostructures are more typical of translational movements along downhill-dipping main slip planes (Fig. 10c). The development of transpressional kinematics with a dominant reverse component found at the Scincina trench site suggests locking of the downhill movement of the frontal block with consequent back thrusting. Back thrusting has two components of deformation: one of contraction along the slope dip, and one of uplift as indicated by the arrow in Fig. 10c. At both the Foscagno and Scincina sites, the block located downhill of the trench (i.e. downhill of the reverse fault) experienced uplift.

The Bregaglia DSGSD is characterised by a well-developed system of downhill- and uphill-facing scarps, with main slip planes dipping towards the valley floor and antithetic slip planes. It is possible that at least one well-developed, basal slip plane extends as far as the valley bottom



**Figure 10.** Section views across different models of DSGSDs. (a) Development of extensional structures at a sackung-type DSGSD; (b) inversion kinematics at a sackung-type DSGSD; (c) translational type with inversion kinematics due to locking of the toe block; (d) well-developed translational type, or block slide type, with antithetic slip planes; (e) same as (d) with reverse movements along an uphill-dipping slip plane; (f) development of reverse slip planes above a basal shear with a complex geometry of the “ramp and flat” type. (a after Gutiérrez-Santolalla et al., 2005; c and e consistent with Jaboyedoff et al., 2013; f modified after McClay and Ellis, 1987).

(block-slide type) (Fig. 10d). However, this architecture does not “explain” the inversion of movement found at the trench site, which is represented by uplift of the block located uphill of the trench (i.e. the block uphill of the reverse fault). This is compatible with an episode of forward thrusting, due either to the locking of a block in a more frontal position or to a higher rate of downslope movement of the rear block with rotational movements (Fig. 10e). This may produce the local, reverse reactivation of a previously normal slip plane also at a higher elevation within the DSGSD.

Another possibility for the development of reverse motions during the evolution of a DSGSD is represented by the presence of a main basal slip plane with a complex geometry. The sketch of Fig. 10f, which refers to an analogue model developed by McClay and Ellis (1987) for extensional tectonics, is provided just as an example of the complexity of structures that may develop above a multi-curved basal plane, and caution must be taken when applying it to real-case DSGSDs. However, this example with a “ramp and flat” type geometry of the basal plane in section view shows that the hanging-wall block undergoes different deformation during the translation of the rock succession above parts of the basal sliding plane marked by different geometries: the translation above parts of the sliding plane with a downward convex side produces local extension, whereas the translation above parts with an upward convex side produces local compression. During the slip of the DSGSD rock mass, different parts of the rock succession may experience translation across the extensional

dominion and then across the compressional domain. This creates the conditions for inversion of kinematics. The hypothesis that the basal sliding planes of the Bregaglia or the Scincina DSGSDs may be marked by a complex geometry cannot be ruled out.

Regarding the lithology of the involved rock masses, it can be pointed out that the Foscagno and the Scincina DSGSDs are characterised by a quite monotonous succession of micascists, whereas the Bregaglia DSGSDs have more varied lithologies, albeit all belonging to metamorphic rock types. Although it may be claimed that the presence of different lithotypes at the Bregaglia site is consistent with the more complex structural architecture of this DSGSD, we argue that the amount, orientation and kinematics of the various slip planes of a DSGSD can result from a more complex series of parameters; these may be explained in terms of (i) the presence of slip planes inherited from previous tectonic phases, (ii) the amount of gravity deformation and hence the degree of development of the DSGSD, (iii) the geometry of the basal main slip plane, (iv) the topography, and (v) the lithology of the involved rock types.

### 3.4 Creep vs. stick-slip behaviour and related hazard

The hazard posed by DSGSDs can be very different based on their behaviour. The literature suggests that DSGSDs generally evolve with long-term creep movements (e.g. Bisci et al., 1996), although episodic accelerations of deformation can occur (McCalpin and Irvine, 1995). In the case of large, sudden offset at a DSGSD, the hazard can be much larger with the possibility of having local very shallow earthquakes due to stick-slip and more diffuse damage to the infrastructures and edifices resting above the sliding block.

The trenches analysed in this work are useful to gain further insight into the evolution of deformation at DSGSDs and to help improve hazard assessment. We also believe that the application of trenching techniques can help to better understand the behaviour of DSGSDs elsewhere. The Scincina and Foscagno trenches show the presence of buried debris wedges developed at the foot of the slip plane scarp. In tectonic contexts, debris wedges usually result from the erosion of fault scarps exhumed by coseismic increments of fault offsets and can be individuated based on their inner lithological characteristics, the presence of palaeosoils, and the geometry of their limiting surfaces (McCalpin, 2009, and references therein). The same debris wedges may be, in turn, offset by successive increments of faulting. The formation of a debris wedge is related to the rapid and localised erosion induced by the creation of an unstable scarp. However, the slow continuous faulting of the creeping type is usually not accompanied by any debris wedge formation. In the case of an uphill-facing scarp, creeping movements may act as a continuous trap for colluvial deposits originating uphill. This geometry, with deposits overlapping the uphill-facing scarp, is more consistent with our observations at the Bregaglia trench, and thus

here creeping probably represents the main mechanism of deformation.

Instead, the presence of debris wedges at the Foscagno DSGSD, supported also by findings at other trenches there (Forcella et al., 2001), indicates that this DSGSD moved through sudden increments in movement, which resembles the stick-slip behaviour of tectonic faults. We point out that, also in other instances, palaeoseismological investigations at trenches showed the presence of debris wedges compatible with a stick-slip behaviour, such as at the Mt Serrone DSGSD (Italy) (Moro et al., 2012) and at the Canelles Reservoir DSGSD (Spain), where a sudden slip increment took place in correspondence with a historic earthquake (Gutierrez et al., 2015). At the Mt Morrone DSGSD, Gori et al. (2014) documented a dominant creeping behaviour, punctuated by abrupt gravitational displacements, similar to several other examples of DSGSDs studied by means of trenches.

However, our work suggests taking caution in establishing the creeping behaviour of a DSGSD. In fact, it has to be clarified that the inversion of kinematics along the sliding planes is accompanied by fault scarp enhancement, and thus debris wedge formation, if the uplifting block is located downward with respect to the fault, as in the case of the Scincina and Foscagno trenches. However, if the uplifting block is located uphill with respect to the normal slip plane with an inverted kinematic, as in the case of the Bregaglia trench, the scarp is subjected to a reduction in height. As a consequence of the above, in the latter case the debris wedge will not form and the possible occurrence of stick-slip motion will not be recorded.

#### 4 Conclusions

Through the application of paleoseismological techniques in artificial trenches excavated in different position at three DSGSDs in the Italian Alps, it has been possible to observe that at all trenches there is evidence of extensional deformations, given by normal movements along slip planes dipping downhill or uphill, and/or fissures, as expected in gravitational failure. At the Foscagno trench, cross-cutting relationships with the deposits indicate that fissure formation postdates the development of steeply dipping slip planes, suggesting that fissuring does not always precede shear.

Moreover, we illustrated in trenches evidence of reverse motions. The reverse slips occurred mostly along the same planes that hosted the normal slips and produced drag folds of unconsolidated Holocene sediments and superimposition of substrate rocks onto the same sediments. This suggests the possibility of inversion kinematics at DSGSD slip planes. Since we found inversion kinematics at trenches located in different positions with respect to the slope affected by the DSGSD, we also propose that reverse slip might occur both at the toe of slope deformation and in its central-upper sector.

Inversion kinematics may be due either to the effect of locking of frontal blocks of a DSGSD or to the relative

decrease in the rate of downward movement of the frontal blocks with respect to the rear blocks.

*Author contributions.* Both authors studied the three trenches in the field. Federico Pasquaré Mariotto described the Bregaglia Valley trench in the manuscript; Alessandro Tibaldi described the other two trenches. Both authors contributed to the discussion and conclusions.

*Acknowledgements.* This work is dedicated to our teacher and then colleague and friend Franco Forcella, who introduced us to the study of deep-seated gravity slope deformations. He will always remain in our memory. We acknowledge the precious comments and suggestions on an earlier version of the paper by two anonymous referees and the editor, Andreas Günther.

Edited by: A. Günther

Reviewed by: two anonymous referees

#### References

- Agliardi, F., Crosta, G., Zanchi, A., and Ravazzi, C.: Onset and timing of deep-seated gravitational slope deformations in the eastern Alps, Italy, *Geomorphology*, 103, 113–129, 2009.
- Akinci, A., Mueller, C., Malagnini, L., and Lombardi, A. M.: Seismic hazard estimate in the Alps and Apennines (Italy) using smoothed historical seismicity and regionalized predictive ground-motion relationships, *B. Geofis. Teor. Appl.*, 45, 285–304, 2004.
- Ambrosi, C. and Crosta, G. B.: Valley shape influence on deformation mechanisms of rock slopes, *Geol. Soc. Spec. Publ.*, 351, 215–233, 2011.
- Anderson, J. G., Wesnousky, S. G., and Stirling, M. W.: Earthquake size as a function of fault slip rate, *B. Seismol. Soc. Am.*, 86, 683–690, 1996.
- Antonello, G., Casagli, N., Farina, P., Leva, D., Nico, G., Sieber, A. J., and Tarchi, D.: Ground-based SAR interferometry for monitoring mass movements, *Landslides*, 1, 21–28, 2004.
- Apuani, T., Corazzato, C., Merri, A., and Tibaldi, A.: Understanding Etna flank instability through numerical models, *J. Volcanol. Geoth. Res.*, 251, 112–126, 2013.
- Bachmann, D., Bouissou, S., and Chemenda, A.: Analysis of massif fracturing during deep-seated gravitational slope deformation by physical and numerical modelling, *Geomorphology*, 103, 130–135, 2009.
- Baron, I., Cilek, V., Krejci, O., Melichar, R., and Hubatka, F.: Structure and dynamics of deep-seated slope failures in the Magura Flysch Nappe, outer Western Carpathians (Czech Republic), *Nat. Hazards Earth Syst. Sci.*, 4, 549–562, doi:10.5194/nhess-4-549-2004, 2004.
- Baron, I., Agliardi, F., Ambrosi, C., and Crosta, G. B.: Numerical analysis of deep-seated mass movements in the Magura Nappe; Flysch Belt of the Western Carpathians (Czech Republic), *Nat. Hazards Earth Syst. Sci.*, 5, 367–374, doi:10.5194/nhess-5-367-2005, 2005.
- Beget, J. E.: Tephrochronology of antislope scarps on an alpine ridge near Glacier Peak, Washington, USA, *Arctic Alpine Res.*, 17, 143–152, 1985.

- Berger, A., Rosenberg, C., and Schmid, S. M.: Ascent, emplacement and exhumation of the Bergell pluton within the Southern steep belt of the Central Alps, *Schweiz Miner. Petrol.*, 76, 357–382, 1996.
- Bisci, C., Dramis, F., and Sorriso-Valvo, M.: Rock flow (sackung), in: *Landslide Recognition, Identification, Movement and Causes*, edited by: Dikau, R., Brunsten, D., Schrott, L., and Ibsen, M. L., John Wiley and Sons, New York, USA, 150–160, 1996.
- Boriani, A., Giobbi Origoni, E., Borghi, A., and Caironi, V.: The evolution of the Serie dei Laghi (Strona-Ceneri and Scisti dei Laghi): the upper component of the Ivrea-Verbano crustal section; Southern Alps, North Italy and Ticino, Switzerland, *Tectonophysics*, 182, 103–118, 1990.
- Braathen, A., Blikra, L. H., Berg, S. S., and Karlsen, F.: Rock-slope failures of Norway, type, geometry deformation mechanisms and stability, *Norsk Geol. Tidsskr.*, 84, 67–88, 2004.
- Calderoni, G., Guglielmin, M., and Tellini, C.: Radiocarbon dating and postglacial evolution, upper Valtellina and Livignese area (Sondrio, Central Italian Alps), *Permafrost Periglac.*, 9, 275–284, 1998.
- Chemenda, A., Bouissou, S., and Bachmann, D.: Three-dimensional physical modeling of deep-seated landslides: New technique and first results, *J. Geophys. Res.-Earth*, 110, F04004, doi:10.1029/2004JF000264, 2005.
- Chiarabba, C., Jovane, L., and DiStefano, R.: A new view of Italian seismicity using 20 years of instrumental recordings, *Tectonophysics*, 395, 251–268, 2005.
- Chigira, M.: Long-term gravitational deformation of rocks by mass rock creep, *Eng. Geol.*, 32, 157–184, 1992.
- Dramis, F. and Sorriso-Valvo, M.: Deep-seated gravitational slope deformations, related landslides and tectonics, *Eng. Geol.*, 38, 231–243, 1994.
- Dula Jr., W. F.: Geometric Models of Listric Normal Faults and Rollover Folds, *AAPG Bull.*, 75, 1609–1625, 1991.
- Evans, S. G. and Clague, J. J.: Origin and activity of antislope scarps in the mountains of southwestern British Columbia, *Geol. Soc. Am., Abstracts with Programs*, 35, p. 310, 2003.
- Ferrucci, F., Amelio, M., Sorriso-Valvo, M., and Tansi, C.: Seismic prospecting of a slope affected by deep-seated gravitational slope deformation: the Lago Sackung, Calabria, Italy, *Eng. Geol.*, 57, 53–64, 2000.
- Forcella, F., Onida, M., and Tibaldi, A.: Risultati preliminari di un'indagine di tipo paleosismologico applicata allo studio di deformazioni recenti in ambiente alpino, alta Valtellina (Alpi Centrali, Italia), *Geol. Insubr.*, 3, 63–72, 1998.
- Forcella, F., Tibaldi, A., Onida, M., and Galadini, F.: Tecniche paleosismologiche per lo studio di deformazioni gravitative profonde di versante in ambiente alpino: esempi nella Valle del Foscagno e al Passo del Mortirolo (Alpi Centrali, Italia), in: *Tettonica Recente e Instabilità di Versante nelle Alpi Centrali*, edited by: Pasquaré, G., Vol. Spec. CARIPO, Milano, 103–149, 2001.
- Forlani, F., Gioda, G., and Scavia, C.: Finite element analysis of a deep-seated slope deformation, *Rock Mech. Rock Eng.*, 34, 135–159, 2001.
- Genevois, R. and Tecca, P. R.: Alcune considerazioni sulle deformazioni gravitative profonde in argille sovra consolidate, *Boll. Soc. Geol. Ital.*, 103, 717–729, 1984.
- Gori, S., Falcucci, E., Dramis, F., Galadini, F., Galli, P., Giaccio, B., Messina, A., Pizzi, P., Sposato, A., and Cosentino, D.: Deep-seated gravitational slope deformation, large-scale rock failure, and active normal faulting along Mt. Morrone (Sulmona basin, Central Italy): Geomorphological and paleoseismological analyses, *Geomorphology*, 208, 88–101, 2014.
- Grasemann, B., Martel, S., and Passchier, C.: Reverse and normal drag along a fault, *J. Struct. Geol.*, 27, 999–1010, 2005.
- Gutiérrez, F., Ortuño, M., Lucha, P., Guerrero, J., Acosta, E., Coratza, P., Piacentini, D., and Soldati, M.: Late Quaternary episodic displacement on a sackung scarp in the central Spanish Pyrenees: Secondary paleoseismic evidence?, *Geodin. Acta*, 21, 187–202, 2008.
- Gutiérrez, F., Lucha, P., and Galve, J. P.: Reconstructing the geochronological evolution of large landslides by means of the trenching technique in the Yesa Reservoir (Spanish Pyrenees), *Geomorphology*, 124, 124–136, 2010.
- Gutiérrez, F., Linares, R., Roqué, C., Zarroca, M., Carbonel, D., Rosell, J., and Gutiérrez, M.: Large landslides associated with a diapiric fold in Canelles Reservoir (Spanish Pyrenees): Detailed geological–geomorphological mapping, trenching and electrical resistivity imaging, *Geomorphology*, 241, 224–242, 2015.
- Gutiérrez-Santolalla, F., Acosta, E., Ríos, S., Guerrero, J., and Lucha, P.: Geomorphology and geochronology of sackung features (uphill-facing scarps) in the Central Spanish Pyrenees, *Geomorphology*, 69, 298–314, 2005.
- Hermann, S. W., Madritsch, G., Rauth, H., and Becker, L. P.: Modes and structural conditions of large scale mass movements (Sackungen) on crystalline basement units of the Eastern Alps (Niedere Tauern, Austria), *Mitteilungen des Naturwissenschaftlichen Vereines für Steiermark*, 130, 31–42, 2000.
- Higgs, W. G., Williams, G. D., and Powell, C. M.: Evidence for flexural shear folding associated with extensional faults, *Geol. Soc. Am. Bull.*, 103, 710–717, 1991.
- Hippolyte, J.-C., Brocard, G., Tardy, M., Nicoud, G., Bourlès, D., Braucher, R., Ménard, G., and Souffaché, B.: The recent fault scarps of the Western Alps (France): tectonic surface ruptures or gravitational sackung scarps? A combined mapping, geomorphic, levelling, and <sup>10</sup>Be dating approach, *Tectonophysics*, 418, 255–276, 2006.
- Hürlimann, M., Ledesma, A., Corominas, J., and Prat, P. C.: The deep-seated slope deformation at Encampadana, Andorra: Representation of morphologic features by numerical modelling, *Eng. Geol.*, 83, 343–357, 2006.
- Jaboyedoff, M., Penna, I., Pedrazzini, A., Baron, I., and Crosta, G. B.: An introductory review on gravitational-deformation induced structures, fabrics and modeling, *Tectonophysics*, 605, 1–12, 2013.
- Mahr, T.: Deep-Reaching gravitational deformations of high mountain slopes, *Bull. Intern. Assoc. Eng. Geol.*, 16, 121–127, 1977.
- Mahr, T. and Nemčok, A.: Deep-seated creep deformation in the crystalline cores of the Tatry Mts, *Bull. Intern. Assoc. Eng. Geol.*, 16, 104–106, 1977.
- Margielewski, W. and Urban, J.: Crevice-type caves as initial forms of rock landslide development in the Flysch Carpathians, *Geomorphology*, 54, 325–338, 2003.
- McCalpin, J. P.: Criteria for determining the seismic significance of sackungen and other scarplike landforms in mountainous regions, in: *Techniques for Identifying Faults and Determining their Origins*, edited by: Hanson, K. L., Kelson, K. I., Angell,

- M. A., and Lettis, W.R., U.S. Nuclear Regulatory Commission, Washington, USA, 255–259, 1999.
- McCalpin, J. P.: Paleoseismology, 2nd edition, Academic Press, San Diego, CA, USA, 2009.
- McCalpin, J. P. and Hart E. W.: Ridge-top spreading features and relationship to earthquakes, San Gabriel Mountain region, southern California, in: Ridge-Top Spreading in California; Contributions Toward Understanding a Significant Seismic Hazard, Hart, E. W., California Geological Survey, CD 2003-05, disk 1 of 2, 2003.
- McCalpin, J. P. and Irvine, J. R.: Sackungen at the Aspen Highlands Ski Area, Pitkin County, Colorado, *Environ. Eng. Geosci.*, 1, 277–290, 1995.
- McCalpin, J. P., Bruhn, R. L., Pavlis, T. L., Gutierrez, F., Guerrero, J., and Lucha, P.: Antislope scarps, gravitational spreading, and tectonic faulting in the western Yakutat microplate, south coastal Alaska, *Geosphere*, 7, 1143–1158, 2011.
- McClay, K. R. and Ellis, P. G.: Geometries of extensional fault systems developed in model experiments, *Geology*, 15, 341–344, 1987.
- Meric, O., Garambois, S., Jongmans, D., Wathélet, M., Chatelain, J. L., and Vengeon, J. M.: Application of geophysical methods for the investigation of the large gravitational mass movement of Séchilienne, France, *Can. Geotech. J.*, 42, 1105–1115, 2005.
- Moro, M., Saroli, M., Gori, S., Falcucci, E., Galadini, F., and Messina, P.: The interaction between active normal faulting and large scale gravitational mass movements revealed by paleoseismological techniques: a case study from central Italy, *Geomorphology*, 151, 164–174, 2012.
- Nemcok, A.: Gravitational slope deformation in high mountains. Proceedings of the 24th International Geological Congress, 21 August–1 September 1972, Montreal, Canada, 13, 132–141, 1972.
- Onida, M., Tibaldi, A., Forcella, F., and Galadini, F.: Analysis of deep-seated slope deformations by paleoseismic technique, in: Proceedings of the Fourth North American Rock Mechanics Symposium, Balkema, Rotterdam, the Netherlands, edited by: Girard, J., Liebman, M., Breeds, C., and Doe, T., 515–521, 2000.
- Pánek, T., Hradecký, J., Minár, J., Hungr, O., and Dušek, R.: Late Holocene catastrophic slope collapse affected by deep-seated gravitational deformation in flysch: Ropice Mountain, Czech Republic, *Geomorphology*, 103, 414–429, 2009.
- Pánek, T., Tábořík, P., Klimeš, J., Komárková, V., Hradecký, J., and Šťastný, M.: Deep-seated gravitational slope deformations in the highest parts of the Czech Flysch Carpathians: evolutionary model based on kinematic analysis, electrical imaging and trenching, *Geomorphology*, 129, 92–112, 2011.
- Pellegrino, A. and Prestininzi, A.: Impact of weathering on the geomechanical properties of rocks along thermal–metamorphic contact belts and morpho-evolutionary processes: The deep-seated gravitational slope deformations of Mt. Granieri–Salincriti (Calabria–Italy), *Geomorphology*, 87, 176–195, 2007.
- Radbruch-Hall, D. H., Varnes, D. J., Colton, R. B.: Gravitational Spreading of steep-sided ridges (“Sackung”) in Colorado, *J. Res. US Geol. Surv.*, 5, 359–363, 1977.
- Rohn, J., Resch, M., Schneider, H., Fernandez-Steeger, T. M., and Czurda, K.: Large-scale lateral spreading and related mass movements in the Northern Calcareous Alps, *B. Eng. Geol. Environ.*, 63, 71–75, 2004.
- Ruch, J., Acocella, V., Storti, F., Neri, M., Pepe, S., Solaro, G., and Sansosti, E.: Detachment depth revealed by rollover deformation: An integrated approach at Mount Etna, *Geophys. Res. Lett.*, 37, L16304, doi:10.1029/2010GL044131, 2010.
- Saroli, M., Stramondo, S., Moro, M., and Doumaz, F.: Movements detection of deep seated gravitational slope deformations by means of InSAR data and photogeological interpretation: northern Sicily case study, *Terra Nova*, 17, 35–43, 2005.
- Savage, W. Z. and Varnes, D. J.: Mechanics of gravitational spreading of steep-sided ridges (sackung), *Bull. Intern. Assoc. Engin. Geol.*, 35, 31–36, 1987.
- Schmid, S. M., Berger, A., Davidson, C., Giere, R., Hermann, J., Nievergelt, P., Puschnig, A. R., and Rosenberg, C.: The Bergell pluton (southern Switzerland, northern Italy): overview accompanying a geological-tectonic map of the intrusion and surrounding country rocks, *Schweiz Miner. Petrog.*, 76, 329–355, 1996.
- Stead, D. and Wolter, A.: A critical review of rock slope failure mechanisms: The importance of structural geology, *J. Struct. Geol.*, 74, 1–23, 2015.
- Tarchi, D., Casagli, N., Moretti, S., Leva, D., and Sieber, A. J.: Monitoring landslide displacements by using ground based synthetic aperture radar interferometry: Application to the Ruinon landslide in the Italian Alps, *J. Geophys. Res.-Sol. Ea.*, 108, 2387, doi:10.1029/2002JB002204, 2003.
- Thompson, S. C., Clague, J. J., and Evans, S. G.: Holocene activity of the Mt. Currie scarp, Coast Mountains, British Columbia, and implications for its origin, *Environ. Eng. Geosci.*, 3, 329–348, 1997.
- Tibaldi, A. and Pasquaré, F.: Quaternary deformations along the “Engadine–Gruf tectonic system”, Swiss-Italian Alps, *J. Quaternary Sci.*, 23, 475–487, 2007.
- Tibaldi, A. and Viviani, C.: Prima individuazione di deformazioni profonde di versante nella Valle Agogna, Brovello-Carpugnino (VB): loro geometria, età e dinamica. Vol. Spec. Studi Geografici e Geologici in Onore di S. Belloni, Genova, Italy, 609–630, 1999.
- Tibaldi, A., Onida, M., Pasquaré, G., and Forcella, F.: Trenching and palaeoseismic researches along Holocene deformation zones in the upper Valtellina region, Central Alps (Italy). 3rd Workshop on Alpine Geological Studies, Oropa-Biella, 29 Sept.–1 Oct. 1997, *Quaderni di Geodin. Alpina e Quat.*, 4, 219–220, 1998.
- Tibaldi, A., Rovida, A., and Corazzato, C.: A giant deep-seated slope deformation in the Italian Alps studied by paleoseismological and morphometric techniques, *Geomorphology*, 58, 27–47, 2004.
- Varnes, D. J.: Slope movements types and processes, in: Analysis and Control, Schuster, R. L. and Krizek, R. J., Landslides, *Natl. Acad. Sci., Washington DC, Transp. Res. Board, Spec. Rep.*, 176, 11–33, 1978.
- Wells, D. L. and Coppersmith, K. J.: New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *B. Seismol. Soc. Am.*, 84, 974–1002, 1994.
- Wernicke, B. and Burchfiel, B. C.: Modes of extensional tectonics, *J. Struct. Geol.*, 4, 105–115, 1982.
- Zischinsky, U.: On the deformation of high slopes. Proc. 1st Conf. Int. Soc. Rock Mech., Lisbon, Sect. 2, 179–185, 1966.