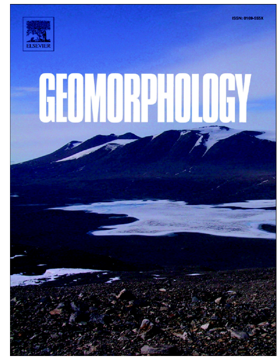
The gravitational landscape of Montespertoli (Valdelsa Basin, Tuscany, Italy): State of activity and characteristics of complex landslides

Accepted Manuscript



The gravitational landscape of Montespertoli (Valdelsa Basin, Tuscany, Italy): State of activity and characteristics of complex landslides

Mauro Coltorti, Sofia Tognaccini

PII: S0169-555X(19)30187-4
DOI: https://doi.org/10.1016/j.geomorph.2019.04.030
Reference: GEOMOR 6758

To appear in: *Geomorphology*

Received date: 14 September 2018
Revised date: 13 January 2019
Accepted date: 27 April 2019

Please cite this article as: M. Coltorti and S. Tognaccini, The gravitational landscape of Montespertoli (Valdelsa Basin, Tuscany, Italy): State of activity and characteristics of complex landslides, Geomorphology, https://doi.org/10.1016/j.geomorph.2019.04.030

THE GRAVITATIONAL LANDSCAPE OF MONTESPERTOLI (VALDELSA BASIN, TUSCANY, ITALY): STATE OF ACTIVITY AND CHARACTERISTICS OF COMPLEX LANDSLIDES

COLTORTI MAURO [a], TOGNACCINI SOFIA [a,b]

[a] Università degli studi di Siena, Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Strada Laterina, 8, 53100, Siena, Italy

[b] Università degli studi di Firenze, Dipartimento di Scienze della Terra, Via La Pira, 4, 50121, Florence, Italy

Corresponding autor: Tognaccini Sofia; e-mail: sofia.tognaccini@unifi.it

Abstract

The town of Montespertoli (Florence Province) is located on a NW–SE ridge that separates the Valdelsa River Basin to the west from the Val di Pesa Basin to the east. The bedrock is characterised by alternations of alluvial, transitional, and marine deposits with a maximum gradient of 5°. The slopes surrounding the town are affected by a series of rock slides, flows, and complex landslides, usually roto-translational slides that evolve into rock flows. The headward evolution of the landslide escarpments threatens the stability of several buildings and streets. The conditions leading to the activation of these gravitational movements are mainly based on the lithological setting and downcutting of river valleys. In addition, recent inappropriate water management plays an important role locally. The aim of this study is to illustrate the importance of gravitational phenomena in the modelling of areas with this type of structural setting, which is very common in many Italian regions, and to identify the geometry and state of activity of gravitational movements. To verify the activity of the movements in recent decades, multitemporal analysis was carried out using orthophotos of four different periods: 1954, 1988, 1996, and 2013. Based on the results, a classification of the degree of activity of the landslides was introduced,

which can be applied at the regional scale by the regional authority. Several researchers proposed to utilise Synthetic Aperture Radar (SAR) technology. The use of aerial photos is of advantage because these photos are easily available at a very low price, as needed by professional geologists.
Keywords: Landslide, State of activity, Rate of movement, Geomorphological map, Tuscany

1. Introduction

Montespertoli (Fig. 1) is located in central West Tuscany at the top of an elongated hill that separates the Pesa, Elsa, and Virginio valleys. The historical town mostly lies on a conglomerate layer. Unfortunately, the slopes are almost entirely affected by landslides, some of which are active and create a constant hazard to nearby houses and infrastructures. Other landslides are dormant, although the conditions and causes of the movements apparently did not change. The geological setting is characterised by subhorizontal alternations of pebbly, sandy, and silty–clayey layers without significant faults. This homogeneous setting stimulated us to investigate other reasons, apart from geological factors, for the different shapes and sizes of various landslides. In fact, in the beginning of the survey, it was evident that the characteristics of the landslides affecting the northern slopes are slightly different from that of the southern ones. A geomorphological investigation was carried out to understand the behaviour of different landslide bodies, reason for the asymmetry, and different state, distribution, and style of activity. This investigation contributes to the knowledge of landslides that occur in similar geological settings. In fact, many cities in Italy and elsewhere are built on a ridge modelled on horizontal or subhorizontal interlayers of soft/impermeable and hard/permeable rocks and show instability problems. Famous cases in Tuscany include Chiusi della Verna (Canuti et al. 1990), Orvieto (Cencetti et al. 2005), Volterra (Hobbs et al. 2000), and Civita di Bagno Regio (Margottini 2013). Because of the large number of landslides with similar characteristics, Montespertoli is an ideal area for the investigation of the velocity of the movements, eventual variations over time, and possible relationships with land use changes. We also tested the landslide classification proposed by Hungr et al. (2014) and studied the landslide characteristics in more detail, as proposed by Cruden and Lan (2014). The classic subdivision of the state of activity (Varnes 1978; Bisci and Dramis 1991; WP/WLI 1993a) can be improved with detailed investigation involving multitemporal analysis.

Varnes (1978) distinguished ‘active’ landslides, that is, those that are ongoing and moved ‘within the last cycle of seasons’, from ‘suspended-quiescent’ landslides with a longer return time. Movements are ‘dormant’ when the conditions that led to the activation are still at work. More recently, the Geological Survey of Italy (IFFI Project) established that a landslide must be considered ‘active’ if the movement is ongoing (Trigila and Iadanza 2008). Other landslides, even if the movement occurred a few months ago, must be considered ‘quiescent/dormant’.

The rates of movement have been evaluated by measuring the displacement of the reference point (Thomson and Hayley 1975) based on the report of people living in the area (Tavenas et al. 1971), Global Positioning System (GPS) methods (Corsini et al. 2005), sometimes combined with digital photogrammetry (Mora et al. 2003), ground-based SAR (GBSAR) interferometry (Tarchi et al. 2003; Strozzi et al. 2005), and relationships between landslide volumes and landslide mobilisation rates (Guzzetti et al. 2009). The application of remote sensing techniques, especially SAR applications, is a relatively simple method to establish if an area is affected by ongoing movements (Colesanti et al. 2003; Catani et al. 2005, 2006; Herrera et al. 2013; Ciampalini et al. 2014, 2016). However, the location and boundaries of a landslide must be geomorphologically identified. Moreover, reactivated movements do not always affect the entire body but only a part of it, and not the entire thickness. The use of SAR methodologies is expensive and not all professional geologists can afford them. On the other hand, classic geomorphological mapping and photo interpretation are more affordable and can be used to understand the problems associated with hazards and to face related vulnerabilities and risks.

2. Methodology

We created a new geomorphological map at the 1:10.000 scale following the Regione Toscana guidelines (http://www.regione.toscana.it/bancadati/atti/Contenuto.xml?id=5144092&nomeFile=Decreto_n.4505_del_10-04-2017-Allegato-A). This map represents an improvement of the knowledge regarding the distribution and classification of new landslides placed in Montespertoli study area and not yet fully reported in the Inventory of the Italian Landslides database of the basin’s authority (IFFI). In this paper, the map was significantly reduced, simplified, and transformed into a black and white (B/W) sketch map for easier reproduction, which preserves the readability. The geomorphological field survey and mapping were carried out by the authors between 2014 and

2017. At the same time, photo interpretation was used to perform a multitemporal analysis; however, the analysis was limited to landslides affecting the margins of the town.

A refinement of the field map was carried out by analysis of the digital raster orthophotos 1:10,000 scale map provided by the Regione Toscana Environmental Agency (http://www.regione.toscana.it/web/geoblog/-/open-geodata) and uploaded within a Geographic Information System (GIS). To detect the rate of movements, we selected B-W aerial photos from 1954, 1988, and 1996 and colour photos from 2013. The data concerning landslide areas and escarpments were measured and extrapolated from line and polygon features digitalised within the GIS environment.

The multitemporal analysis allowed us to test, for the first time, the classification of the degree of activity of landslides proposed in this work. Four levels of activity have been distinguished in the classification: 1) ‘First-level active landslides’ with continuous movements since the 1970s; 2) ‘Second-level active landslides’ with movements from the 1950s to now; 3) ‘First-level quiescent landslides’ without movements since the 1970s; and 4) ‘Second-level quiescent landslides without movements since the 1950s. The 1950s were chosen because the first aerial photos of Italy were obtained in this decade. Landslides that have not been investigated with multitemporal analysis are classified to be active if movements in the last decades are evident (e.g. scarps, undulations, and counter slopes); quiescent landslides show no evidence of movements during this time interval.

3. Geological setting and lithological subdivision

The town of Montespertoli is located in central West Tuscany in the catchment of the Elsa River, a major left tributary of the Arno River. Montespertoli is in the Valdelsa Basin, a Late Tertiary and Early Quaternary synform basin (Pascucci et al. 1999; Coltorti et al. 2012) that developed in NW–SE direction and is ~60 km long and 25 km wide. The basin is bounded by the Albano–Chianti Mountains (Outer Tuscany Ridge) to the northeast and by the Livorno Mountains to the southwest (Inner Tuscany Ridge; Abbazzi et al. 2008; Benvenuti et al. 2014; Fig. 1). The ridges are characterised by outcrops of pre-Miocene tectono-sedimentary units. From the higher to the lower units, they are: 1) Ligurian and Subligurian Units; 2) Non-Metamorphic Tuscany Unit; and 3) Metamorphic Tuscany Units (Carmignani et al. 2004, 2013).

Fig. 1. Location of the study area. Simplified geological sketch of the Valdelsa Basin. [2 COLUMNS]

The basin is filled with over 2000 m of Upper Miocene to Early Pleistocene continental and coastal–marine sediments (Pascucci et al. 1999; Abbazzi et al. 2008; Benvenuti et al. 2014). The horizontal or very gently inclined layers (maximum 5°) of the Plio-Pleistocene deposits were divided into various synthems that include different lithofacies, which are separated by recognizable unconformities. From top to bottom, they are (Fig. 2a):

a) San Casciano Synthem (SC): interlayers of alluvial pebbles, sands, and mudstones, which are tentatively attributed to the Gelasian;

b) San Miniato Synthem (SM): fluvial coastal pebbles, sands, and mudstones that from the NE to the SW sectors became deltaic sands and mudstones. It contains mammal continental vertebrates of the Montopoli Mammal Unit of the Lower Gelasian (Benvenuti et al. 2001);

c) Ponte a Elsa Synthem (PE): fluvial and coastal pebbles and sands alternating with delta-lagoon and platform mudstones. It contains sporadic foraminifera of the G. Aemiliana zone (Dominici et al. 1995) and continental mammal vertebrates attributed to the Triversa Mammal Unit (Upper Piacenzian; Benvenuti et al. 2001);

d) Certaldo Synthem (C): deltaic sands interlayered with platform mudstones cropping out in the central sector of the basin (G. puncticulata–Discoaster tamalis biozones, Upper Zanclean–Lower Piacenzian; Bossio et al. 1993a, b; Benvenuti and Degli Innocenti 2001). These sequences have been deeply dissected in the study area and Late Pleistocene and Holocene alluvial and colluvial deposits lie unconformably over older synthems.

In the geomorphological map, we grouped various synthems according to four main lithological units (Fig. 2b): a) pebbles that are found only in the San Casciano Synthem; b) sands and pebbles belonging to the San Miniato and Ponte a Elsa synthems; c) sands and silts belonging to the San Casciano and San Miniato synthems; and d) silts and clays belonging to the San Miniato, Ponte a Elsa, and Certaldo synthems.

Eluvio-colluvial deposits, usually found at the foot of the slopes, and Holocene alluvial sediments were also mapped.

Fig. 2. Geological and geomorphological background of the study area: (a) Schematic sketch of Plio-Quaternary deposits of the Valdelsa Basin nearby the study area: C - Certaldo Synthem, SB - Sambuca Synthem, FP - F. Pesa Synthem, PE - Ponte a Elsa Synthem, SM - San Miniato Synthem, SC - San Casciano Synthem; (b) lithological units that have been recognised in the study area during the field survey, synthems, and lithofacies subdivision; (c) hydrographic network and main roads of Montespertoli. The dendritic pattern is represented by white lines, while the main roads are shown in black. Torrente and Borro are both local names for streams. [2 COLUMNS]

4. Geomorphological setting

The historical centre of the town is located at an elevation ranging from 230–240 m a.s.l. on a structural flat surface at the top of the NW–SE-oriented ridge. It is mostly modelled on pebble and sand lithofacies. The dissection of the Orme Stream generates two secondary ridges in the NW. The overall morphology of the ridge is slightly sinuous, mostly due to the occurrence of various landslides. The different lithologies generate stepped slopes, where gently dipping surfaces and rock benches of soft rocks alternate with vertical or very steep escarpments in more solid rocks. The hydrography is characterised by a dendritic pattern with low drainage density and a moderate centrifugal trend (Fig. 2c). The main river in the study area is Torrente Virginio, a stream which flows NW-ward.

5. The landslides

After the geomorphological mapping of the area, we investigated 14 main landslide bodies in detail (Fig. 3). Some of them consist of a single body (2, 4, 9, 10, 11, and 12) but all can be defined as ‘complex’ because at least two types of movements occur in sequence (Cruden and Varnes 1996; Cruden and Lan 2014). There is also a series of landslides that can be defined as ‘composite’ (1, 3, 5, 6, 7, 13, and 14) because different types of movement occur in different areas of the displaced mass, sometimes simultaneously (WP/WLI 1993b; Cruden and Couture 2011); moreover, these different areas of the displaced mass may show different sequences of movements (Cruden and Lan 2014). With the new term ‘coalescent’, we indicate ‘composite’ landslides that originate from different parts of the slope and merge down-valley in a single body, which is usually a rock or earth flow (landslides 1, 7, 13, and 14). Research on landslide complexes

(Malamud et al. 2004) or deep-seated slope deformations that include landslides with coalescent behaviour (Fonseca et al. 2010) did not provide a descriptive explanation of this term.

Based on the scale of the map, we followed recommendations of the ISPRA-APAT (1994) guidelines and reported only the dominant movement, a criterion that has also been adopted by many regional mapping agencies. However, for complex landslides, it is difficult to distinguish when a type of movement ends and another begins. The transitions are frequently gradual and difficult to establish, especially for quiescent landslides, where the original morphology has been degraded by centuries of erosional processes and/or agricultural activities. The landslides in Montespertoli study area can be classified into: 1) slides (Cruden and Varnes 1996) or slips (Hutchinson 1988); 2) complex landslides, usually slides evolving into flows; and 3) flows (Varnes 1978; Cruden and Varnes 1996; Table 1).

Fig. 3. Geomorphological map of Montespertoli (originally produced at 1:10,000). The movements have been divided in flows and slides, whereas the classification of the state of activity follows Cruden and Varnes (1996) and the recent classification proposed in this paper. [2 COLUMNS]

[Table 1 goes here]

Table 1. Main properties of landslide bodies: type of movements, dominant mechanism, length/width ratio (L/W), estimated thickness for every gravitational movement (for composite and complex movements we consider the average ratio), length [m], width [m], size [m^2]; state of activity and period of major activity and salient features of landslide escarpments (length [m], main escarpment height [m], direction).

We also report the classification of the landslides according to Hungr et al. (2014). Most of the landslides can be defined as slow to very slow rock or clay/silt compound, rotational or planar slides. The planform and other surface morphologies partially indicate the type of movement. According to Hutchinson (1988), slips are usually not very elongated in the direction of the movement and have the main escarpment before the hill crest. A rotational sliding mechanism is revealed by the occurrence of downslope secondary escarpments (DD geometry in Hutchinson

1988). In some cases, these escarpments affect the entire width of the landslide body (i.e. landslides 1, 3, and 4), but these are confined only to a part of the movement in many cases. In all cases, the main escarpments developed inside the most competent layers at the top of the ridge. Evidence of rotational movements is represented by trenches and counter slopes, especially in northern areas. A trench or counter slope is frequently not recognizable because the base of the escarpment is sealed with material from the degradation and/or smaller landslides affecting the escarpment.

Boreholes are not available to constrain the thickness of the landslides, but a preliminary assessment has been made to evaluate the height of the escarpments. The vertical or almost vertical nature of the main escarpments and the structural setting, characterised by subhorizontal layers, suggest that most of the sliding surfaces listricate at the contact of different layers. Large bulging is observed after the toe in rock slides evolve into rock flows, followed by an area characterised by large-scale undulations down-valley. This morphology is similar to that described for complex slides with high brittleness (Hutchinson 1988). The landslide bodies generally reach the valley floor. The flows are usually elongated down-valley, indicating that the bodies were disarticulated after their activation and started to flow. The elongation is usually moderate, revealing that the body did not incorporate enough water to move in a semi-fluidal or fluidal way.

Rock flows, sometimes affected by more superficial flows, are widespread at the southern slopes, where the morphology is dominated by undulations and bulges. Below San Ripoli and Cafaggio streets evidence of flow is indicated by tearings in the turf, undulations and degraded, sometimes ‘naked’, escarpments (Fig. 4a). The movements especially affected the sandy–clayey bedrock. Most of the crop boundaries and roads had regular geometrical boundaries in the past, which were lost when movement occurred. Many roads have lost their original straight line and are affected by small bumps and counter slopes, particularly evident for unpaved or secondary roads (Fig 4c).

Complex landslides (Varnes 1978; Cruden and Varnes 1996; Cruden and Lan 2014) are usually characterised by sliding movements in the crown area, which evolve into flows in the distal part. The sliding surface is only clearly visible at the base of the escarpments soon after reactivation because the scarp is rapidly degraded by erosional processes due to rock tenderness. Near the valley floor, the flow movement is represented by undulations and bumps (Fig. 4b). When rotational movement prevails, the bodies have a mean L/W ratio of 1.9 (Table 1). When flow movement prevails (slide evolving into flows), the mean L/W value is 2.4, implying a more fluidal behaviour.

The rate of movements of the landslides bordering the town was generally slow to extremely slow during the investigation (Hungr et al, 2014). However, it is possible that extreme rainy events, which did not occur during the study, could lead to moderate rates, at least on a local scale.

The land was almost entirely ploughed up to the 1950s, but this activity was later abandoned in many cases, mostly due to the changing economy but also because the ongoing movements prevented the practicability of the terrain and profitability of the land.

Fig. 4. Evidences of landslides within the study area: (a) scarp associated with a flow that affects a vineyard; (b) view of landslides 3 (right) and 4 (left) affecting the left side of the Torrente Orme. From top to bottom: main escarpment, secondary scarp (in black), and portion of the body which is flowing (area marked white); (c) undulations and cracks in a secondary road associated with landslide 5. [2 COLUMNS]

6. Multitemporal analysis

The multitemporal analysis was carried out on 14 landslides whose activation triggers damage to buildings and streets (Fig. 5). In the following pages we describe only four movements, considered as the most representative of the study area. These landslides include a rock flow (no. 13, Fig. 6), a composite movement with prevailing rotational slides (no. 11–12), a complex movement (no. 4), and a composite landslide (no. 7; Fig. 6).

Fig. 5. Study area: all the 14 landslides investigated with multitemporal analysis (black) and other detected landslides (white). [2 COLUMNS]

Fig. 6. Four movements selected out of the14 landslides investigated with multitemporal analysis for detail studies: (a) Location of the four landslides; (b) landslide 13; (c) landslide 12; (d) landslide 7; (e) landslide 4. The white arrows indicate the positions of the sections reported in Fig. 10. The star in Fig. 6e indicates the location of the outcrop described in Fig. 9. [2 COLUMNS]

6.1. Landslide 4 – Volano Landslide

The Volano landslide (Figs. 6e and 7a,b,c,d) on the north-eastern side of the ridge is characterised by a scarp that affects the 'sands and silts' and underlying 'silt and clay' lithotypes of the upper part of the Plio-Pleistocene sequence. The top of the main escarpment is located at an elevation of 240 m a.s.l.; the height is ~30 m and the length is ~700 m. It has an arcuate shape with an east-facing arc. The landslide body is approximately 560 m long and 400 m wide and covers an area of ~130.000 m^2.

A counter slope at an elevation of 218 m a.s.l. and various secondary escarpments in form of steps indicate multiple rotational slips. The top of the slope has a concave shape, while the downslope, close to the nail of the movement, is convex. Small active earth flows affect the soil in the distal sector and generate areas without vegetation and undulations.

In 1954, the main escarpment was smoothed due to s erosional processes and agricultural activities. The historical centre of the town was located along the edges of the crown. The upper part did not show any evidence of movement and was therefore inactive. Minor topographic changes and the occurrence of several secondary streams subdivided the upper sector into five different bodies (Fig. 7a). The middle and distal sectors were affected by many active movements on the downslope continuation of the upper bodies. Based on their elongation, widespread undulations, and deformation of rows of plants, these were flow movements. Secondary escarpments, steps, and cracks and deformations of the surface are other evidences of movements.

In 1988, following the rapid economic growth after world war II, a series of buildings was created at the feet of the main escarpment and in the dormant upper part. A series of small escarpments affected the northern slope. All active flows in the middle part of the body had a retrogressive activity, enlarging their size. The middle and distal parts of the slope were completely forested and agricultural activity was abandoned. The activity of the landslides in the middle sector was testified by deformations that affected the rows of plants and property boundaries and widespread undulations. Downslope steps and scarps in the ploughed field and, to a minor extent, in the wooded lands were well distinguishable.

In 1996 active movements characterized by small escarpments and deformations are recognizable in the central part and in the middle lower sectors, where large portions had turned into woodland in the previous decade.

Fig. 7. Aerial photos of landslides analysed during the multitemporal analysis. Landslide 4: (a) 1954; (b) 1988; (c) 1996; and (d) 2013. Landslide 7: (e) 1954; (f) 1988; (g) 1996; and (h) 2013. Landslide 11 and 12: (i) 1954; (j) 1988; (k) 1996; and (l) 2013. Landslide 13: (m) 1954; (n) 1988; (o) 1996; and (p) 2013. The dotted lines indicate the bodies and main escarpment of active landslides; dashed lines delimit quiescent bodies and the main escarpment; continuous white lines define the boundaries of other investigated landslides. [2 COLUMNS]

6.2. Landslide 7 – Gabbiano Landslide

This landslide, located on the southward slopes (Fig. 6a,d), is one of the most active and dynamic landslides of the area. The crown area is characterised by two escarpments that cut the sandy–silty unit. The main eastern scarp is located at an elevation of ~260 m and the head zone extends almost to the SP 79 street. The escarpment is slightly over 10 m in height and laterally extends over 900 m with an approximately E–W-oriented bow string. It is mostly vegetated except for minor areas where smaller landslides were activated in recent times. The secondary western escarpment is vegetated and located at an elevation of ~240 m. It laterally extends over approximately 340 m with a NE–SW-oriented bow string. The western body has a length of ~500 m and an area of ~53.400 m^2, while the eastern one has a length of ~500 m and an area of ~60.000 m^2. A secondary 5–10 m high escarpment in the eastern body at an altitude of ~230 m separates the upper sector affected by rotational movement from the lower sector that evolves as a flow, as suggested by many steps and undulations. The western body is narrow and elongated; it also has several secondary escarpments in the upper sector and secondary steps and undulations down-valley. Currently, it is almost completely covered with trees.

In 1954 the main eastern escarpment was almost in the same position as in the present day, it was degraded and mostly devoid of vegetation. A series of small secondary escarpments were located at the foot of the main one. A secondary heart-like landslide affected the eastern middle part of the slope. This area was covered by vegetation.

The western body showed retrogressive activity with multiple secondary escarpments. Down-valley a series of secondary escarpments alimented a long flow tongue, the lower part of which was already largely covered with vegetation. Steps, undulations, and deformed rows of trees were evident everywhere (Fig. 7e). Deformations affected also the local roads and field boundaries.

Despite the ongoing movements, large parts of the territory were still utilised for agricultural purposes. In limited areas, agricultural activities were prevented by more intense movements.

In 1988, the main eastern escarpment was affected by small landslides. Secondary scarps were fresh and easily recognizable. A small trench created a counter slope in the middle of this sector. However, smaller flows also affected this area. A secondary escarpment marked the transition to the lower sector that evolved as a flow. The central body of the three bodies was more dynamic and longer than in 1954.

The western body was characterised by a long flow originating from the inner northernmost scarp. The sectors to the southwest were still active. Due to the intense movements and possibly also to the socioeconomic changes, agricultural activities were abandoned and the landslide area was mostly covered with shrubbery.

The situation was not very different in 1996. Small unvegetated areas are visible along the main escarpments, indicating the occurrence of minor flows. The flows that affected the central part of the middle slope evolved upward, partially incorporating the flow coming from the north-western side. The other western sector remained unchanged, indicating a general slowing down of the movements, except for the middle distal part of the southwestern flow, which was active. Undulations and steps were widespread on the landslide body. The entire area was largely unploughed and covered with bushes.

6.3. Landslides 11 and 12 – Fornace Landslide

This composite landslide, consisting of a series of different rock slides evolving into rock flows (Fig. 6a,c), affects the ‘pebble, sand, and silt’ lithologies. The inner northernmost body (landslide 12) originates from the narrow arc-shaped main escarpment, which has an even smaller arc in its centre. The escarpments are ~30 m high and extend laterally over more than 360 m with a E–W-oriented bow string. They cover an area of ~32000 m^2. The main escarpment continues along the right flank with another arc-shaped east facing landslide scarp, which continues to the south with a further southeast-facing landslide escarpment (Figs. 3 and 5).

The top of the main inner escarpment is located at an elevation of ~230 m, nearby the buildings facing the SP Volterrana and San Ripoli streets. The foundations of several buildings (Fig. 8a), parts of the parking floor and the San Ripoli street have been damaged. Cracks parallel to the scarp and undulations are clearly recognizable above the crown area, marking embryonic, concentric, and radial fracture. The foundations of several buildings in the west have also been affected by retrogressive destabilisation due to these slow movements.

The main escarpment is vertically subdivided into two sections due to the occurrence of a clay–silt interlayer between two thicker sand levels, which generates a small bench. Small active flows are concentrated beneath the main scarps, which are affected by small falls and topplings. A minor counter slope is located at an elevation of ~190 m at the foot of the main inner escarpment.

Landslide 11, which originates east of the previous one and interferes with it, covers an area of ~52000 m^2 and is ~300 m long. The main scarp is located in correspondence with the lower sandy unit. The upper sandy layer was affected by headward retreat and generated a small escarpment that nowadays is masked by urbanisation. Only a small U-shaped landslide affects the sector between these two escarpments that generates a 'successive' slip involving two different lithological units (Hutchinson, 1988). Minor escarpments are visible in this uppermost landslide and one of these scarps deeply penetrates the sandy layer because of its strong retrogressive nature. Large undulations, which are sometimes associated with small escarpments, are widespread in the middle–lower part of the various landslides, although the slope angle rapidly decreases down-valley. The entire area is covered with bushes and woodland. Several trees are aligned along the slope and mark the edges of the more dynamic area. However, nowadays the landslide bodies show no vegetation-deprived sectors, indicating that the movements slowed down and/or are not intense.

In 1954, the area was entirely ploughed (Fig. 7i). The main inner escarpment, including the small arced scarp in the middle, had no vegetation and was affected by many small earth flows. Vegetation covered most of the other escarpments, except for the sectors located on the eastern side. The escarpments were active and there was evidence of movement along their feet; however, slightly down-valley, vegetation already covered the slope, indicating that the movements had been too intense to prevent any exploitation of these areas. Similar movement affected the landslide body of the southwestern escarpment. However, vineyard rows in the lower part of the slopes were only slightly deformed by movements. The movements in the central part of the slope had been more intense and recognizable due to the existence of bumps and undulations in the ploughed field. The ploughing activity most likely cancelled the local escarpments.

In 1988, most of the area was covered with bushes and woodland; vineyard rows still existed at the southwestern slope. The main escarpment was still deprived of vegetation due to the movements.

A small landslide affected the eastern side of the valley and the south-eastern sector; alignments of trees, large bumps, cracks in the bushes, and discontinuities in the woodland are the main evidences of slow and continuous activity of these flows.

In 1996, the innermost escarpments showed evidence of small and large collapses that evolved into flows (Fig. 7l). Similar evidence was found in the escarpment on the eastern. A large movement was activated along the southwestern side and destroyed a large part of the 1988 vineyard rows. Vineyard rows still existed slightly down-valley but embryonic movements progressively affected this area. Undulations characterised the rest of the landslide body, which was completely covered by woodland.

6.4. Landslide 13 – Gas Station Landslide

This landslide is in the north-western periphery of the town north of the junction between SP Volterrana and Mandorli Streets, at the head of the Turbone Stream (Fig. 6a,b). The landslide has three main bodies, each with its own escarpment, although the southern one is more evident. Minor landslides also affect the escarpment east of this area, where a group of houses were built between 2003 and 2007. The scarps, the top of which is located at an average elevation of 230 m, have a height between 5 and 10 m. The western and eastern scarps laterally extend over a total length of ~235 m and ~155 m, respectively, and were affected by intense anthropogenic remodelling, firstly associated with intense agricultural work and later with progressive urbanisation. Major damages were recorded in correspondence of a Gas station, where a retaining wall had to be built because of the progressive fracturing and displacement of the armoured concrete platform foundation, which hosted a carwash, and part of the main road surface. To prevent further movement, the upper part of the landslide scarp was reinforced by bulkhead of piles with a reinforced concrete beam. Their upper part is now undermined by diffuse degradation processes. Recent movements also occurred below a new group of houses (Fig. 8b).

The two western landslide bodies are ~300 m long and cover an area of ~36.500 m^2. The eastern landslide has a length of ~200 m and covers an area of 20.000 m^2. Along the flank, especially in the eastern sector, there are small fresh escarpments deprived of vegetation. In the west, the escarpments are more degraded and the slope is more regular. The large undulations along the body of the three landslides allow us to establish the occurrence of rock flows. Based on the height of the main escarpments, the rock flows can reach ~10–15 m of depth.

The area was entirely ploughed in 1954. Evidences of deformation affected Mandorli street and some field boundaries, especially in the upper part of the landslide body. The landslide scarps were covered with trees, and were located near the margin of the roads, almost in the current position. The landslide body was entirely characterised by undulations. However, the widespread agricultural works, with almost regularly spaced crops parallel to the contour lines, indicates that there were no or very slow movements of large sectors (Fig. 7m). Pre-existing rows were slightly deformed only in the upper part of the northern body. The most active area was in the central–upper part of the southern movement, where a minor escarpment associated with a small landslide had reactivated part of the large body.

In 1988, a series of houses were built at the tops of the central and southern escarpments. The northern landslide body was split in two. The northern sector was still stable, except for very small areas in the distal part. The southern and central sectors of the northern landslide were characterised by widespread deformations of existing rows. The central body enlarged and incorporated part of the southern body. Due to ongoing movements agricultural activities were abandoned in the distal part of these bodies. Very moderate deformations occurred in the upper part of the southern body.

In 1996 the tops of the central and southern escarpments are masked by buildings. The northern landslide body was still stable, although the lower part of the valley was completely masked by shrubs. Agricultural activities were abandoned, possibly because this sector had been slightly more dynamic. The activity of the central movement was very moderate. However, small local undulations were visible.

Fig. 8. Photographs of landslides. (a) Landslides 11 and 12 nearby La Fornace area: main escarpment and detail of the bulkhead poles with bead head; the poles are undermined and fractured. (b) Landslide 13: view of bulkhead of piles below a new building on the Suor Anselmi Street on the left and the gas station on the right. The undermined bulkhead of piles is marked with a black circle. [2 COLUMNS]

7. Evidence of the landslide behaviour at depth

Evidence of the type and behaviour of the landslides that affected the area was found in the middle part of the Volano landslide (landslide no. 4, Fig. 9) within an area affected by gully erosion due to the construction of a depuration system. The escarpment of the gully cuts several metres of sands and silty–clayey bedrock. The outcrop shows that the landslide consists of a series of bodies moving at different velocities. In fact, the upper part, few metres thick, is sliding over a subhorizontal layer of sands. The sliding surface is very sharp and the body has a series of sandy layers tilted ~20° upslope in the innermost part (Fig. 9a). The tilting affects also the silty–clayey layers cropping out below the sands, although the layering is less recognizable. This thin body is affected by a limited number of fractures, which are normal to the tilted layers and spaced several metres apart from each other. The horizontally layered sands below the sliding surface of the uppermost body are affected by a thick network of vertical fractures with 20–50 cm spacing. Below this level there are gray–greenish clayey–silty deposits, which are intensely fractured and intercalated with decimetre-thick fossiliferous dark layers. The clays and silts are cut by three main sets of fractures and small faults, which are the result of the fragile landslide behaviour:

a) system 1: N 90° S 85° (Fig. 9b)

b) system 2: N 20° E 65° (Fig. 9c; black lines);

c) system 3: N 180° W 90° (Fig. 9c; white lines).

The evaluation of the relationships between the fracturing systems allows the reconstruction of their relative chronology. System 2 is the more recent one because it cuts system 3.

The fracture systems affecting the clays must be associated with a movement that most probably originates in a deeper layer of sand. The horizontally layered and fractured sands suggest that the movement could be a translational slide with an almost horizontal sliding surface. This does not exclude that the movement occurs along a rotational plane slightly down-valley from the outcrop in the more dynamic part.

Fig. 9. Outcrop of the landslide body consisting of sand, silt, and clay near Amedeo Bassi Street: (a) tilted layers lie over a superficial sliding surface; the layering of deposits is shown in black and the major fractures are shown in white; (b) fracture system associated with the shearing surfaces; (c) fracture systems within the clay. [2 COLUMNS]

8. Discussion

The Montespertoli area is characterised by many landslides affecting the surrounding slopes. The geomorphological mapping allows the detailed delimitation of the landslide areas, while multitemporal analysis of the 14 major landslides that affect the periphery of the town allows to group them based on the typology of the movement and degree of activity. All landslides already existed in 1954 but with a variable degree of activity. Four landslides have been described in detail. Most of the movements can be classified as complex rock slides evolving into rock/earth flows and composite rock slides/rock flows. The transition from slide to flow can occur in different portions of the body. Sometimes, the rock slide dominates almost the entire body (landslides 2, 5, and 7) and only the distal part evolves into a flow. In another landslide, the two types of movements are equally spaced (landslide 6). However, some landslides are mostly dominated by earth flows after activation as rock slide (landslides 9, 10, 11, 12, and 13). Moreover, the collected data allow us to make several preliminary hypotheses on the location and geometry of the sliding surfaces of the four movements (Fig. 10) that have been hypothesized according to the data collected during the geological and geomorphological field survey.
We described landslides 4, 7, 11, 12, and 13 in detail.

Landslide 4 is a complex landslide consisting of a deeper rock slide with a horizontal sliding surface covered by a shallow rock/earth flow. The upper part of the large slide does not show evidence of active dynamics since 1954, maybe before. In the 1954 – 1988 interval the middle–lower part of the landslide was already affected by an active slide evolving into a flow and by flows, while the lower part was affected by earth/rock flows. The thickness of a landslide could be estimated based on the height of the escarpment and the thickness of the homogeneous rocks involved. The localisation of the sliding surface inside a sandy layer (Fig. 10a) could be associated with the existence of confined water pressure. The outcrop along the banks of a gully in landslide 4 shows an unexpected brittle behaviour of the clay layers (Fig. 9).
The movement could be accelerated by intense rain. Several problems could also be created by the increased amount of water due to urbanisation, which was not channelized out of the landslide area. Nowadays, only localised areas of the landslide body show reactivation of movements, while the main escarpment is still stable. The landslide is therefore complex, not only because of the presence of two different types of movements but also because part of the landslide is active and part is dormant. Even if the rate of movement differs in various sectors of the same landslide body

(Petley et al. 2005), there is no name for this characteristic state of activity, which might be quite common, especially for large landslides, and is often characterised by partial reactivation of a dormant body. In the classification proposed in this work, the upper part can be considered to be quiescent/dormant of second level, while the lower part of the landslide is active and of second level. We suggest to name landslides with these characteristics "super complex landslides".

Landslide 7 is a composite landslide consisting of an inner complex rotational slide that evolves into rock/earth flows and a western body, which is mainly a flow. The sliding surface is probably located inside a sands and silts layer interbedded within the clays (Fig. 10b). The movement has been active since the 1954, although the retrogressive evolution of the crown area and central part of the body seems to have slowed down in recent times. However, the activity of the landslide body and socioeconomic changes led to the abandonment of the agricultural activity after 1954 and the rates of movement seem to have slowed down.

From 2013 to the geomorphological mapping in 2016, the active movements were concentrated at the head, where the main escarpment retreated, almost reaching several buildings and the main road. However, the central flow body is progressively more dynamic and incorporated the north-western flow, indicating that the entire body is prone to be easily reactivated, although the size of the landslide has generally been 'diminished' since 1954. This landslide is active of second level based on the classification proposed in this work.

Landslides 11–12 are composite landslides consisting of different complex landslides that originated from the coalescence of rotational or translational slides that evolve into rock flows and, locally, earth flows. The inner body is presumably ~30 m thick and the sliding surface is localised between sand–pebbles and silts–clays units (Fig. 10c).

It has been active since 1954, although at very different degrees. The entire area was covered with woodlands in 1996. Active movements were still recognizable by the occurrence of sectors without or with limited vegetation cover. In 1996, active movements affected the southwestern sector and led to the abandonment of the vineyard. In 2013 a series of retrogressive rock/earth flows affected the main escarpment, almost reaching several buildings and roads. However, despite several local movements that were activated from time to time, active movements seem to

have progressively ‘diminished’ (Cruden and Lan 2014) in the last 50 years. Naturally, the possibility that an extreme event could reactivate them cannot be ignored.
Based on the new classification proposed in this work, this movement can be classified as a complex quiescent slide of second level.

Landslide 13 is a composite landslide consisting of multiple complex bodies that originated as rock slide and evolved as rock/earth flows. The sliding surface of the eastern main body reaches the maximum depth of ~10 m (Fig. 10d). In 1954 landslide 13 was characterized by three main bodies and three main escarpments, resulting from the evolution of a single movement with limited ongoing activity. A moderate activity has been recognised in 1988, with slow movements up to 1996. Recently, damages of the concrete pillars at the foot of the escarpment have been observed. This landslide is therefore diminishing; the movement slowed down and ‘partially stabilised’ due to artificial interventions. We use the word ‘partially’ because the interventions are not exhaustive and the retrogression of the main escarpment still progresses, although with a reduced rate. The landslide has been classified as an active slide of second level based on the classification proposed in this work.

Fig. 10. Cross section of the landslides: (a) landslide 4; (b) landslide 7; (c) landslide 12; (d) landslide 13. [2 COLUMNS]

The landslides of the southern slope are characterised by more activity. Some of them, such as landslide nos. 11, 12, and 14, affect sectors of the urban fabric. Active movements, although at minor rates, also affect the northern slope, as shown for landslides 4 and 13. Part of this different behaviour might be associated with the mean gradient of the southern slope (~16°) that is higher than that of the northern slope (~10°).
Examples of complex and/or roto-translational movements affecting areas characterised by similar lithological features are widespread along the Italian Peninsula, both in Central Italy (Guzzetti et al. 2008) or along the coastal slopes facing the Adriatic Sea (Fiorillo 2003; Iadanza et al. 2009; Della Seta et al. 2013). However, Montespertoli is a type area because landslides affect both sides of a ridge on subhorizontal alternations. The relationship with the local lithology indicates that the landslide thickness usually does not exceed 10-30 m as pointed out in the cross section (Fig. 10).

This is probably due to the maximum thickness of homogeneous layers involved (sliding surfaces are located within the weak interlayers). In many cases clay layers were involved, indicating that the sliding surface should be located in the underlying sandy layers (i.e. Landslide 4). Sliding surfaces located inside sandy layers have been suggested, for instance, in the Pienza landslide (Calabresi et al. 1995), where clays overlaid by sands and calcarenites crop out. The sliding surface has been located within sand-bearing aquifer levels that interfered with pre-existing tectonic discontinuities. In the Ancona landslide, boreholes crossed over 90 m of clay involved in deep-seated gravitational movement (Coltorti et al. 1984), suggesting that the sliding surface was located within an underlying sandy layer.

Most of the landslides are active with slow to very slow rates of movements (Cruden and Lan 2014). Most of the landslides already existed in 1954 and the factors that contribute to their activation should be studied considering past conditions. However, most of them, but not all, continue to be active under present-day conditions. The inner part of some of them (i.e. landslide 4) is still dormant, although the middle lower part of the body is active. The activity was even more intense in the 1950s when the landscape was still intensively exploited for agriculture. With the progressive abandonment of the ploughing activities and the growth of vegetation, the movements progressively decreased. It is unclear how urbanisation affects their activity, but, as a preliminary measure, it is necessary to investigate the location of the channelization of the rainwater and consequently divert it to less susceptible areas. Monitoring to reduce the hazards and risks should also be continued.

Multitemporal analysis allowed us to classify the landslides according to the new proposal (Table 1). We also noted that active dynamics were localised in small areas and not associated with the activation/reactivation of the entire body.

The investigated landslides were already in existence in 1954, but various degrees of activity were recorded over the years. The period of major activity of the movements is the one between 1954–1988. The traditional agricultural land use of the ‘alberata’, consisting of rows of vineyards combined with fruit trees, was progressively transformed into large ploughing fields, where mechanisation was possible. At the steeper slopes or in areas affected by landslide activity, agriculture was abandoned. Due to the ‘alberata’, the slopes were crossed by small artificial channels that rapidly diverted the rainy water to the valley bottom. The water infiltrated due to the abandonment of the crops, overloading the landslide body. On the other hand, after the 1980s, the growth of vegetation reduced the mass wasting and the landslide activity.

9. Conclusion

The area of Montespertoli is characterised by an unusual large number of landslides affecting thick alternations of subhorizontal pebbles, sands, and silty–clay. These are composite and complex landslides, usually rock rotational and translational slides (Varnes 1978; 1988; Cruden and Varnes 1996; Cruden and Lan 2014) or rock planar slides (Hungr et al. 2014) evolving into rock and earth flows described as progressive compound slides by Hutchinson (1988). The sliding surfaces have a vertical geometry in the continuation of the main escarpment and generally flatten or progressively listricate at depth inside sandy layers (i.e. Landslide 4); the landslide thickness usually does not exceed 10-30 m. Regarding complex movements, a clear transition from slide to flow is hard to define and can occur in different portions of the body.

The aspect seems to have played an important role in landslide distribution. Northern slopes are dominated by degraded cliffs with a lateral width of tens or hundreds of meters and a height that rarely exceeds 10 m. The southern slopes are characterised by a denser dendritic drainage network and landslides are dominated by higher and steeper cliffs, typically exceeding 10 m of heights and sometimes up to 30 m. Many of the main scarps show a clear retrogressive trend. A similar trend was recognised not far from Montespertoli in Volterra, where marine clays overlie subhorizontal (usually north-east dipping) sands and calcarenites (Bianchini et al., 2015).

A new method to establish the degree of activity of a landslide has been applied. The analysis shows that only a few landslides are quiescent/dormant, while most of them show a second degree of activity (active at least since 1954). Such a classification makes it possible to distinguish the period of major activity and, for the same movement, which areas can be considered more unstable over the years.

The deepening of the valleys is one of the possible landslides triggering factors. Furthermore changes in land use, such as the conversion from native forest and bush to pasture, have been recognised throughout the world as one of the most important factors inducing the occurrence of rainfall-triggered landslides.

This study provide an example of how a detailed geomorphological study of a local area, coupled with multitemporal analysis of different orthophotos, can shed light on the conditions of mass wasting processes, allowing to identify the morphological peculiarities of landslides and define their state of activity.

Acknowledgements

We are grateful to Aurora Martini for the contribution provided during the field work and to Goro Komatsu for the detailed and constructive reviews that led to a significantly improved manuscript.

References

Abbazzi, L., Benvenuti, M., Ceci, M.E., Esu, D., Faranda, C., Rook, L., Tangocci, F., 2008. The end of the Lago-Mare time in the SE Valdelsa Basin (Central Italy): interference between local tectonism and regional sea-level rise. Geodiversitas, 30, 611-639.

Benvenuti, M., Degli Innocenti, D., 2001. The Pliocene deposits in the Central-Eastern Valdelsa Basin (Florence, Italy), revised through facies analysis and unconformity-bounded stratigraphic units. In: Paleontology and Stratigraphy (Research In Paleontology and Stratigraphy) , 107, pp. 265-286. https://doi.org/10.13130/2039-4942/5434

Benvenuti, M., Del Conte, S., Scarselli, N., Dominici, S., 2014. Hinterland basin development and infilling through tectonic and eustatic processes: latest Messinian- Gelasian Valdelsa Basin, Northern Apennines, Italy. Basin Research, 26, 387-402.

Bianchini, S., Pratesi, F., Nolesini, T., Casagli, N., 2015. Building deformation assessment by means of persistent scatterer interferometry analysis on a landslide-affected area: the Volterra (Italy) case study. Remote Sensing, 7,4678-4701. https://doi.org/10.3390/rs70404678

Bisci, C., Dramis, F., 1991. Il concetto di attività in Geomorfologia: problemi e metodi di valutazione. Geogr Fis Dinam Quat, 14, 193-199.

Bossio, A., Costantini, A., Lazzarotto, A., Liotta, D., Mazzanti, R., Mazzei, R., Salvatorini, G., Sandrelli, F., 1993 a. Rassegna delle conoscenze sul neoautoctono toscano. Mem Soc Geol Ital, 49, 17-98.

Bossio, A., Mazzei, R., Salvatorini, G., Sandrelli, F., 1993b. Nuovi dati sui depositi Mio-Pliocenici del settore meridionale del Bacino del Fiume Elsa. Paleopelagos, 3, 97-108.

Calabresi, G., Izzo, S., Lazzarotto, A., Menicori, P., Pieruccini, U., 1995. Movimenti gravitativi nell'area di Pienza. Mem Soc Geol Ital, 50, 67-82.

Canuti. P, Casagli, N., Garzonio, C.A., Vannocci, P., 1990. Lateral spreads and landslide hazards in the Northern Apennine: the example of Mt. Fumaiolo (Emilia Romagna) and Chiusi della Verna (Tuscany). In: Proceedings 6th Congr. IAEG, Amsterdam, pp. 1525–1533.

Carmignani, L., Conti, P., Cornamusini, G., Meccheri, M., 2004. The internal Northern Apennines, the northern Tyrrhenian sea and the Sardinia-Corsica block. Geology of Italy. Special Volume, Italian Geological Society, IGC, 32, pp. 59-77.

Carmignani, L., Conti, P., Cornamusini, G., Pirro, A., 2013. Geological map of Tuscany (Italy). J Maps, 9, 487-497. https://doi.org/10.1080/17445647.2013.820154

Catani, F., Farina, P., Moretti, S., Nico, G., Strozzi, T., 2005. On the application of SAR interferometry to geomorphological studies: estimation of landform attributes and mass movements. Geomorphology, 66, 119-131. https://doi.org/10.1016/j.geomorph.2004.08.012

Catani, F., Colombo, D., Farina, P., Fumagalli, A., Kukavicic, M., Marks, F., Menduni, G., Moretti, S., 2006. Utilizzo di dati telerilevati nella mappatura e nel monitoraggio dei fenomeni franosi e nell'analisi della suscettibilità da frana. Giornale di Geologia Applicata, 3, 173-180.

Cencetti, C., Conversini, P., Tacconi, P., 2005. The Rock of Orvieto (Umbria, Central Italy). Giornale di Geologia Applicata, 1, 103-112. https://doi.org/10.1474/GGA.2005-01.0-10.0010

Ciampalini, A., Bardi, F., Bianchini, S., Frodella, W., Del Ventisette, C., Moretti, S., Casagli, N., 2014. Analysis of building deformation in landslide area using multisensor PSInSAR™ technique. International Journal of Applied Earth Observation and Geoinformation, 33, 166-180. https://doi.org/10.1016/j.jag.2014.05.011

Ciampalini, A., Raspini, F., Lagomarsino, D., Catani, F., Casagli, N., 2016. Landslide susceptibility map refinement using PSInSAR data. Remote Sens Environ, 184, 302-315. https://doi.org/10.1016/j.rse.2016.07.018

Colesanti, C., Ferretti, A., Prati, C., Rocca, F., 2003. Monitoring landslides and tectonic motions with the Permanent Scatterers Technique. Eng Geol, 68, 3-14. https://doi.org/10.1016/S0013-7952(02)00195-3

Coltorti, M., Crescenti, U., Dramis, F., Gentili, B., Pambianchi, G., Sorriso-Valvo, M., 1984. The dicember 1982 Ancona (Italy) landslide: a case of deep seated gravitational slope deformation evolving at unsteady rate. Zeit Fur Geomorphologie, 29, 335-345.

Coltorti, M., Firuzabadi, D., Pieruccini, P., 2012. Geomorphological map and land units at 1:200,000 scale of the Siena Province (Southern Tuscany, Italy). J Maps, pp. 536-551.

Corsini, A., Pasuto, A., Soldati, M., Zannoni, A., 2005. Field monitoring of the Corvara landslide (Dolomites, Italy) and its relevance for hazard assessment. Geomorphology, 66, 149-165. https://doi.org/10.1016/j.geomorph.2004.09.012

Cruden, D.M., Varnes, D.J., 1996. Landslides: investigation and mitigation. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides - Investigation and Mitigation, Washington, DC. National Research Council, Transportation Research Board Special Report, 247, pp. 36-75.

Cruden, D.M., Couture, R., 2011. The working classification of landslides: material matters. In Proceedings of 64th Canadian Geotechnical Conference and 14th Pan-Am CGS Geotechnical Conference. ESS Contribution

Cruden, D., Lan, H.X., 2014. Using the Working Classification of Landslides to assess the danger from a natural slope. In: Lollino G, Giordan D, Crosta GB, Corominas J, Azzam R, Wasowski J, Sciarra N (Eds.) Engineering geology for society and territory: landslide processes. Proceedings of the XII international IAEG congress, Turin. Springer, pp. 3–12.

Della Seta, M., Martino, S., Mugnozza, G.S., 2013. Quaternary sea-level change and slope instability in coastal areas: Insights from the Vasto Landslide (Adriatic coast, central Italy). Geomorphology, 201, 462-478. https://doi.org/10.1016/j.geomorph.2013.07.019

Dominici, S., Mazzanti, R., Nencini, C., 1995. Geologia dei dintorni di San Miniato tra l’Arno, l’Elsa e l’Era. Quad Mus St Nat di Livorno, Suppl. 14, 1-35.

Fiorillo, F., 2003. Geological features and landslide mechanisms of an unstable coastal slope (Petacciato, Italy). Eng Geol, 67, 255-267.

Fonseca, A., Zêzere, J.L., Madeira, J., Faleh, A., Sadiki, A., 2010. Deep-seated slope deformation in the headwaters of the Audour River (Central Rif Mountains): morphology, kinematics and present day activity. V Congresso Nacional de Geomorfologia

Guzzetti, F., Ardizzone, F., Cardinali, M., Galli, M., Reichenbach, P., Rossi, M., 2008. Distribution of landslides in the Upper Tiber River basin, central Italy. Geomorphology, 96, 105-122. https://doi.org/10.1016/j.geomorph.2007.07.015

Guzzetti, F., Ardizzone, F., Cardinali, M., Rossi, M., Valigi, D., 2009. Landslide volumes and landslide mobilization rates in Umbria, central Italy. Earth Planet Sc Lett, 279, 222-229. https://doi.org/10.1016/j.epsl.2009.01.005

Herrera, G., Gutiérrez, F., García-Davalillo, J.C., Guerrero, J., Notti, D., Galve, J.P., Fernandez-Merodo, J.A., Cooksley, G., 2013. Multi-sensor advanced DInSAR monitoring of very slow landslides: The Tena Valley case study (Central Spanish Pyrenees). Remote Sens Environ, 128, 31-43. https://doi.org/10.1016/j.rse.2012.09.020

Hobbs, P.R.N., 2000. Landslides at Volterra, Tuscany, Italy. Q J Eng Geol Hydroge, 33, 101-103. https://doi.org/10.1144/qjegh.33.2.101

Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an update. Landslides, 11, 167-194.

Hutchinson, J.N., 1988. General report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. In: Proceedings of the 5th International Symposium on Landslides, Lausanne, 1, pp. 3-35.

Iadanza, C., Trigila, A., Vittori, E., Serva, L., 2009. Landslides in coastal areas of Italy. Geological Society, London, Special Publications, 322, pp. 121-141. https://doi.org/10.1144/SP322.5

Malamud, B.D., Turcotte, D.L., Guzzetti, F., Reichenbach, P., 2004. Landslide inventories and their statistical properties. Earth Surf Proc Land, 29, 687-711. https://doi.org/10.1002/esp.1064

Margottini, C., 2013. Low environmental impact consolidation works in the rock cliff of Civita di Bagnoregio (Central Italy). In Landslide Science and Practice. Springer Berlin Heidelberg, pp. 647-654.

Mora, P., Baldi, P., Casula, G., Fabris, M., Ghirotti, M., Mazzini, E., Pesci, A., 2003. Global Positioning Systems and digital photogrammetry for the monitoring of mass movements: application to the Ca'di Malta landslide (northern Apennines, Italy). Eng Geol, 68, 103-121.

Gruppo di Lavoro per la Cartografia Geomorfologica, 1994. Carta geomorfologica d'Italia 1:50.000 – Guida al rilevamento. Quaderni SGN, serie III, 4,42.

Pascucci, V., Merlini, S., Martini, I.P., 1999. Seismic stratigraphy of the Miocene-Pleistocene sedimentary basins of the Northern Tyrrhenian Sea and western Tuscany (Italy). Basin Research, 11, 337-356.

Petley, D.N., Mantovani, F., Bulmer, M.H., Zannoni, A., 2005. The use of surface monitoring data for the interpretation of landslide movement patterns. Geomorphology, 66, 133-147. https://doi.org/10.1016/j.geomorph.2004.09.011

Strozzi, T., Farina, P., Corsini, A., Ambrosi, C., Thüring, M., Zilger, J., Wiesmann, A., Wegmüller, U., Werner, C., 2005 Survey and monitoring of landslide displacements by means of L-band satellite SAR interferometry. Landslides, 2, 193-201.

Tarchi, D., Casagli, N., Fanti, R., Leva, D.D., Luzi, G., Pasuto, A., Pieraccini, M., Silvano, S., 2003. Landslide monitoring by using ground-based SAR interferometry: an example of application to the Tessina landslide in Italy. Eng Geol, 68, 15-30. https://doi.org/10.1016/S0013-7952(02)00196-5

Tavenas, F., Chagnon, J. Y., Rochelle, P.L. 1971. The Saint-Jean-Vianney landslide: observations and eyewitnesses accounts. Can Geotech J, 8, 463-478. https://doi.org/10.1139/t71-048

Thomson, S., Hayley, D., 1975. The little smoky landslide. Can Geotech J, 12, 379-392. https://doi.org/10.1139/t75-042

Trigila, A., Iadanza, C., 2008 Landslides in Italy. Special report 2008 (Rapporti 83/2008), ISPRA, Roma

Varnes, D.J., 1978. Slope movement types and processes. In: Schuster RL, Krizek RJ (Eds.) Landslides, analysis and control, special report 176: Transportation research board, National Academy of Sciences, Washington, DC, pp. 11–33.

WP/WLI, 1993a. A suggested method for describing the activity of a landslide. Bulletin International Association of Engineering Geology. 47, pp. 53-57.

WP/WLI, 1993b. Multilingual Landslide Glossary. Bitech, Richmond, British Columbia.

Table 1

Landslide N°	Type of movement	Dominant mechanism	L/W ratio	Estimated thickness (m)	Landslides body Length (m)	Width (m)	Extension (m^2)	State of activity	Landslides main escarpment Length (m)	Height (m)	Direction
1	Complex	Flow	2	10-20	650	380	173000	Active 2°level	750	>10	E-W
2	Slide	Slide	1.2	10-20	400	340	110600	Active 2°level	260	>10	SE-NW
3	Complex	Slide	1.5	10-20	320	210	54000	Active 2°level	160	>10	NE-SW
4	Slide	Slide	1.9	10-20	560	300	130000	Active 2°level	700	>10	N-S
5	Complex	Slide	1.7	10-20	420	190	86000	Active 2°level	340	>10	WNW-ESE
6	Complex	Slide	2.4	10-20	500	210	91000	Active 2°level	400	>10	E-W
7	Complex	Flow	2.9	10-20	500	380	113400	Active 2°level	1200	>10	E-W
8	Flow	Flow	2.8	10-20	475	170	70400	Active 2°level	500	>10	NE-SW
9	Flow	Flow	1.6	10-20	155	100	13000	Active 2°level	350	>10	NW-SE
10	Flow	Flow	3.3	5-10	300	90	18000	Active 2°level	230	5-10	NW-SE
11	Complex	Flow	1.7	20-30	300	180	52000	Active 2°level	300	>10	NW-SE
12	Complex	Slide	2	10-20	300	150	33000	Active 2°level	360	>10	E-W
13	Flow	Flow	2	5-10	300	250	57000	Active 2°level	390	5-10	WNW-ESE
14	Flow	Flow	2.2	10-20	200	265	35000	Active 2°level	350	>10	W-E

Highlights

1. The gravitational landscape of Montespertoli (Valdelsa Basin, Tuscany, Italy)
2. Geomorphological field survey coupled with multitemporal analysis of orthophotos
3. Subhorizontal alternations of pebbly, sandy, silty and clayey deposits
4. Geomorphological evidences related to complex and composite landslides
5. Landslides characterized by a different state of activity

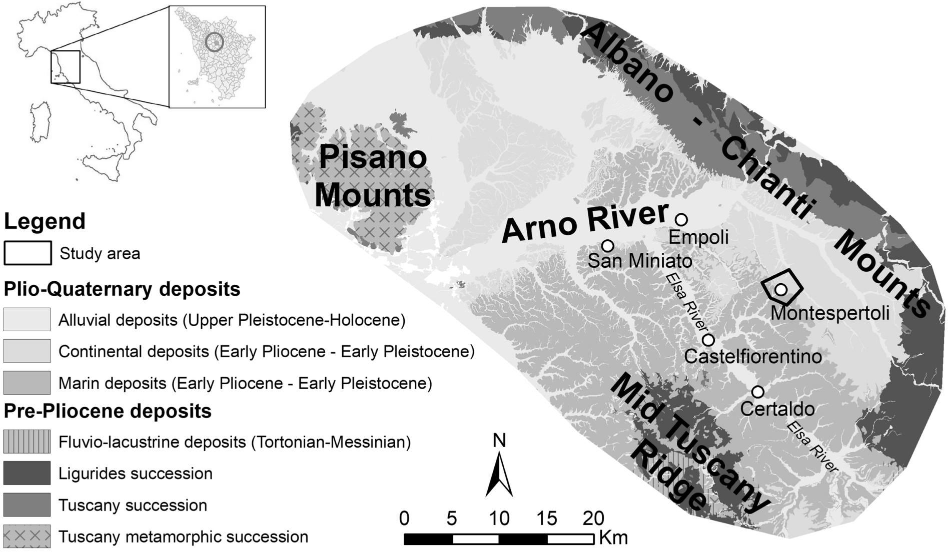
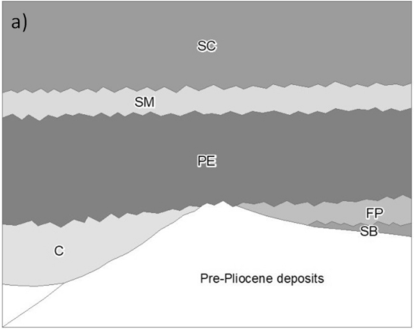

Legend
Study area
Plio-Quaternary deposits
Alluvial deposits (Upper Pleistocene-Holocene)
Continental deposits (Early Pliocene - Early Pleistocene)
Marin deposits (Early Pliocene - Early Pleistocene)
Pre-Pliocene deposits
Fluvio-lacustrine deposits (Tortonian-Messinian)
Ligurides succession
Tuscany succession
Tuscany metamorphic succession
Pisano Mounts
Albano - Chianti Mounts
Arno River
Empoli
San Miniato
Elsa River
Montespertoli
Castelfiorentino
Certaldo
Mid Tuscany Ridge
Elsa River
N
0 5 10 15 20
Km

Figure 1



b) Lithological Unit	Synthem	Lithofacies
Pebbles	San Casciano	Pebbly lithofacies
Sands and pebbles	San Miniato	Sandy-pebbly lithofacies
	Ponte a Elsa	
Sands and silts	San Casciano	Sandy-silty lithofacies
	San Miniato	
Silts and clays	San Miniato	Silty-clayey lithofacies
	Ponte a Elsa	
	Certaldo	

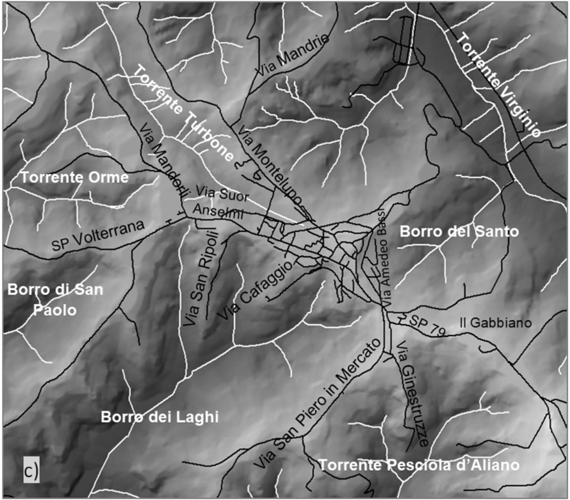


Figure 2

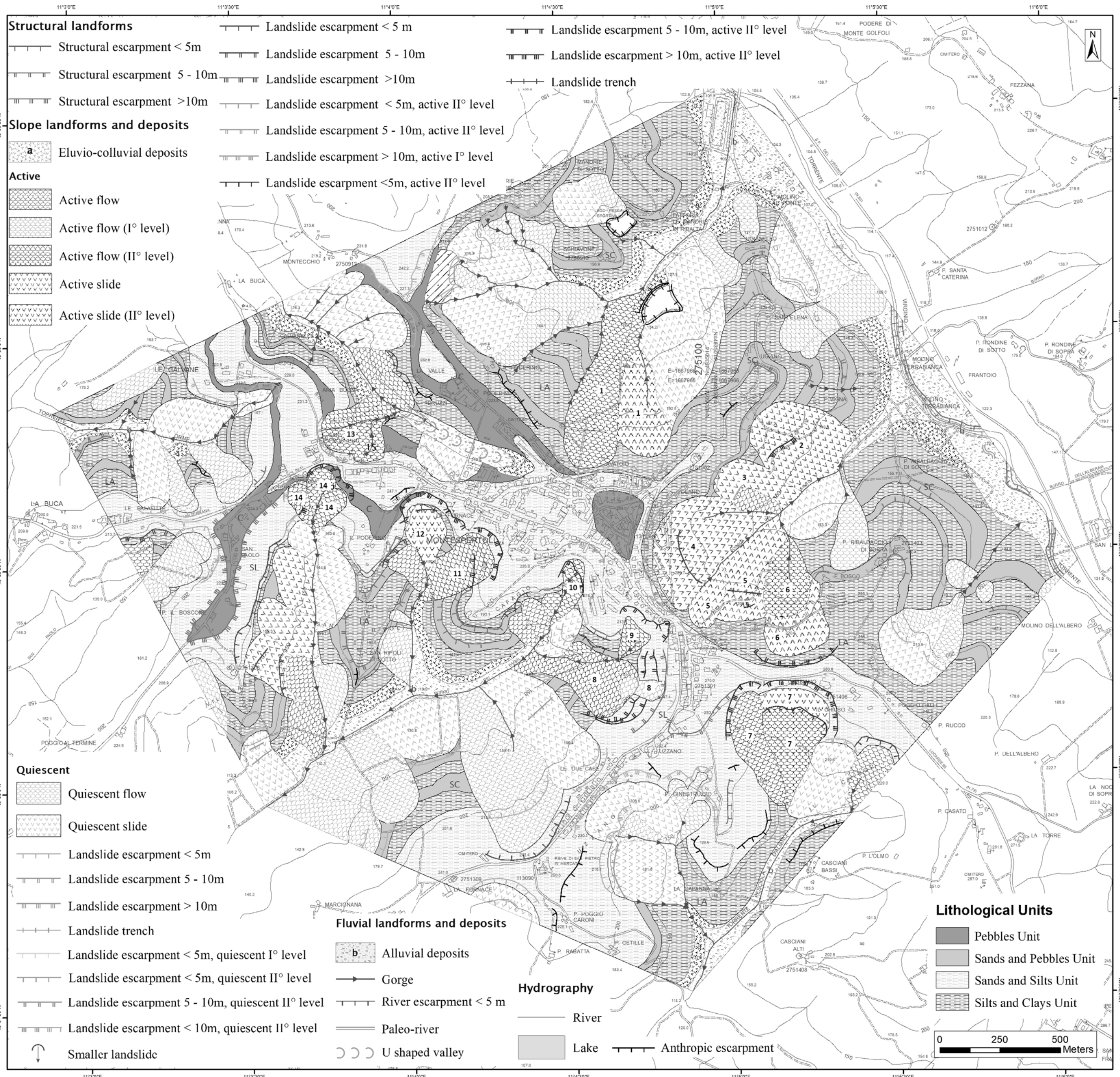

Structural landforms
Structural escarpment < 5m
Structural escarpment 5 - 10m
Structural escarpment >10m
Slope landforms and deposits
a
Eluvio-colluvial deposits
Active
Active flow
Active flow (I° level)
Active flow (II° level)
Active slide
Active slide (II° level)
Landslide escarpment < 5 m
Landslide escarpment 5 - 10m
Landslide escarpment >10m
Landslide escarpment < 5m, active II° level
Landslide escarpment 5 - 10m, active II° level
Landslide escarpment > 10m, active I° level
Landslide escarpment <5m, active II° level
Landslide escarpment 5 - 10m, active II° level
Landslide escarpment > 10m, active II° level
Landslide trench
Quiescent
Quiescent flow
Quiescent slide
Landslide escarpment < 5m
Landslide escarpment 5 - 10m
Landslide escarpment > 10m
Landslide trench
Landslide escarpment < 5m, quiescent I° level
Landslide escarpment < 5m, quiescent II° level
Landslide escarpment 5 - 10m, quiescent II° level
Landslide escarpment < 10m, quiescent II° level
Smaller landslide
Fluvial landforms and deposits
b
Alluvial deposits
Gorge
River escarpment < 5 m
Paleo-river
U shaped valley
Hydrography
River
Lake
Anthropic escarpment
Lithological Units
Pebbles Unit
Sands and Pebbles Unit
Sands and Silts Unit
Silts and Clays Unit
0
250
500
Meters
N
11°3'0"E
11°3'30"E
11°4'0"E
11°4'30"E
11°5'0"E
11°5'30"E
11°6'0"E
43°39'30"N
43°39'0"N
43°38'30"N
43°38'0"N
43°37'30"N
MONTESPERTOLI
LA BUCA
LE GALVANE
P. IL BOSCONE
MONTECCHIO
SCHIAVONE
MANDRIE DI SOTTO
MOLINO DI PONTE
FEZZANA
P. SANTA CATERINA
P. SANT'ELENA
P. RONDINE DI SOTTO
P. RONDINE DI SOPRA
FRANTOIO
MOLINO DELL'ALBERO
P. RIBALDACCIO DI SOTTO
P. RIBALDACCIO DI SOPRA
P. BOSCO
P. RUCCO
P. DELL'ALBERO
P. CASATO
LA TORRE
P. L'OLMO
CASCIANI BASSI
CASCIANI ALTI
P. GINESTRUZZO
LE DUE CASE
P. POGGIO CARONI
P. RABATTA
P. CETILLE
MARCIGNANA
LA FORNACE
POGGIO AL TERMINE
SAN RIFOLI DI SOTTO
IL PODERINO
LA

Figure 3

Figure 4

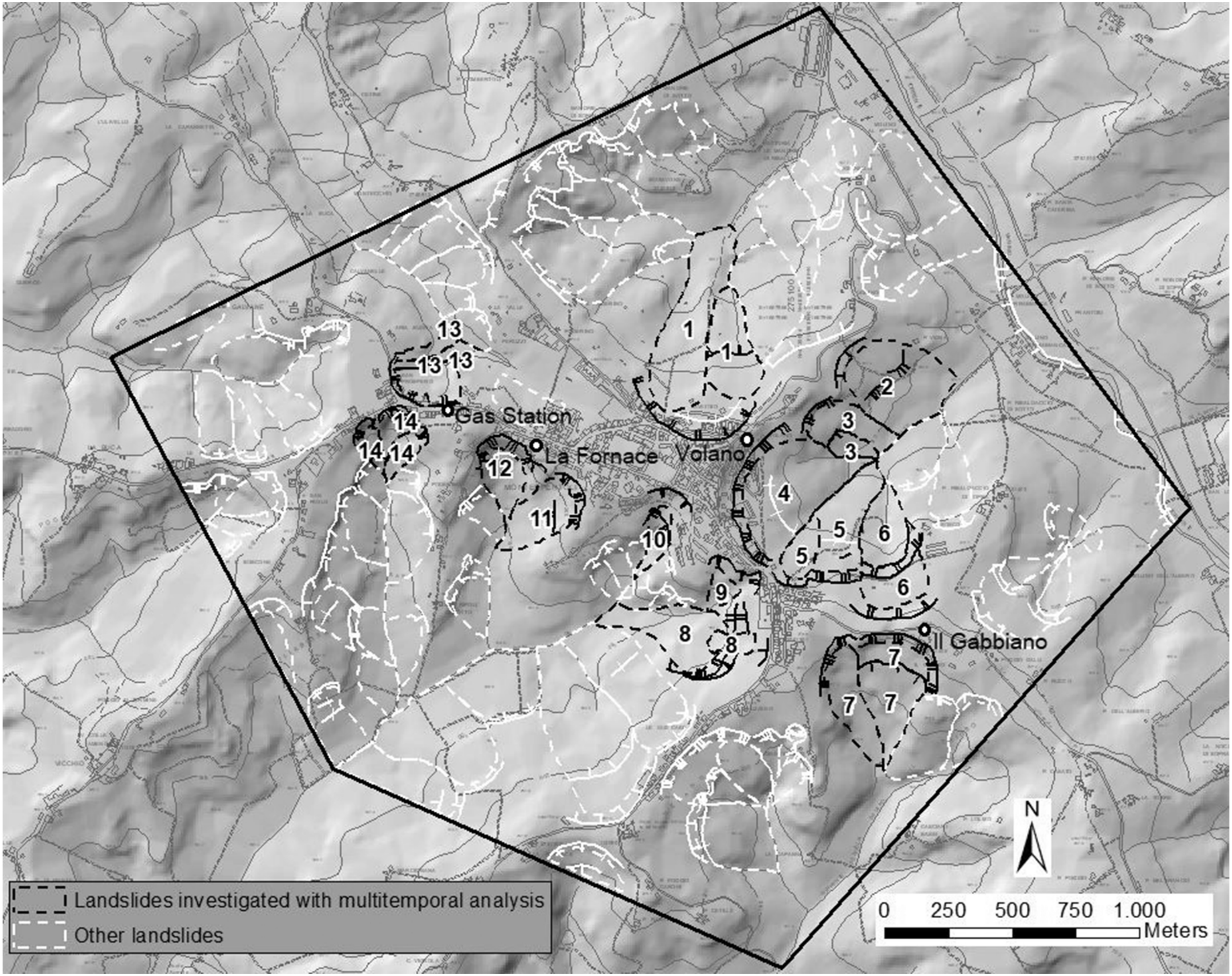

13
13
13
14
14
14
Gas Station
La Fornace
Volano
12
11
10
1
1
2
3
3
4
5
5
6
6
9
8
8
7
7
7
Il Gabbiano
N
Landslides investigated with multitemporal analysis
Other landslides
0 250 500 750 1.000
Meters

Figure 5

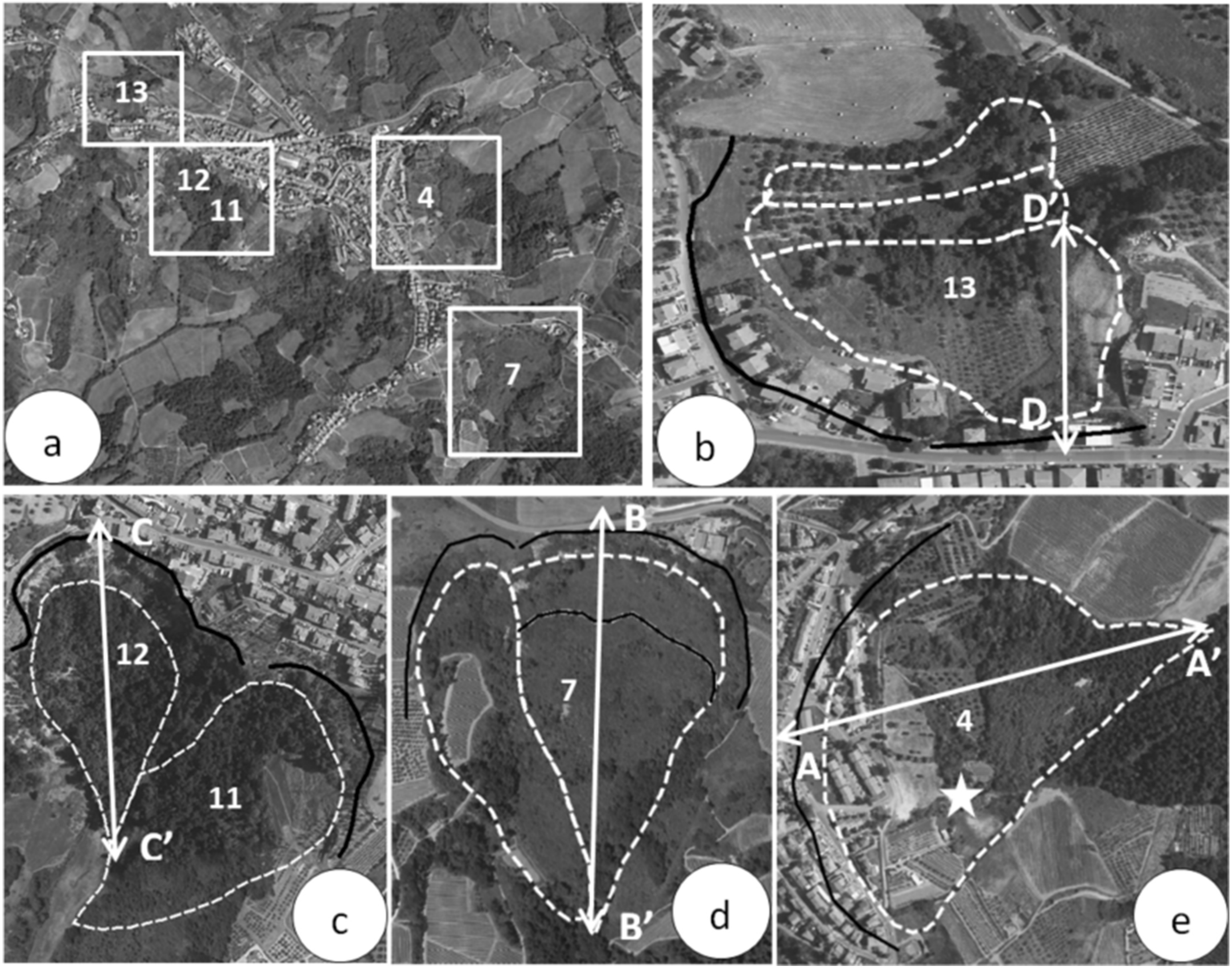


Figure 6

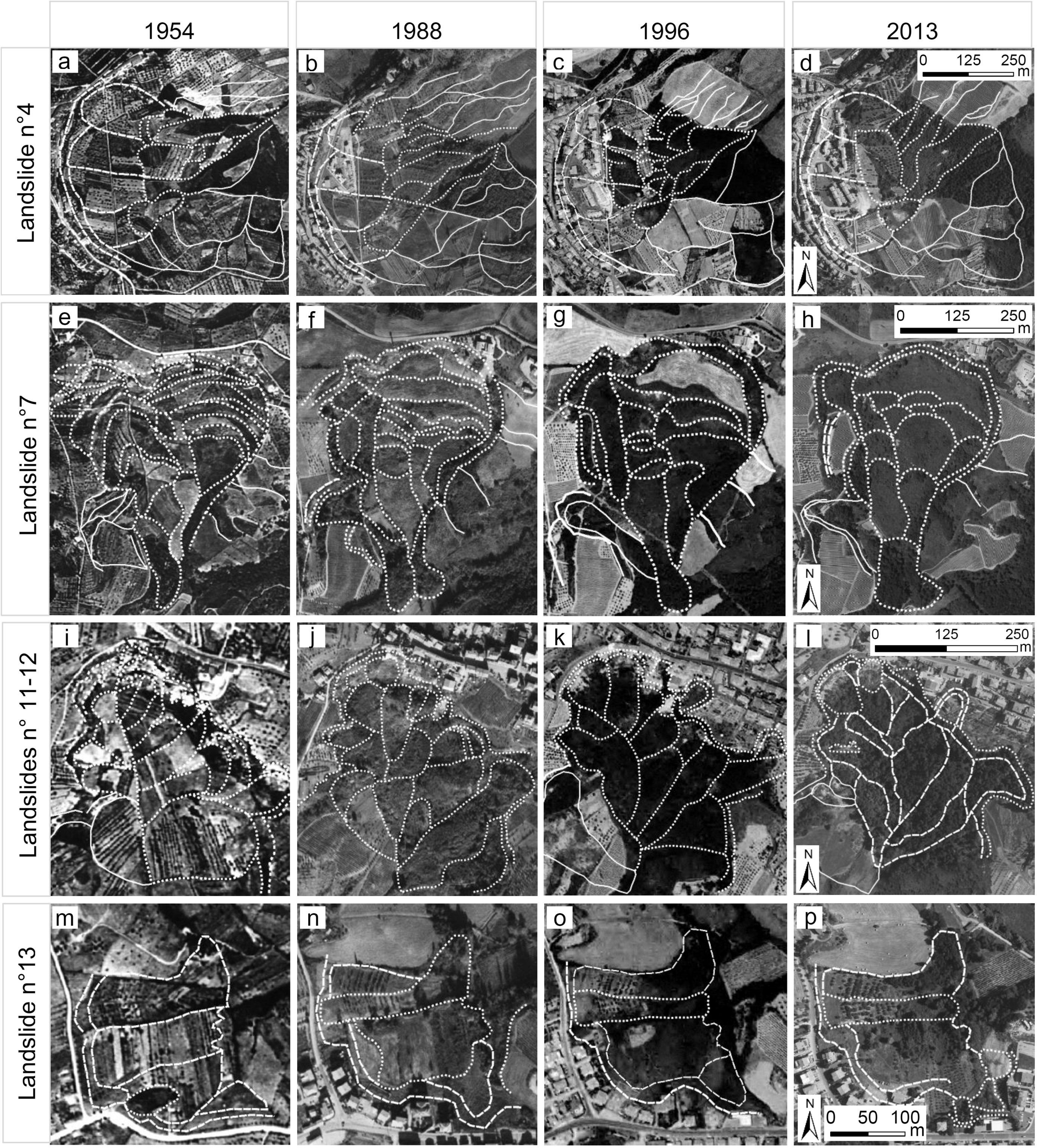

1954
1988
1996
2013
Landslide n°4
Landslide n°7
Landslides n° 11-12
Landslide n°13
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p
0 125 250
m
N
0 50 100
m

Figure 7

Figure 8

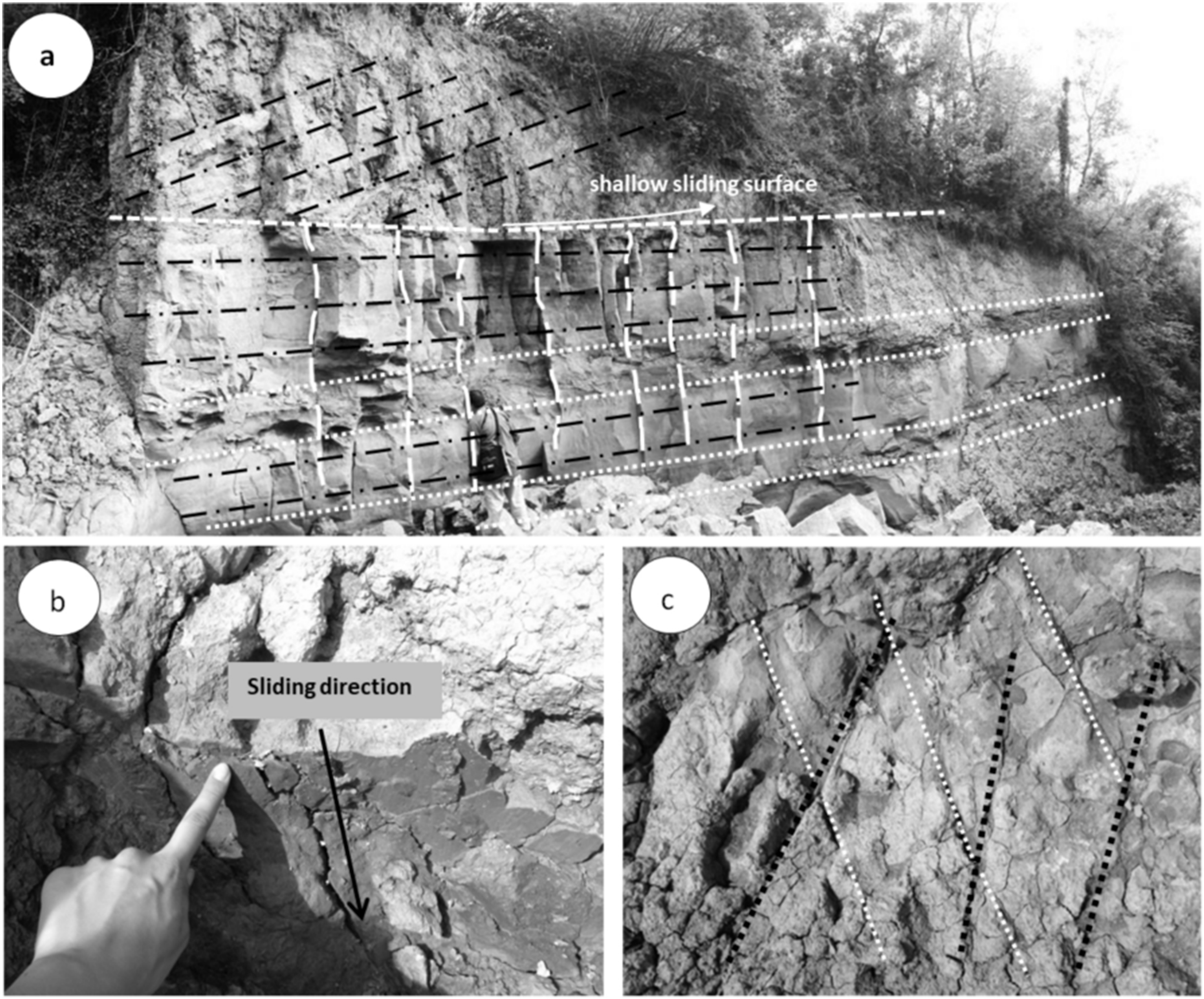


Figure 9

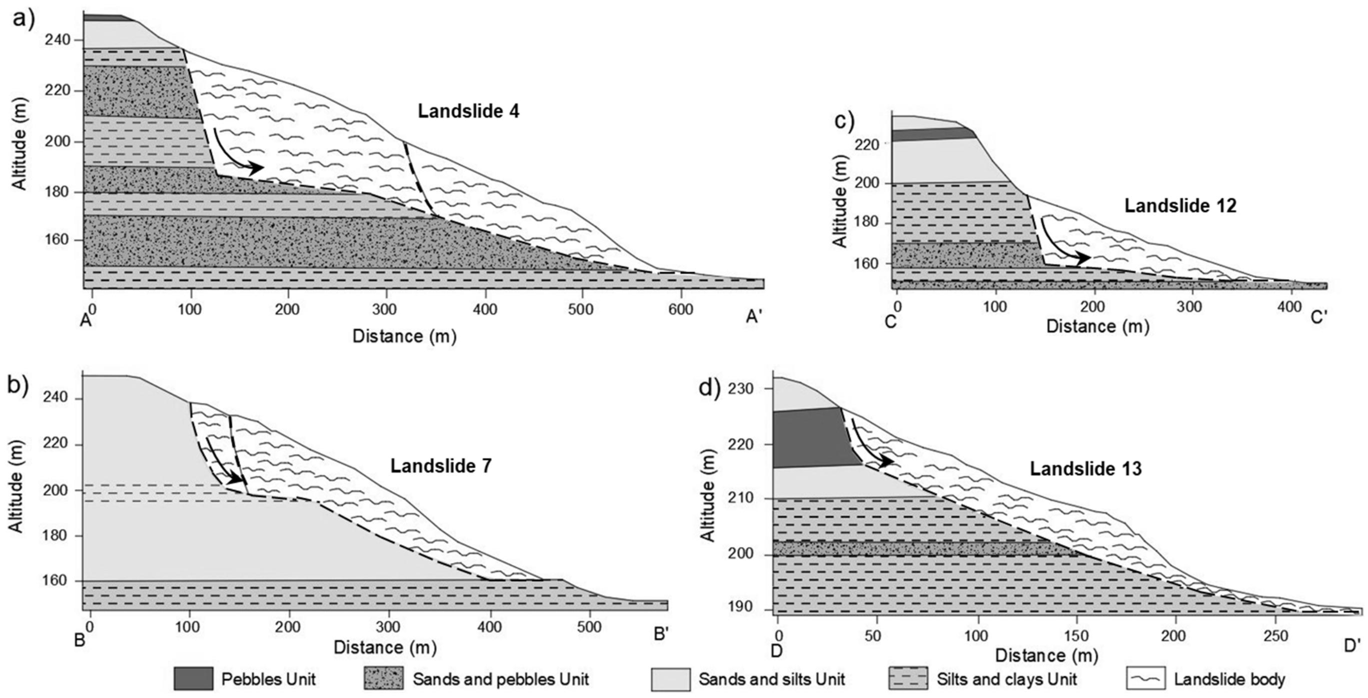

a)
Landslide 4
Altitude (m)
240
220
200
180
160
0
100
200
300
400
500
600
A
A'
Distance (m)
c)
Landslide 12
Altitude (m)
220
200
180
160
0
100
200
300
400
C
C'
Distance (m)
b)
Landslide 7
Altitude (m)
240
220
200
180
160
0
100
200
300
400
500
B
B'
Distance (m)
d)
Landslide 13
Altitude (m)
230
220
210
200
190
0
50
100
150
200
250
D
D'
Distance (m)
Pebbles Unit
Sands and pebbles Unit
Sands and silts Unit
Silts and clays Unit
Landslide body

Figure 10