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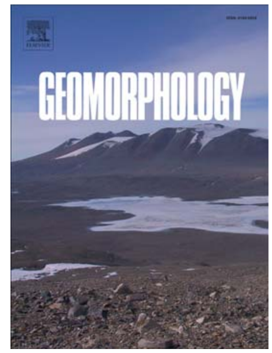

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Mirko Carlini*, Alessandro Chelli*°, Paolo Vescovi*, Andrea Artoni*, Luca Clemenzi**, Claudio Tellini*, Luigi Torelli*

* Department of Physics and Earth Sciences "M. Melloni", University of Parma (Italy)

** ENI S.p.A.

° corresponding author: alessandro.chelli@unipr.it

ABSTRACT

The causes of landslides generally invoked in the Northern Apennines of Italy does not fully explain some observed oriented distributions of large landslides along regional-scale tectonic structures (late orogenic antiforms). The aim of the work is to deeply explore the role of tectonics in controlling the development and arrangement of large landslides. We employed a multidisciplinary approach which took into account geomorphological and geological field data, topographic analysis and deep seismic reflection profiles integrated with previously published apatite fission track cooling ages, shallow geophysical and GPS data. In order to explore these relationships, the Valmozzola area was selected as suitable case study, owing to the presence of clearly expressed relationships between recent extensional faults and related fractures and elements of active landslides. Moreover, in the Valmozzola area contractional tectonics acted to produce rock uplift and thus topographic growth. These processes caused hillslopes to approach their threshold angle, and promoted landslides triggered mainly by climate factors. The geological and geomorphological features characterizing the Valmozzola case study affect the entire study area, as they evolved during the same tectonic and climatic phases that characterized this part of the Northern Apennines.

Therefore, the results from the Valmozzola area act as a proxy to constrain the control exerted by tectonics on large landslides across a wider area. The distribution of the large landslides has been controlled by tectonics which determined lines of weakness and failure surfaces (passive role) affecting the slopes. On the other hand, tectonics also caused the topographic growth and over-steepening of the slopes (active role) that promoted the occurrence of large landslides. The distribution of large landslides may, therefore, highlight the existence of tectonic processes and it may be used as an indicator of regional-scale tectonic activity, once the geological and geomorphological framework is well constrained.

Keywords

large complex landslides, recent tectonics, rock uplift, Northern Apennines

1. Introduction

Large landslides are hillslope processes capable of performing significant erosion and transport of slope material and, thus, effective in characterizing the geomorphology of an area (Crozier, 2010). Major understudied or controversial aspects in the study of large landslides are still the subject of debate, e.g.: a) the cause of regional distribution of landslides within active mountain ranges and b) the type of controls exerted by tectonics on landslide development (e.g., Crosta and Clague, 2006). The first topic has been treated in several papers, documenting, as in the case of the central Italian Alps, the spatial and geometric relation existing between large sackung and other landslides and regional tectonic features (Ambrosi and Crosta, 2006; Seno and Thuring, 2006). In the Scottish Highlands, Jarman (2006) highlighted how difficult it can be to weigh the relative contribution of geological, hydrological, physiographic and glacial features in the control of the spatial distribution of rock slope failures. In recent papers, Carlini et al. (2012) and Chelli et al. (2013), highlighted in the Northern Apennines of Italy the existence, at regional-scale, of oriented distributions of large landslides, spatially related to late orogenic antiformal structures. The authors suggested a control exerted by recent tectonic features on landslides distribution. Still in the Northern Apennines, a concentration of large landslides has been observed in the areas affected by glacial and periglacial climate conditions during late Quaternary (Bertolini and Pellegrini, 2001).

Concerning the passive and active roles of tectonics affecting the landslides, the passive control is exerted mainly by tectonic features such as joints, faults and foliation. These elements cause a progressive increase in the fatigue of rock complexes and represent zones of weakness that may control the shape and size of the failure surface. The landslides may result from the reactivation of these pre-existing features, giving rise to detachment surfaces characterized by residual or lower-than-peak strength, or to the development of composite failure surfaces (Jaboyedoff et al., 2011). The active tectonic control is usually seen in terms of vertical movements and surface uplift that cause the steepening of slopes. The subsequent approach of the hillslopes to their threshold angle, together with the action of trigger factors, promote landsliding.

Many papers explore landslide development by analysing case studies that are individually correlated to the local geological framework. From this perspective, some recent papers treat landslides affecting the bedrock, such as rock avalanches and Deep-Seated Gravitational Slope Deformations (DSGSDs), in terms of their relationships with faults and related deformation (e.g. Bianchi Fasani et al., 2014; Di Maggio et al., 2014; Gori et al., 2014).

In the Emilia Romagna region, Northern Apennines of Italy (Fig. 1), large earth flows and complex landslides number a few tens of thousands (Landslide inventory map of Regione Emilia Romagna – http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/cartografia-dissesto-idrogeologico), and they represent, probably, the most widespread geomorphological process in this mountainous area (Bertolini et al., 2001). This paper is focussed on large complex landslides (sensu Cruden and Varnes, 1996), in which rock slide and earth flow types of movement are combined. These slides affect the detensioned bedrock in the detachment zone, often reaching depths of 20-30 m.

In general, many causes have been invoked for the occurrence of landslides in the Northern Apennines; geological (lithology, structural and geotechnical/geomechanical characteristics, faults and fractures), geomorphological (slope angle, stream erosion) and climatic (late Quaternary glacial and periglacial processes) features have been recognized as potential causes of slope instability (Bertolini and Pellegrini, 2001 and references therein). On the other hand, precipitation is well documented as main trigger factor for landslide occurrence (Bertolini et al., 2005 and references therein). Tectonic activity has been often proposed among the causes of landsliding in the Northern Apennines in terms of rock mechanical fatigue due to their intense tectonization (Bertolini and Pellegrini, 2001 and references therein). Nonetheless, the observations presented in previous works (Carlini et al., 2012; Chelli et al., 2013) highlighted that the aforementioned causes do not fully explain the spatial correlation between large complex landslides and regional-scale tectonic features.

The aim of this research is to explore in this studied portion of the Northern Apennines:

1. the effective control (and type, i.e. active vs. passive) exerted by tectonics as main cause of landslide development;
2. the meaning of the spatial correlation between landslide distribution and regional-scale tectonic features (late orogenic antiforms) observed in previous papers.

Within this framework, the valley of the Mozzola torrent (Valmozzola) (Fig. 2) has been selected as a suitable case study, because of the presence of large complex landslides and the availability of data to constrain recent tectonic activity in the area. This case study clearly exposes the role played by tectonics as cause of landslides and can be used as a paradigmatic case for the whole investigated area. The present paper investigates available and newly acquired data with a multidisciplinary approach including geomorphology, structural geology, geochronology and geophysics, as suggested for instance by Crosta and Clague (2009).

2. Regional setting

The area investigated in this paper is located on the NE slopes of the Northern Apennines of Italy (Figs. 1, 2), between the main divide of the mountain chain, exceeding ~1800 m in altitude (Mt. Orsaro, 1836 m asl, is the highest peak of the main divide in this area) and the foothills (~500 m asl) (Fig. 2). The area lies between the drainage basins of Enza torrent and Taro river that flow from SW to NE towards the Po river. These streams flow roughly orthogonal to the main geologic structures of the mountain belt, driving their sediment load out of the mountainous area towards the higher part of Po river plain (alluvial fan area).

2.1 Tectonic framework

The Northern Apennines originated during the Late Cretaceous to Present convergence between the European and Africa plates (Boccaletti et al., 1971; Kligfield, 1979; Vai and Martini, 2001 and references therein). The overall structural framework resulted from the middle Eocene-Pliocene thrusting of oceanic and continental allochthonous units (Ligurian and Subligurian units overlain by the Epiligurian wedge-top Succession) over Oligocene-Miocene foredeep turbidite units (Ricci Lucchi, 1986; Pini, 1999).

Starting from early Miocene, the Northern Apennines orogenic wedge was affected by widespread thrusting and folding, which, since late Miocene, coexisted with extensional tectonics (e.g., Carlini et al 2013, Clemenzi et al 2014, and references therein). As confirmed by the widespread seismic activity and GPS data, the two tectonic regimes acted until recent times at different structural levels, in particular, contraction at deeper levels (> ~ 10-15 km) and extension at shallower ones (< ~ 10-15 km) (Boccaletti and Martelli, 2004; RSNI – University of Genova; ISIDe Working Group –

INGV database; Baldi et al., 2011, Bennett et al., 2012; Serpelloni et al., 2013; Eva et al., 2014) (Fig. 1). The exhumation of the western portion of the orogenic wedge has been active since the late Miocene-late Pliocene, as testified by thermochronological data (Balestrieri et al., 2003, Fellin et al., 2007; Thomson et al., 2010; Carlini et al., 2013) (Fig.1) and its rate almost doubled during middle-late Pleistocene (Bartolini et al., 1982).

Within the investigated area, the latest tectonic deformation is represented by high-angle extensional faults which are widely exposed SE of the River Taro system, a long-recognized regional-scale SW-NE-trending deformation zone (Vescovi, 1988; Argnani et al., 2003). Along the River Taro system, the high-angle extensional tectonics gives rise to prominent morphological features that show three main orientations. Most of these are NW-SE-oriented, following the strike of the belt, while others are SW-NE oriented, and in some cases the orientation becomes N-S (Fig. 2).

The study area is characterized by the presence of differentially uplifted zones, as highlighted by new and published geological field data (Bernini et al., 1997; section 1 - supplementary material). Within the less uplifted areas (central portion of Fig. 2), the upper portion of the Ligurian allochthonous units and the Epiligurian Succession are preserved. In this central area, tectonic windows highlight the presence of gentle late-orogenic antiformal structures which are generally affected by the aforementioned late high-angle extensional faulting (Carlini et al., 2012; Chelli et al., 2013) (Fig. 2, 3, section 1 - supplementary material). As shown by commercial seismic profiles, these shallow uplifted antiforms and related faults were produced, within the study area, by deep structures related to the Pliocene contractional tectonics (Carlini et al., 2012). The axes of the antiforms progressively change their trends rotating from N130° to N100°-90°, moving from SE to NW (Fig. 2). The Valmozzola case study area, in particular, lies on the northern flank of the Ghiare antiform, one of these regional-scale structures which has been clearly imaged by the seismic profile in Fig. 3.

2.2 Large landslides

In the study area, the large landslides are mainly earth flows and complex landslides (Fig. 2).

Earth flows are often characterized by multiple material sources. In general, these landslides start as a slide involving earth or regolith and evolve into a viscous flow moving down slope because of the complete loss of cohesion of the depleted mass. In general, these landslides involve materials constituted by a predominance of clay or claystone and show a very elongated and narrow main track and a fan-shaped accumulation zone. This type of landslides is, in general, a shallow (< 10-15 m) process that does not involve a substantial portion of the bedrock. These landslides are driven by the lithological features of the substratum and deposits rather than by the structural and tectonic features. One of the largest (more than 3 km long) and most striking landslides in the study area is the Signatico earthflow, located in the torrent Parma valley (Mandrone et al., 2009).

Large complex landslides, on the other hand, often show a unique source area where the failure surface deepens in the rock substratum. The depleted rock mass slides down the slope, usually in its entirety. Then, at the foot of the landslide, the type of movement evolves into a flow because of the great amount of fine-sized (pelitic) material and the water content of the involved moving mass. This type of landslide usually involves rock masses that can be considered as "weak rocks" (sensu Marinos and Hoek, 2001; Mandrone, 2004), and they are recognized as one the most landslide-prone terrains in the Northern Apennines. These rocks are often flysch and are characterized by alternating beds of limestones, marly limestones or sandstones, and claystones or marls. From a geomorphologic point of view, the overall shape of the slope is characterized by concave to convex forms, respectively related to the landslide niche and the deposit, directly connected to each other. Among the complex landslides in the area, two of the best examples are Corniglio landslide, in the valley of the Parma torrent (Larini et al., 2001), and the Tosca landslide, in the valley of the Ceno torrent (Tellini et al., 2002; Tellini and Chelli, 2003).

In the Northern Apennines, intense and prolonged rainfalls have been claimed to be the main trigger factors since reactivations of the large complex landslides occur especially in autumn and in spring, when also the snowmelt (April) may locally contribute to the groundwater circulating within the slopes (Chelli et al., 2006, Chelli et al., 2015). Earthquakes, generally recognized as one of the main tectonic-related trigger factors for landslides, played only a secondary role in this portion of the Northern Apennines (Tosatti et al., 2008). The authors, in fact, highlighted that only 18 landslides, mainly complex or characterized by slide-type of movement, resulted to be induced by seismic shocks, and only in 5 cases earthquakes undoubtedly played a decisive role. Among these landslides, only the aforementioned Corniglio landslide is located in our study area.

Landslides located within our study area underwent many reactivations during the last few thousands of years (Bertolini and Tellini, 2001; Soldati et al., 2006). In some cases they were completely reactivated, while more often, only a portion of the accumulated mass moved, leaving the detachment zone almost undisturbed.

2.3 Episodes of Quaternary erosion

In the Northern Apennines, the main erosional phases also represent episodes of enhanced landslide activity, as recognized in different periods during the Quaternary (Bertolini and Tellini, 2001; Soldati et al., 2006). At a regional-scale, denudation rates have been obtained in different areas of the Northern Apennines from sediment yield estimates, low temperature thermochronology, cosmogenic nuclides and incision rates in fluvial terraces. In order to compare the results, the different spatial and temporal scales characterizing these data have been taken into account (e.g., Cyr and Granger, 2008 and references therein). Long-term sediment yields have been used to calculate the ratio between the volume of sediments drained from the chain and the extension of the source area of the same sediments (Bartolini, 1999 and references therein; Bartolini et al., 2003). These authors invoked a large increase in erosion rates during Quaternary (from ~0.3-0.5 to ~0.7-0.8 mm/yr). In agreement with a Pleistocene increase in erosion rates, middle Pleistocene coarse-grained fluvial sediments were unconformably deposited above late Pliocene-early Pleistocene (Villafranchian) lacustrine deposits. These data testify the enhanced erosional activity during the

Pleistocene (Fig. S1, supplementary material) related to the surface uplift of the main divide of the mountain chain (Bernini et al., 1990). Also the regional-scale distribution of apatite fission-track (AFT) and (U-Th)/He ages confirms an increase in exhumation rates since ~3 Ma (Thomson et al., 2010; Carlini et al., 2013). Nonetheless, the local variability of erosion rates affecting different portions of the orogenic wedge has been highlighted by results of growth strata analysis performed at the foothills of the chain, where a reduction in the mountain front structures growth rate can be observed at ~1 Ma (Gunderson et al., 2013, 2014).

With regard to the erosional phases due to climate conditions, during the Middle and Late Pleistocene the Northern Apennines were characterised, at least twice, by erosional pulses related to glacial and periglacial environments (high precipitation and low air temperature) (see also section 1 in the supplementary material). During these periods, periglacial conditions were particularly effective in promoting, out of the glaciated areas, erosional hillslope processes such as landslides, as demonstrated at least for the Late Pleistocene by radiocarbon dating of landslide occurrence (Bertolini and Tellini, 2001).

Also during the Holocene, erosional pulses are testified by landslide occurrence (Bertolini and Tellini, 2001; Tellini and Chelli, 2003; Soldati et al., 2006). The age of these events imply that during the entire Holocene erosion processes were certainly present in the form of hillslope denudation, mainly triggered by climate factors (enhanced rainfall and freeze-and-thaw cycles). In particular, enhanced landslide activity occurred in the Boreal and Subboreal-early Subatlantic time periods.

3. Methods and dataset

This work has been performed adopting a multidisciplinary approach based on geomorphological, geological and geophysical data integrated with previously published low-T thermochronology, GPS data and shallow geophysics (Careggio et al., 1981; Baldi et al., 2011, Bennett et al., 2012;

Carlini et al., 2013; Serpelloni et al., 2013). This approach has been employed to identify the causes of the most recent (Quaternary) deformation phases (deep seismic data) observed in the study area, to provide a temporal constraint on these deformations (low-T thermochronology), to reveal which structures represent the last deformation phase (field geology) and, finally, to establish the relationship existing between tectonic features and landslides (field geomorphology and shallow geophysics). The field surveys have been performed at scale 1:5000, while the other data give information at a regional-scale. Despite the different scale resolution of the employed methods, it has been possible to integrate the results because they have been mutually constrained following the workflow described above.

The landslides database was built using the 1:10000 landslide inventory map of Regione Emilia Romagna (Landslide inventory map of Regione Emilia Romagna – http://www.isprambiente.gov.it/Media/carg/liguria.html) and digitizing a part of the landslides located in the 1:25000 Liguria region geological map (Regione Liguria geological map – http://www.isprambiente.gov.it/Media/carg/liguria.html).

Korup (2005) stated that, considering different landslides type, large landslides are characterized by planform areas > ~ 10^6 m^2. Guzzetti et al (2009), based on volume/area ratios of slides, on the other hand, identified as large landslides those with a surface at least of 10^5 m^2. Carraro et al. (1979) indicated as large landslides those characterized by an area of at least $5x10^5$ m^2. In this work, considering the type of landslides and the above-mentioned parameters, we took into account landslides characterized by a surface greater than $5x10^5$ m^2, admitting an uncertainty of 5% in the estimation of the area.

We performed a remote sensing survey (aerial photographs of the whole investigated area) in order to detect the landslide features. In particular, we focussed on the typical landforms characterizing complex landslides (rock rotational slides/earth flows); e.g. crown area with the typical half-moon shape, overall concave and convex forms related to the landslide niche and deposit, respectively, the presence of back-tilted slope facets due to the rotational movements.

The geomorphological field survey has been performed in the Valmozzola area in order to study in detail the potential causes and controls of landslide development. We used topographic swath profiles to quantify and analyse major geomorphic features in our study area, in particular to reveal whether the existence of the late antiforms left a signature in the topographic relief of the area. In order to avoid artefacts introduced by topographic features not perpendicular to the swath, we adopted a curved swath profile, according to the method described by Hergarten et al. (2013). The swath's baseline follows the progressive rotation of the antiforms' axes (Fig. 2) due to the rotation of the underlying foredeep units' major structural trends (see section 2.1).

The elevation data have been extracted from a 5 m resolution DTM (Regione Emilia Romagna Topographic Database – http://geoportale.regione.emilia-romagna.it/it/mapshop/). Moreover, meso-structural data have been collected through geological field survey in the Valmozzola area.

A geological cross-section was constructed along the trace of the seismic reflection profile and about orthogonal to the late antiforms, in order to link surface and sub-surface geological data (Figs. 2, 3, and supplementary material).

A seismic profile, provided by ENI S.p.A. and recorded in the 1970s, has been interpreted on its migrated version using the Power View Software (Landmark TM). The line drawing interpretation has been depth converted with Midland Valley's Move software using the stacking velocities. A well log available thanks to the VIDEPI Project (http://unmig.sviluppoeconomico.gov.it/videpi/) is projected on the seismic line from about 3 km NW, to constrain the sub-surface prosecution of the Ligurian units.

4. Results

Valmozzola geological and geomorphological field data

Within the Ghiare tectonic window, the incision of the Taro river clearly exposes the lowermost portion of the Ligurian allochthonous units, which are overthrust by the uppermost ones (Caio helminthoid flysch, CAO) (Figs. 3, 4). The latter are highly tectonized by thrusting and by dismembered overturned folds that involve also their clayey substratum (Ossella Mélange, MSL). On the right slope of the Valmozzola the CAO and MSL overlay the northern limb of the Ghiare antiform.

In the southern portion of the Valmozzola area the normal faults are W-E and NW-SE trending, whereas in the central-northern portion the faults are N-S and SW-NE oriented (Fig. 4). The mesoscale-faults and joints sets collected in the structural stations (Fig. 4) fit with the structural framework related to the evolution of the Ghiare antiform. In particular, joints sets in stations 3, 5, 6, 7 and 8 are parallel and normal to the WNW-ESE trending Ghiare antiform axis (Fig. 4). The relative vertical throw observed among different portions of the antiform, separated by two of the N-S oriented extensional faults, is clearly shown by the outcropping of the same geological units at different elevations. Specifically, the CAO and MSL units of the E block occupy a higher position with respect to the same units belonging to W block (Figs. 4, 9). The N-S oriented fault system, coeval to the development of the Ghiare antiform, as highlighted by the displacement of the tectonic contacts between the geological units, is thus responsible for the relative vertical movements affecting the antiform itself.

Despite the outcropping lithologies not being suitable for the preservation of landforms (due to the high amount of clay), many morphotectonic proofs of tectonic activity are recognizable in the Valmozzola area (Fig. 4). The best preserved evidence is visible along the watershed between Mozzola torrent and Taro river, where planar and altimetric topographic discontinuities that account for fault activity can be observed. Moreover, gullies along the slopes and wind gaps in the watershed contribute to the identification of the presence and direction of faults. Only where the more resistant Scabiazza sandstones (SCB) crop out, triangular or trapezoidal facets survive, testifying throws of ~10 m (Fig. 4). The right side of Valmozzola is almost completely collapsed, owing to several large complex landslides that in most cases are dormant, and show still recognizable but very smoothed landforms. In correspondence of the mouth of the Mozzola torrent valley, the foot of the Ossella landslide, one of the large landslides involving a large part of the slope, reaches the thalweg of the Mozzola torrent (Fig. 4). This landslide is still active, it shows fresh and clear landforms and it has an intermittent activity, with greater reactivations about every 20 years and minor ones which are more scattered in time (Regione Emilia Romagna – Frane e Dissesto Idrogeologico – www.regione.emilia-romagna.it/wcm/geologia/canali/cartografia/sito_cartografia/web_gis_dissesto.htm). The crown of Ossella landslide is represented by a portion of the watershed between Mozzola and Taro valleys. Here, tension cracks appear on the ground surface, denoting different orientations, controlled by the bedding, joints and faults attitude of the outcropping rocks (Fig. 6). Characterized by a wide source area (Fig. 7.1), the detached material moved mainly as rotational and translational slide involving a huge (from ~10^3 to ~10^5 m^3) volume of rock (Fig. 7.2). In the middle portion of the depleted mass, counter slope surfaces occur (Fig. 7.3). The type of movement of Ossella landslide completely changes in the lower half of the slope (Fig. 4). Here earth flows spring from the depleted mass, when the occurrence of rainfall events causes the liquefaction of the landslide material. The accumulation zone is fan-shaped and made up of debris and clays. It ends with a scarp up to 4-5 m high formed by the erosion from the Mozzola torrent. In the crown area, linear morphologic features are characterized by clear orientations. The western flank of the landslide is N-S oriented. In the southern part of the landslide crown elements of the main scarp and tension cracks are mainly NW-SE and secondly SW-NE oriented (Fig. 6). Some of the high-angle faults downthrowing the W portion of the Ghiare antiform are well aligned with the W side of the Ossella landslide, the latter mainly characterized by block detachment.

After the landslide reactivated in 1977, a geophysical survey was made (4 refraction seismic profiles and 16 vertical electric surveys, V.E.S. in Fig. 7.4) (Careggio et al., 1981). The geophysics highlighted that the rock slide involved the substratum down to depths of 30-40 m and revealed the presence of a step in the landslide substratum. Just up-slope of this step, a back-tilted portion of the landslide surface is clearly recognizable because of the presence of sag ponds (Fig. 7.3). This area marks the passage from the landslide depletion to the mass transfer zone.

Regional-scale data

The analysis of the seismic profile shown in Fig. 3 highlighted the presence of deep-rooted (at least ~10 km) thrust faults which produced at surface the late orogenic antiforms previously constrained only by the field geology. Moreover, the seismic profile clearly shows, in the shallower portion (~ 3 km), the extensional faults which represent the latest deformation affecting the antiforms. In the case of the Ghiare antiform, some of the deep thrust-faults cut through the top of the seismic basement and create a bulging structure in the overlying foredeep units, just below the antiform (see section 2.1, and supplementary material). The swath profiles (Fig. 8) cover most of the investigated area, excluding the chain foothills. The topographic analysis highlighted, in the mean topography, the presence of three maxima, A, B and C, separated by a distance of ~10 km one from each other. The amplitude of the A maximum is ~9 km, while the amplitude of the other two is ~2-3 km. The larger amplitude of A is caused by the presence of the main divide of the chain, clearly visible in the maximum topography curve, as shown in A1 (Fig. 8). The location of the late antiforms axial trend has been plotted on top of the topographic profiles. A fair spatial relationship between the antiforms axis and A, B and C topographic maxima is clearly marked in the mean elevation curve, and still recognizable in the maximum and minimum elevation curves.

The geomorphological analysis performed in the investigated area (~ 2000 km^2) improved the definition of the large landslides distribution with respect to the previous works (Chelli et al., 2013). The application of the chosen dimensional parameter to the regional landslides database allowed us to select, among the 6220 landslides present in the study area, 232 large landslides, most of which are characterized by a surface larger than 10^6 m^2. Among the latter, the remote sensing analysis allowed to identify the complex landslides thanks to the recognition of:

-tilted counter-slope surfaces in the detachment zone, associated to hummocky and lobate morphology;

- step-like morphology in the heads of the landslides as a result of successive or retrogressive sliding; and

- fan-shaped accumulation zone due to the switching of the type of movement into a flow.

Usually, these landslides occur in heterogeneous weak rocks that are largely represented within the Ligurian units (Fig. 2). Among the complex landslides, 65 show an important proximity relationship with the regional-scale antiforms (Fig. 2).

5. Discussion

From the combined results it seems that the growth and exhumation of the Ghiare antiform is related to the most recent activity of the deep contractional faults, coeval with the surface high-angle extensional faults. Apatite fission-track ages of rocks, sampled close to the Ghiare antiform, indicate that the cooling under the 110-120 °C isotherm occurred ~3-5 Ma (Pliocene) (Carlini et al., 2013). With erosion rates of ~0.7 mm/yr being considered as reasonable for the study area (Balestrieri et al., 2003, Bartolini et al., 2003; Thomson et al., 2010), the exhumation of the Ghiare antiform can be considered concluded not more than ~1 Ma. On the other hand, the appearance of fresh morphotectonic features suggests that its growth is still ongoing (see section 4.1). The activity of the late high-angle normal faults can be related to the shallow extensional tectonics which, starting from the Pliocene, can be considered still active, as testified by GPS measurements. In fact, the latter demonstrate how this portion of the chain is dominated by an extensional regime with movements towards N-NE that exceeds 3 mm/yr (Toscani et al., 2009; Baldi et al., 2011; Bennett et al., 2012; Serpelloni et al., 2013) (Fig. 1). The shallow extensional tectonic regime within the study area might represent the surface response to the rock uplift that corresponds to the sum of tectonic exhumation and surface uplift (topographic growth) of the Ghiare antiform (Figs. 3, 5). As highlighted by the swath profiles, the present-day topography still preserves the signature of the late antiforms, thus further constraining their presumed still ongoing growth (Fig. 5). In fact, the mean relief curve shows long-wave (~ 10 km) topographic features that are in agreement with the location of the antiforms (Fig. 5).

All these tectonic and temporal constraints allowed us to delineate a framework in which it has been possible to understand the distribution of large landslides and the active and/or passive control exerted by tectonics. Structures resulting from the tectonic deformation heavily conditioned the topography and the landforms characterizing the investigated area. As shown by the Valmozzola case study, the main morphologic elements of investigated landslides (e.g.: tension cracks in the crown area, segments of main scarps and prevailing movement directions) developed along some of the faults and joint sets of the outcropping rocks. In fact, within the crown area of the Ossella landslide, NW-SE and SW-NE oriented tension cracks (Fig. 6) fairly correspond to the surveyed sets of fractures orientations (compare with structural data in stations 7 and 8; Fig. 4). Also, N-S oriented tension cracks can be related to joints and some of the main extensional faults having the same orientation (Fig. 9) and continuing below the landslide body. Besides, the whole W slope of the landslide niche developed as a fault-line controlled erosion scarp (Fig. 4), suggesting a recent activity of the fault. The same fault, in fact, ~450 m S of the landslide crown, creates a well preserved triangular facet, further proof of its recent activity (Fig. 8). The shallow seismic line shown in Fig. 7.4 highlighted a scarp in the bedrock which is located along the prolongation of a SW-NE-trending fault, represented on the geological map and of SW-NE-trending mesoscale faults observed in structural station 1 (Fig. 4). As clearly shown in Fig. 9, the more recently uplifted block (left side of the picture, see also section 4.1), is, at present, the portion of Valmozzola slope affected by the active Ossella landslide. The remaining portion of the Valmozzola right slope lie on blocks uplifted in older times and, in fact, hosts only dormant complex landslides.

In this perspective, the Valmozzola case study shows us that the tectonic activity plays a well-defined role in promoting the landslides beyond the passive control that determined the lines of weakness along which the landslides may have developed. In fact, tectonics exert an active control contributing, through rock uplift, to the topographic growth that favours hillslopes approaching their threshold angle, which, in turn, favours landsliding when trigger factors occur. Moreover, the case study highlights that the Valmozzola landslides are not only distributed along the Ghiare antiform, but they developed during the latest stages of the antiform evolution. This fact is evidenced by the presence, beside the active Ossella landslide, of other complex landslides that are dormant and old, as indicated by their smoothed landforms. These landslides probably activated in different times in response to the different deformation stages of the antiform itself (i.e. differential uplift of the antiform's blocks bounded by the extensional faults).

Therefore, referring to tectonics as a general cause of rock mechanical fatigue and loss of cohesion is not sufficient to fully explain the distribution of the considered large landslides spatially correlated to the late antiforms. The tectonic-controlled distribution of large complex landslides may, indeed, be regarded, like other geomorphological processes showing spatially recognizable arrangements, also as a useful indicator for the existence/activity of regional-scale tectonic features, and, thus, to provide information about the evolution of active orogenic wedges. Furthermore, landslide characteristics such as their large size, the deep engagement of the bedrock, the development of forms following the tectonic lineaments, and their distribution following a specific orientation could be listed as distinctive characters of the relationship with tectonics. Obviously, the use of these characteristics of large complex landslides as indicators of tectonic processes may be cautiously applied only in a framework where geological, geomorphological and climatic features are well constrained.

According to all these considerations, the possible evolution of the Valmozzola slopes is represented in Fig. 10. The evolutionary sketch of Valmozzola case study may be regarded as explanatory of the development of large landslides in response to the antiform’s growth across the entire investigated area. Since information about the palaeotopography of the area is not available, the topographies in stages 1 and 2 are derived from the vertical smoothing and exaggeration, respectively, of the present-day topography.

stage 1

During stage 1 (Fig. 10a) the relief was reasonably characterized by a smoothed surface, representative of the topography of the growing Ghiare antiform. The AFT ages constrained the growth of the Ghiare antiform to the last 3-5 Ma, allowing us to refer stage 1 to the late Pliocene-early Pleistocene (Fig. S1), when the stack of tectonic units was already deformed and in the inner portion of the chain there is evidence of emergence above sea level, i.e. deposition of continental deposits (see section 2). Landslides were probably already an active process at that time.

stage 2

The progressive growth of the antiform was followed by the development of by high-angle normal faults. Stream incision was reasonably responsible for the undermining at the slope foot. In this second stage, since all the main tectonic features observed today were already present, the complex landslides might have begun to develop along these tectonic discontinuities, deeply affecting the bedrock. These processes probably developed during the middle-late Pleistocene (Fig. S1), when in the Northern Apennines climate phases characterized by enhanced precipitation and freeze-and-thaw-cycles (periglacial conditions) might have promoted the action of physical rock weathering and also erosive processes such as landslides.

stage 3

Stage 3 represents the present-day situation, characterized by valley sides with gentler slopes with respect to stage 2. At present, the evolution of the considered landslides doesn’t show any relationship with the stream incision (Fig. 14c). The present-day activity of Ossella landslide is still driven, above all in the depletion zone, by tectonic and structural factors that play as causes promoting the landsliding processes.

The tectonic, lithologic and geomorphological framework of the Valmozzola can be reasonably used as a proxy to represent the evolution of the entire shown in Fig. 2. In fact, the growth of the other antiforms of the area occurred during the same tectonic phase that led to the evolution of the Ghiare antiform. As a consequence, the hillslopes affected by these late structures, having suffered also the same climate-driven erosion phases, reasonably evolved according to a framework in which the tectonics has also exerted an active control on landslides development in the way prospected for the Valmozzola.

6. Conclusions

The factors that classically are reported in the scientific literature as causes of landslides in the Northern Apennines seem not to fully explain the spatial relationships between late orogenic antiforms and landslides. The adopted multidisciplinary approach, which integrated new geomorphological, geological and geophysical data, proved sufficient to elucidate the strong connection existing between tectonic and large landslides. Analysis of the seismic profile together with the geological field survey, in fact, highlighted a tectonic framework characterized by deep contractional structures, at least partially still active, which at surface produced regional-scale antiforms and related high-angle extensional faulting. These tectonic features exerted a passive control on 5 large landslides, determining lines of weakness and the failure surfaces along which residual or lower-than-peak strength exist. Tectonics also exerted an active control in the Valmozzola case study, where the landslides represent the denudational response to the tectonic-driven topographic growth and over-steepening of the slopes, as shown by the active Ossella landslides. The same active control may be reasonably applied to the 65 considered large complex landslides and to be considered a clear trait characterizing the study area at regional-scale. The passive and active control exerted by the tectonic evolution of late orogenic antiforms are, therefore, identified as being the cause of the observed orientation and spatial distribution of large complex landslides.

Future developments will extend the adopted approach to other portions of the Northern Apennines and other case studies in order to constrain the investigated processes in a temporal and quantitative (landslide denudation rates and stream network evolution) sense.

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FIGURE CAPTIONS

Fig. 1 – ASTER 30 m resolution DEM (NASA LP DAAC) of the Northern Apennines showing the main divide of the chain and the location of the area of interest (red rectangle). Arrows represent extension and shortening in the strain field inferred from GPS data (Bennet et al., 2012). Black arrows representing areas tilted during the Quaternary refer to the Neotectonic map by Bartolini et al. (1982). Numbers represent apatite fission track ages by Thomson et al. (2010) and Carlini et al. (2013).

Fig. 2 – Geological map of the area in which the late antiforms and large landslides are indicated. The solid-line rectangle represents the studied Valmozzola landslides denoted in Fig. 4. The dotted lines bound the area covered by the swath profiles shown in Fig. 5. The trace of the seismic and geological cross-sections in Fig. 3 is represented by a solid line along the Taro river.

Fig. 3 – Geological and seismic sections crossing the area of Fig. 2. The two sections are built along the same trace. Bold letters in the seismic section represent the major recent thrust faults. The map on the bottom right corner of the Figure shows the location of the buried thrusts tips with respect to the surface antiforms. Other seismic lines have been used to constrain the 3D geometry of the thrust surfaces, whose depths are represented by the shaded colours.

Fig. 4 – Detailed geomorphological and geological map of investigated area, between the Taro river and the Mozzola torrent, where the Valmozzola landslides developed. Ossella landslide is the easternmost one. The black line crossing Ossella landslide represents the trace of the vertical electric sounding shown in Fig. 7.4. The numbered dots represent the structural stations, whose related stereonets are represented in the lower part of this Figure (bedding: dashed circles; faults: arrowed circles; joint: solid circles; open joints: dotted circles). Stereonets are related to the lower hemisphere and equal area projection and have been produced with Stereonet 8 (Allmendinger et al., 2012; Cardozo & Allmendinger, 2013). a - dormant complex (rock slide-debris/earth flow) landslide; b - active rock block slide; c - active rock slide; d - active debris/earth flow; e - dormant main scarp; f - active main scarp; g - planar discontinuity of ridge; h - planar-altimetric discontinuity of ridge; i - boundary of counter slope surface; j - tension crack; k - wind gap; l - triangular facet; m - erosional scarp due to running waters; n – late extensional fault; al – present-day alluvial deposit; at – terraced alluvial deposit; CCV - Casanova Ophiolite Complex (Early Campanian); CAO - M. Caio Flysch (Late Campanian - Maastrichtian); MSL - Ossella Mélange (Cenomanian - Santonian); SCB - Scabiazza Sandstone (Coniacian - Santonian); BEV - Belvedere Sandstone (Early Eocene); GHR - Ghiare Unit (Early Campanian - Maastrichtian); RCA - Casacca Limestone (Early Eocene).

Fig. 5 – Topographic swath profile of the area indicated in Fig. 2 representing maximum, mean and minimum elevation. Dots represent the projection of the antiforms over the swath area, while the dashed boxes represent the correlation between structural antiforms and positive features in the mean topography.

Fig. 6 – Tension cracks of different size and opening are recognizable in the crown area of Ossella landslide. They often correspond to sets of fractures existing as result of tectonic deformations (Fig. 4). The attitude of the joint and fault planes is expressed as strike / dip.

Fig. 7- The landscape from east shows several diagnostic features of the Ossella landslide (1): rock block (volume ~104 m3) slid as a whole where some portion of the rock strata are still recognizable (in the circles) (2), the counter slope surface containing several sag ponds (3). The counter slope surface corresponds to the step in the bedrock beneath the landslide as revealed by the vertical electric soundings (V.E.S.) after Careggio et al. (1981) (4). The position of V.E.S. 6 and 7 is reported in Fig. 7.1 for reference. Figs. 7.2, 7.3 and 7.4 are referred to the dashed boxes represented in Fig. 7.1.

Fig. 8 – Side view of the Ghiare tectonic window and antiform from ESE. The black arrows indicate the opposite dipping of the NE and SW limbs of the antiform. This fact can be easily recognized following the tectonic contact between M Caio flysch (CAO) and Scabiazza sandstones (SCB) units. The lined triangle represents the triangular facet created by one of the main N-S trending faults.

Fig. 9 - North view of the Ossella landslide. The differential vertical movement of the E and W portion of the slope (left and right sides of the picture, respectively) is revealed by the lack of correspondence between tectonic units cropping out on the two sides of the faults.

Fig. 10 – 3D evolutionary sketch of the Valmozzola landslides area. The view is from the NE. In each stage the white line represents a topographic profile across the DTM. The black circle on the tectonic sketch in stage 3 represents the portion of the topographic profile affected by the Ossella landslide. The tectonic sketch on the right side of the stages is the same of Fig. 4. The black dashed lines in stages 1 and 2 represent the present-day perimeters of the landslides represented as solid lines in stage 3.

Figure 1

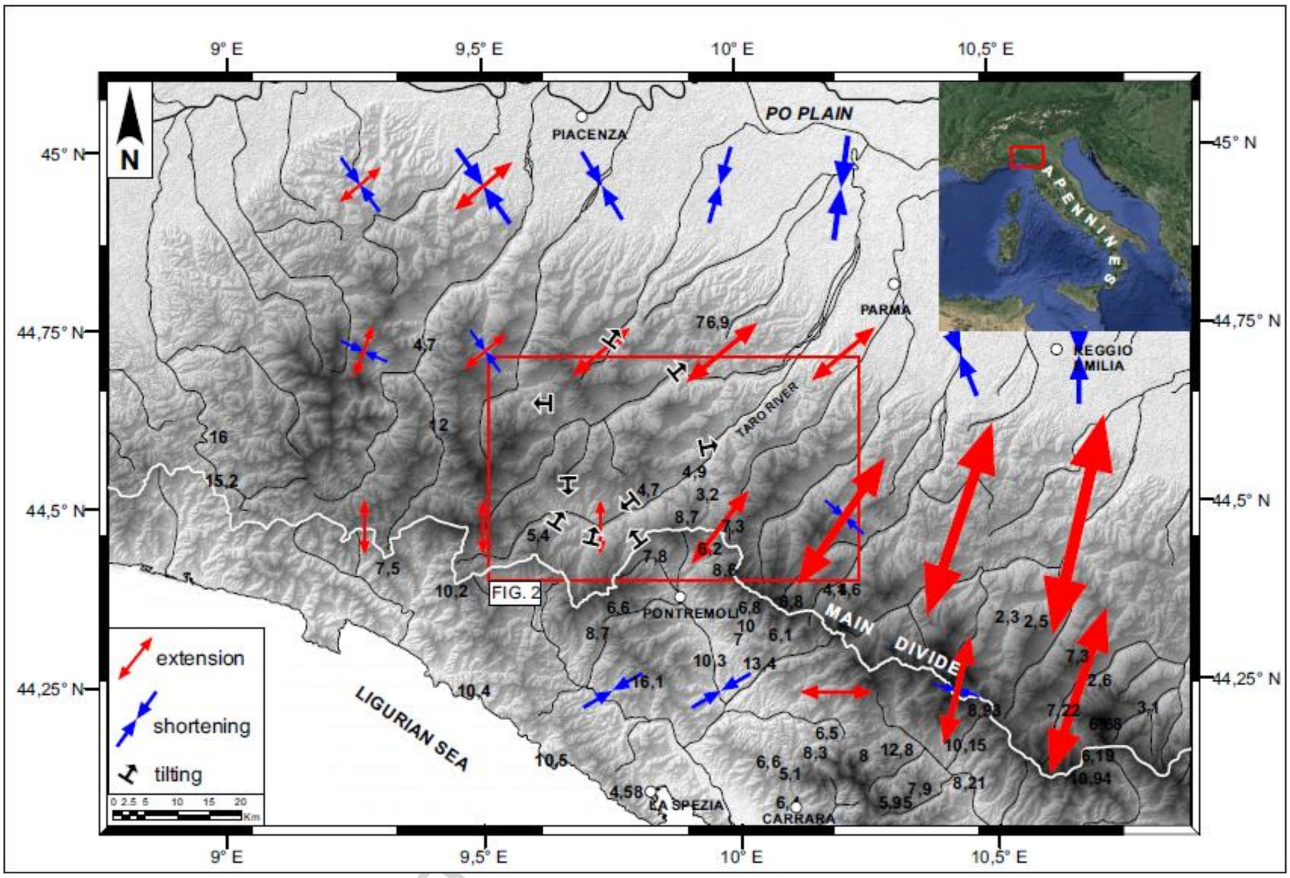

9° E
9,5° E
10° E
10,5° E
45° N
44,75° N
44,5° N
44,25° N
N
PO PLAIN
PIACENZA
PARMA
REGGIO EMILIA
TARO RIVER
PONTREMOLI
MAIN DIVIDE
LIGURIAN SEA
LA SPEZIA
CARRARA
APENNINES
FIG. 2
extension
shortening
tilting
Km

Figure 2

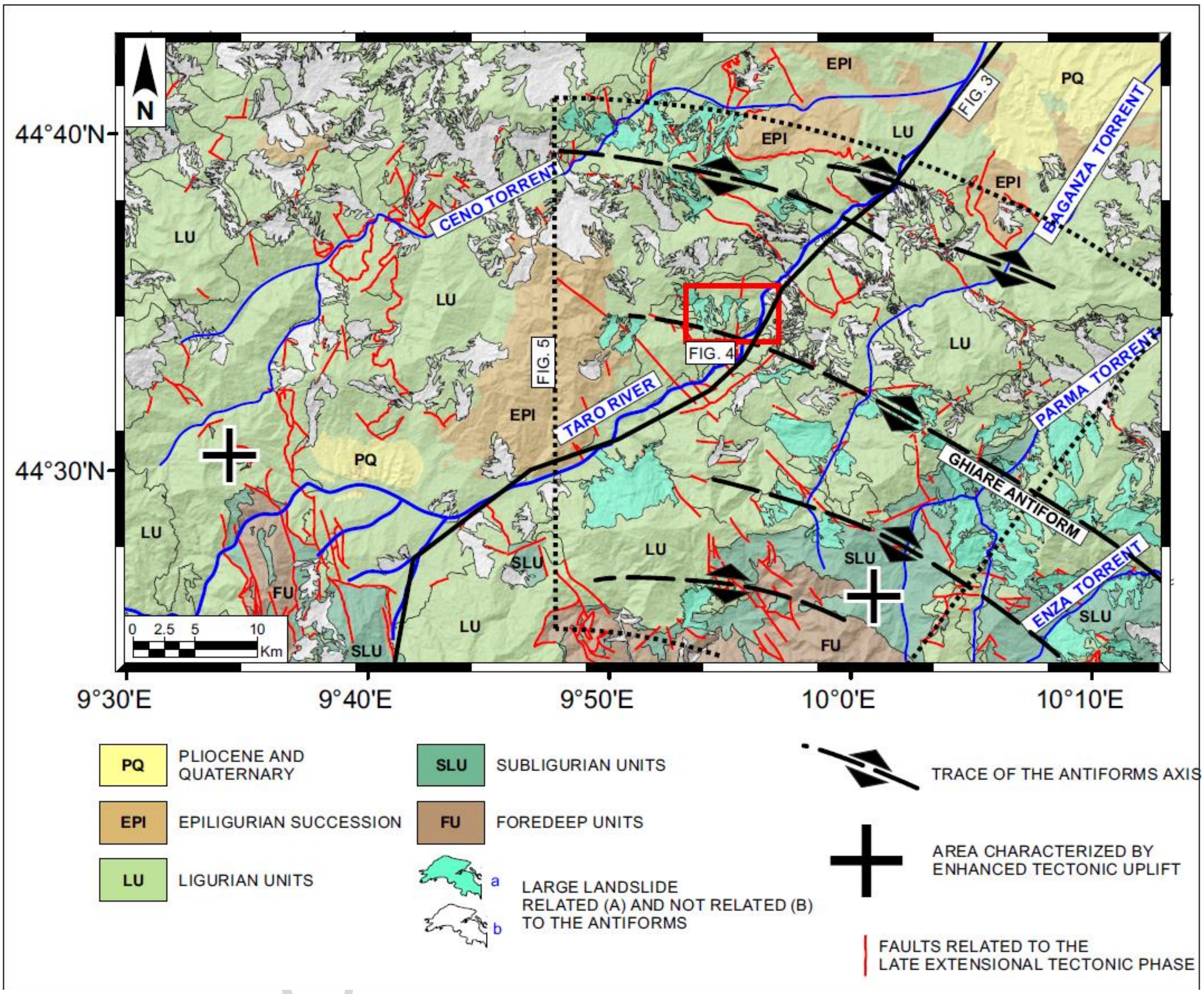

N
44°40'N
44°30'N
9°30'E
9°40'E
9°50'E
10°0'E
10°10'E
CENO TORRENT
TARO RIVER
BAGANZA TORRENT
PARMA TORRENT
ENZA TORRENT
GHIARE ANTIFORM
FIG. 3
FIG. 4
FIG. 5
0 2.5 5 10 Km
PQ
PLIOCENE AND QUATERNARY
EPI
EPILIGURIAN SUCCESSION
LU
LIGURIAN UNITS
SLU
SUBLIGURIAN UNITS
FU
FOREDEEP UNITS
a
b
LARGE LANDSLIDE RELATED (A) AND NOT RELATED (B) TO THE ANTIFORMS
TRACE OF THE ANTIFORMS AXIS
AREA CHARACTERIZED BY ENHANCED TECTONIC UPLIFT
FAULTS RELATED TO THE LATE EXTENSIONAL TECTONIC PHASE

Figure 3

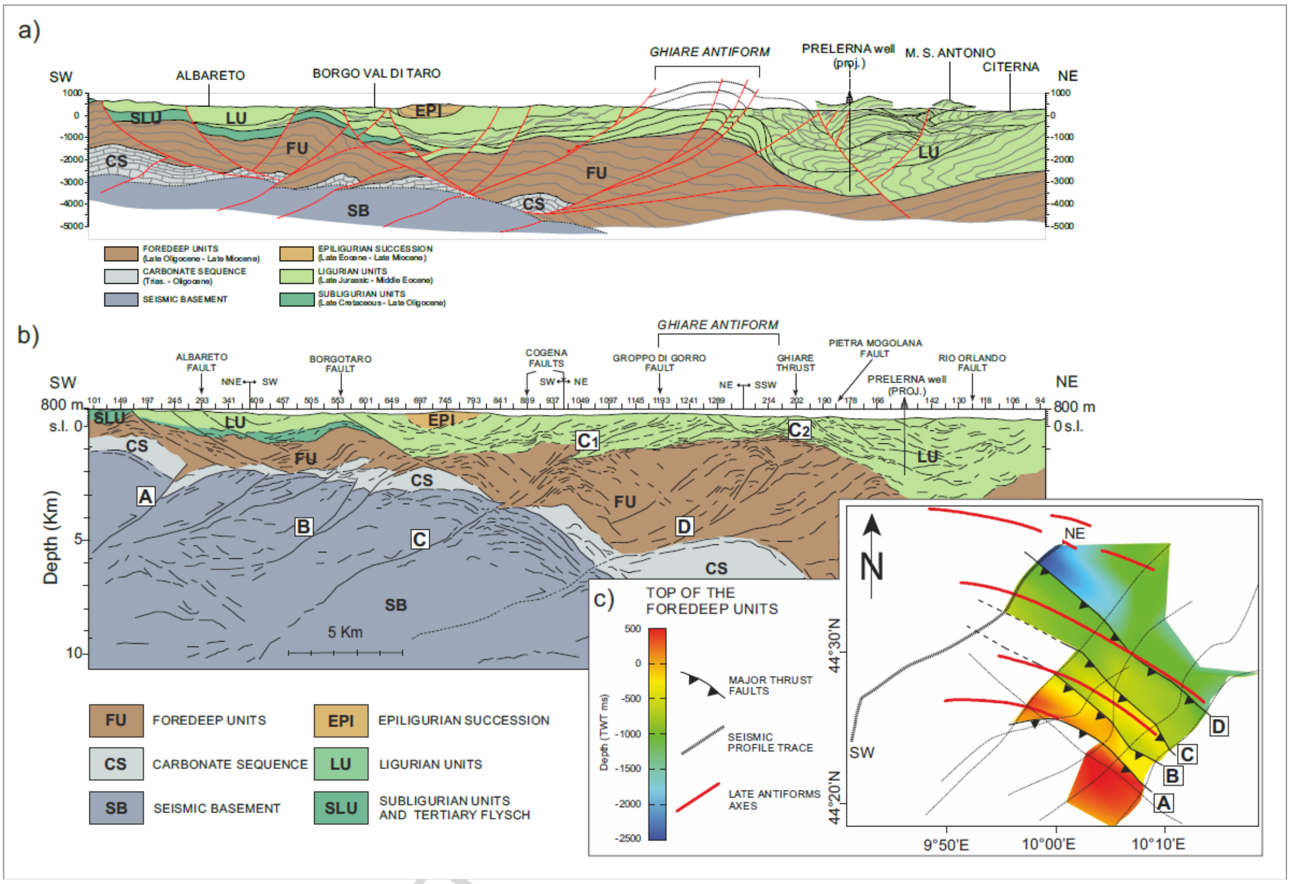

a)
SW
ALBARETO
BORGO VAL DI TARO
GHIARE ANTIFORM
PRELERNA well (proj.)
M. S. ANTONIO
CITERNA
NE
SLU
LU
EPI
FU
CS
SB
FOREDEEP UNITS (Late Oligocene - Late Miocene)
CARBONATE SEQUENCE (Trias. - Oligocene)
SEISMIC BASEMENT
EPILIGURIAN SUCCESSION (Late Eocene - Late Miocene)
LIGURIAN UNITS (Late Jurassic - Middle Eocene)
SUBLIGURIAN UNITS (Late Cretaceous - Late Oligocene)
b)
GHIARE ANTIFORM
ALBARETO FAULT
BORGOTARO FAULT
COGENA FAULTS
GROPPO DI GORRO FAULT
GHIARE THRUST
PIETRA MOGOLANA FAULT
RIO ORLANDO FAULT
PRELERNA well (PROJ.)
800 m
s.l. 0
0 s.l.
Depth (Km)
A
B
C
D
C1
C2
5 Km
FU FOREDEEP UNITS
CS CARBONATE SEQUENCE
SB SEISMIC BASEMENT
EPI EPILIGURIAN SUCCESSION
LU LIGURIAN UNITS
SLU SUBLIGURIAN UNITS AND TERTIARY FLYSCH
c)
TOP OF THE FOREDEEP UNITS
Depth (TWT ms)
MAJOR THRUST FAULTS
SEISMIC PROFILE TRACE
LATE ANTIFORMS AXES
N
44°30'N
44°20'N
9°50'E
10°00'E
10°10'E

Figure 4

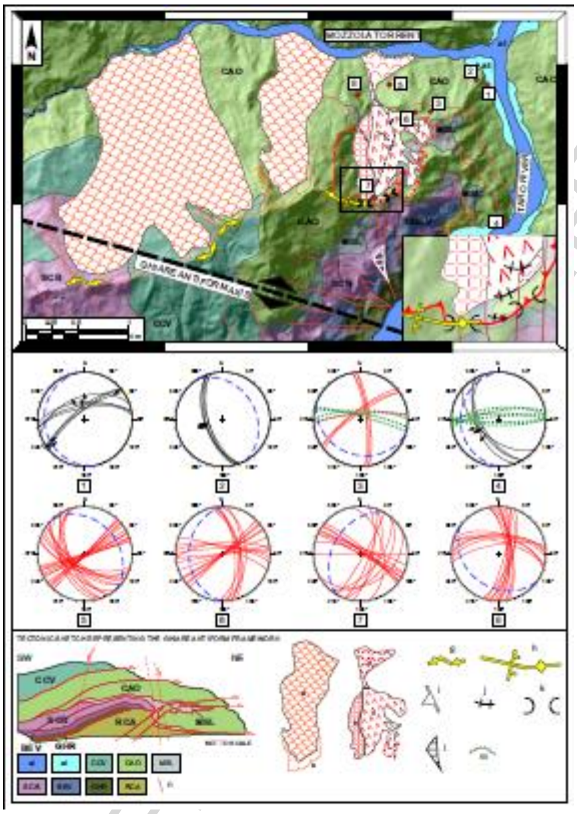


Figure 5

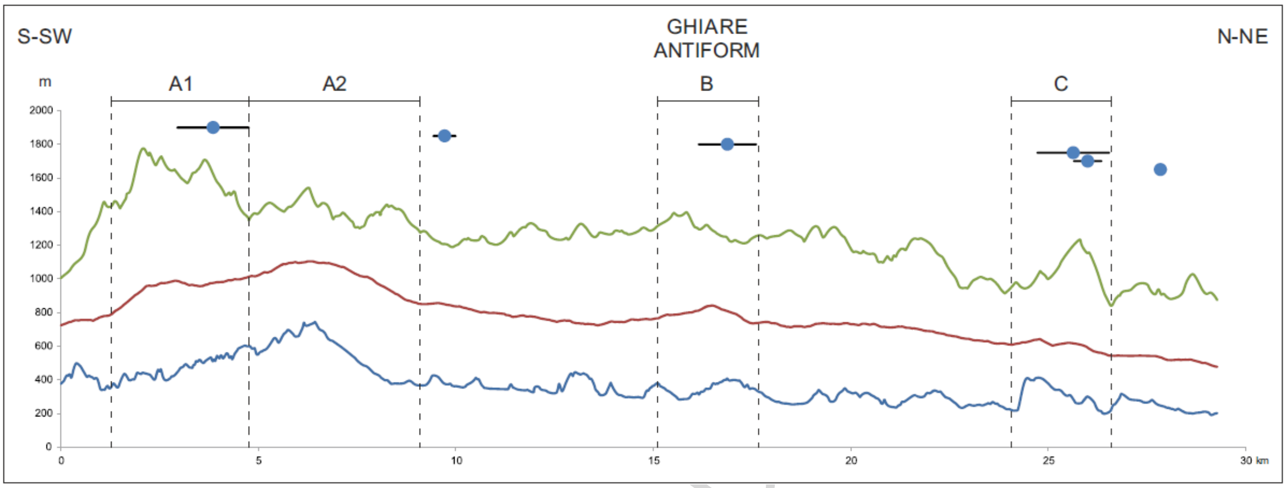

S-SW
GHIARE
ANTIFORM
N-NE
m
A1
A2
B
C
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30 km

Figure 6

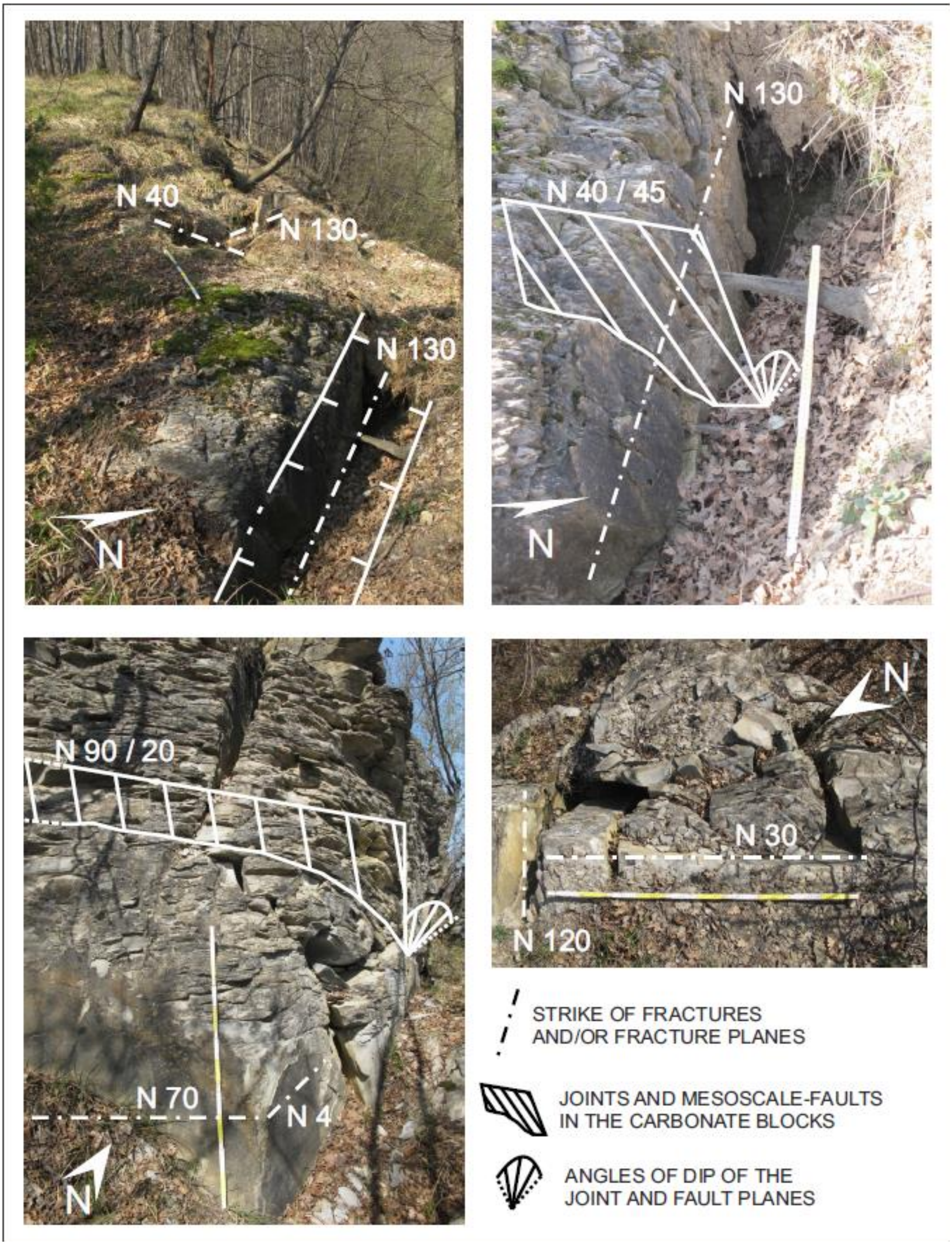

N 40
N 130
N 130
N
N 130
N 40 / 45
N
N 90 / 20
N 70
N 4
N
N
N 30
N 120
STRIKE OF FRACTURES
AND/OR FRACTURE PLANES
JOINTS AND MESOSCALE-FAULTS
IN THE CARBONATE BLOCKS
ANGLES OF DIP OF THE
JOINT AND FAULT PLANES

Figure 7

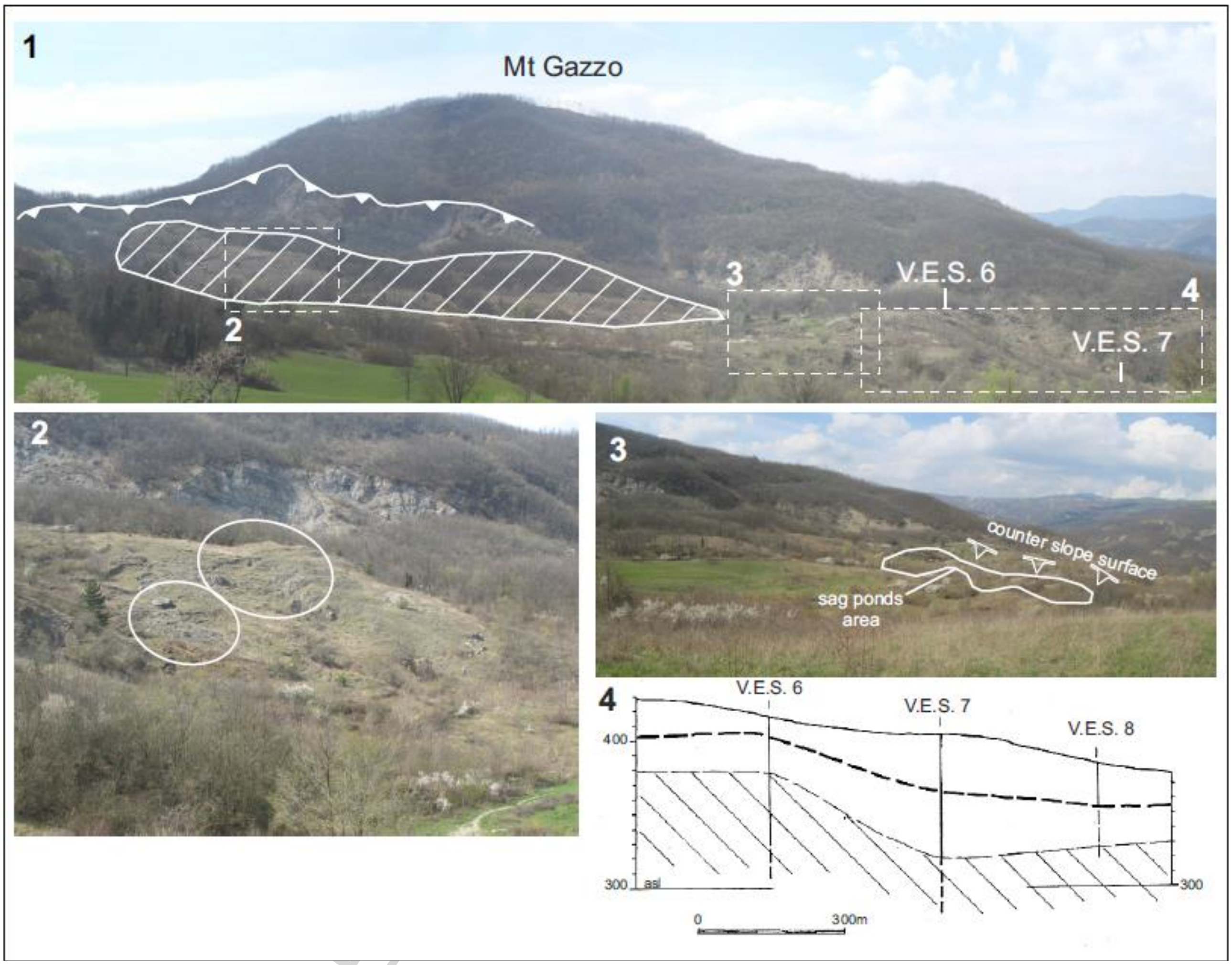

1
Mt Gazzo
2
3
V.E.S. 6
4
V.E.S. 7
2
3
counter slope surface
sag ponds area
4
V.E.S. 6
V.E.S. 7
V.E.S. 8
400
300
asl
300
0
300m

Figure 8

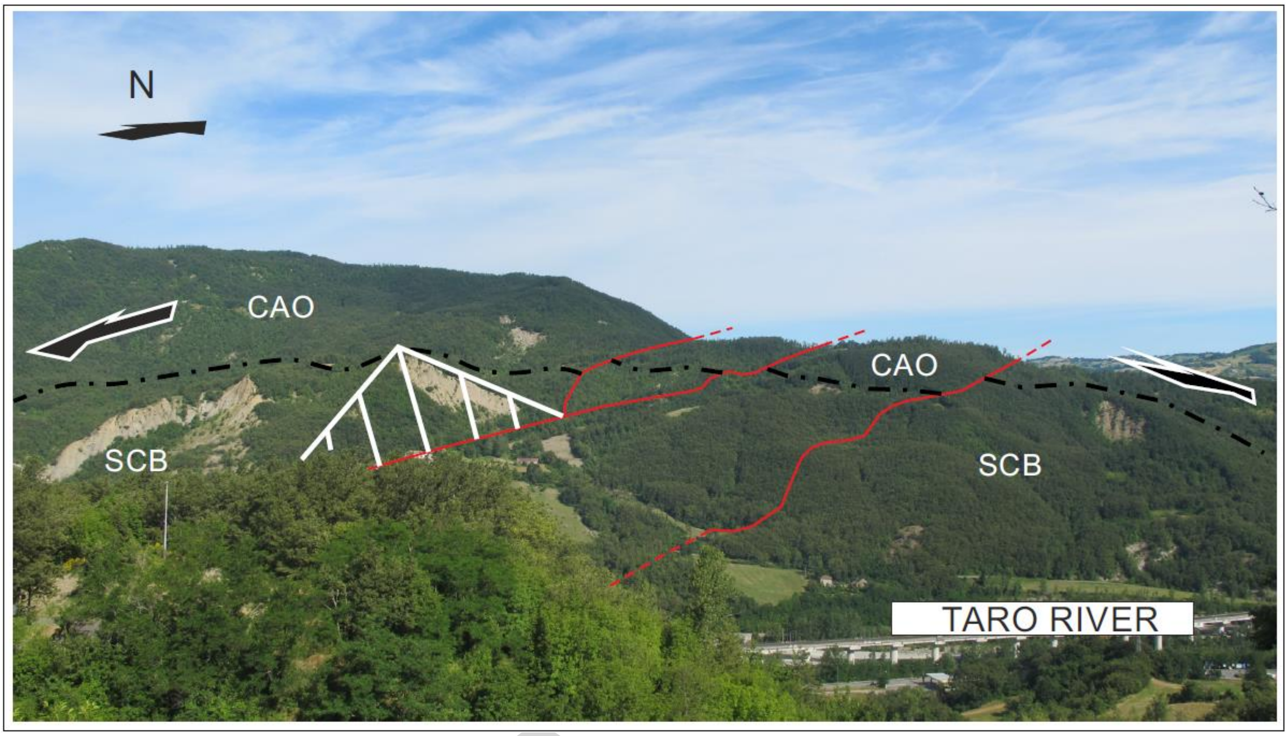


Figure 9

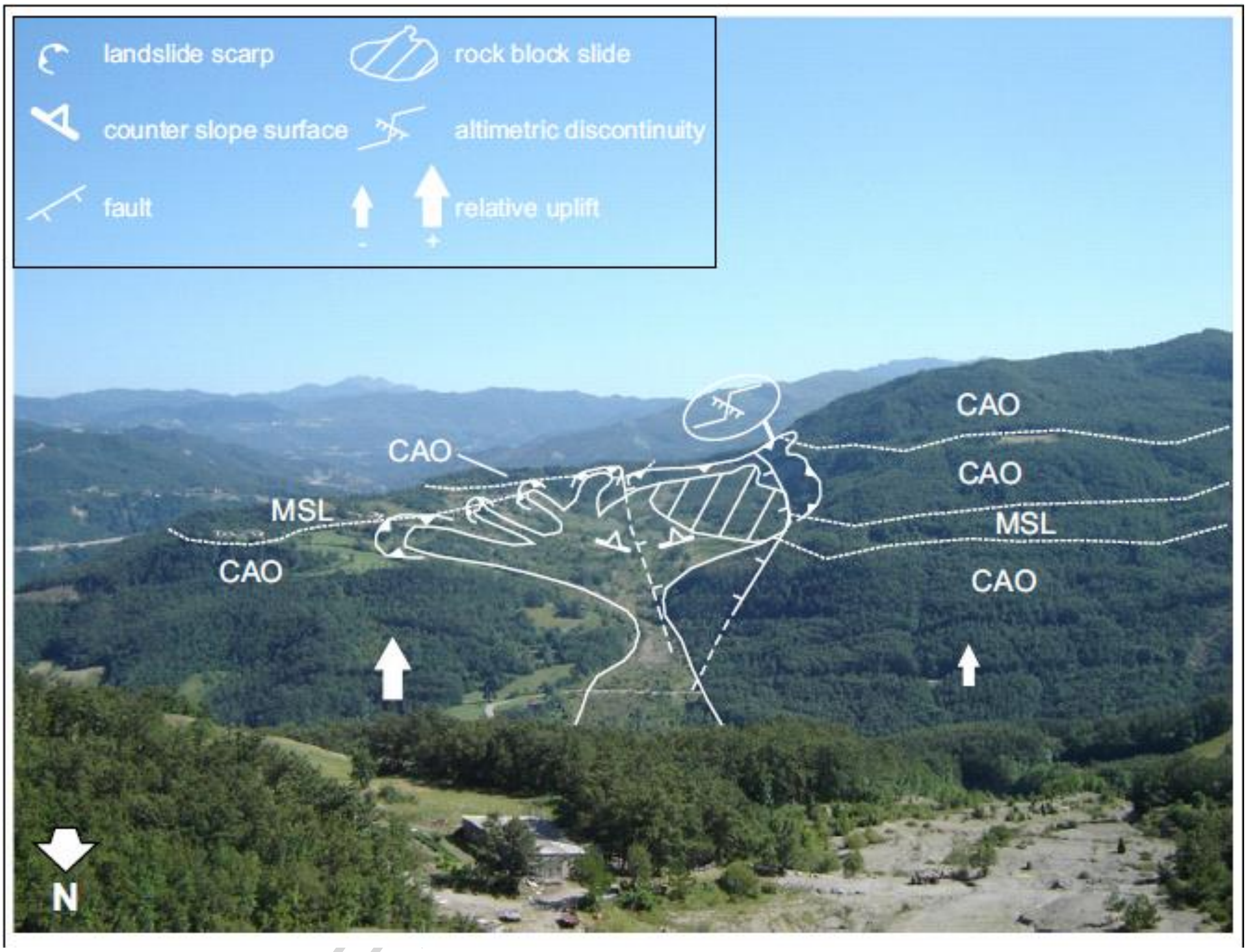
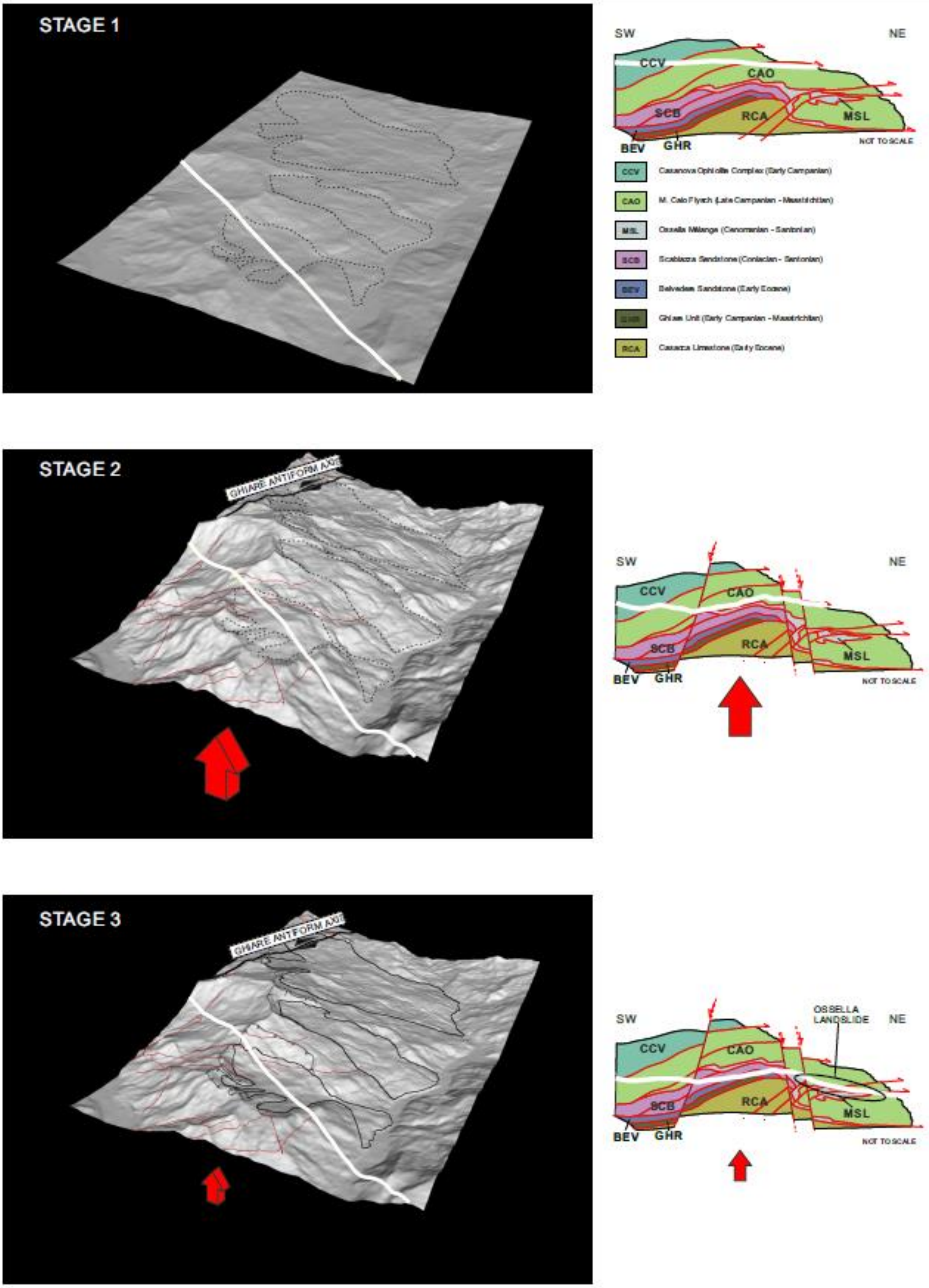

landslide scarp
rock block slide
counter slope surface
altimetric discontinuity
fault
relative uplift
-
+
CAO
CAO
CAO
MSL
CAO
MSL
CAO
CAO
N

Figure 10


STAGE 1
SW
NE
CCV
CAO
SCB
RCA
MSL
BEV
GHR
NOT TO SCALE
CCV
Casanova Ophiolite Complex (Early Campanian)
CAO
M. Caio Flysch (Late Campanian - Maastrichtian)
MSL
Ossella Mélange (Cenomanian - Santonian)
SCB
Scabiazza Sandstone (Coniacian - Santonian)
BEV
Belvedere Sandstone (Early Eocene)
GHR
Ghiare Unit (Early Campanian - Maastrichtian)
RCA
Casazza Limestone (Early Eocene)
STAGE 2
GHIARE ANTIFORM AXIS
SW
NE
CCV
CAO
SCB
RCA
MSL
BEV
GHR
NOT TO SCALE
STAGE 3
GHIARE ANTIFORM AXIS
SW
OSSELLA LANDSLIDE
NE
CCV
CAO
SCB
RCA
MSL
BEV
GHR
NOT TO SCALE

Highlights

The relationships between large complex landslides and tectonic structures are examined.

Landslides develop along lines of weakness and failure surfaces caused by tectonics.

Tectonics cause topographic growth and over-steepening of the slopes.

Tectonics exert an active and passive role on landslide distribution and type.

Landslides may be an indicator of regional-scale, well-constrained tectonic processes.