

Landslides (2018) 15:1881–1887
 DOI 10.1007/s10346-018-1039-4
 Received: 2 May 2018
 Accepted: 6 July 2018
 Published online: 14 July 2018
 © Springer-Verlag GmbH Germany
 part of Springer Nature 2018

Marco Mulas · G. Ciccacese · F. Ronchetti · G. Truffelli · A. Corsini

Slope dynamics and streambed uplift during the Pergalla landslide reactivation in March 2016 and discussion of concurrent causes (Northern Apennines, Italy)

Abstract On March 28, 2016, the toe zone of the apparently dormant Pergalla earthslide-earthflow (Northern Apennines, Italy) had a paroxysmal reactivation. In the course of 2 days, displacements up to almost 8 m severely damaged several houses and roads. At the bottom of the slope, the emersion of rotational sliding surfaces determined the uplift of almost 3 m of the Nure river streambed that was consequently partially dammed. The paper describes the landslide event on the basis of field surveys and analysis of post-event aerial photos, as well as data from geophysical surveys and pre- to post-failure displacement monitoring. It also discusses the possible concurrent causes of the event, including antecedent rainfall, the migration of active streambed channels of Nure river toward the landslide toe in the previous year, and the existence of long-term pre-failure slow movements. It is concluded that these factors, together with the presence of sliding surfaces extending beneath the valley floor, should be primarily considered if a preventive assessment of river damming potential due to streambed uplift should be made for other similar landslides in the Apennines.

Keywords Streambed uplift · Landslide · Reactivation · Northern apennines

Introduction

Landslide dams are reported in many mountain chains of world (Costa and Schuster 1988) and their stability in time depends upon different geomorphic factors (Ermini and Casagli 2003). Rotational earth slides, together with complex phenomena, can cause river damming primarily under the following circumstances (Costa and Schuster 1988): (i) streambed infill by large volumes of high-mobility debris (see, for example, Wang et al. (2008) in the Three Gorges area in China); (ii) streambed uplift due to the emersion of sliding surfaces extending beneath the present-day alluvial deposits of valley floors (see for example Bartarya and Sah (1995) in the Himalaya and Micu and Bălțeanu (2013) in the Carpathians).

In Italy, a recent database of landslide dams indicates rotational slides and complex phenomena among the most common causes of river damming (Tacconi Stefanelli et al. 2015). Specifically, in the Northern Apennines, several hundreds of dormant large-scale complex earthslides-earthflows exist (Bertolini et al. 2005). Their episodic reactivation in historic and recent times (Piacentini et al. 2018) is governed by complex geomorphological, geomechanical, and hydrogeological processes (Borgatti et al. 2006; Ronchetti et al. 2007; Bertolini and Pizziolo 2008; Ronchetti et al. 2009; Berti and Simoni 2012; Bertolini et al. 2017). In several cases in the past, their reactivation has also determined river damming (Casagli and Ermini 1999). For instance, in 1960, the Secchia river streambed was infilled by the Lupazzo landslide, causing the

formation of a 2-km²-wide “Ceredolo Lake” that lasted as long as 8 months (event no. 60170 in Regione Emilia-Romagna (2015) and references therein). Also, in 1978, the Bramaiano landslide caused the partial blockage of Nure river due to uplift of streambed gravel banks (event no. 221204 in Regione Emilia-Romagna (2015) and references therein). Similarly, in April 2004, the Ponte Dolo landslide reactivation caused 5 m of streambed uplift and the partial damming of Dolo stream (Corsini et al. 2006).

This paper deals with another recent case of partial river blockage due to streambed uplift, i.e., the Pergalla landslide reactivation occurred in March 28, 2016. This event involved the toe zone of a very large earthslide-earthflow, causing severe damages to several houses and roads and the partial blockage of Nure river due to about 3-m uplift of the streambed. Specifically, the paper aims to (i) describe the characteristics of the Pergalla landslide event of March 2016; (ii) discuss its possible concurrent causes with respect to rainfall, streambed fluvial dynamics, and pre- and post-failure slope dynamics; (iii) conclude by pointing out how these factors could also be relevant for a possible preventive assessment of large landslide toes that, upon reactivation, might determine streambed uplift and river damming.

Slope dynamics and streambed uplift during the 26 March 2016 reactivation

The Pergalla landslide is a complex earthslide-earthflow located in the Northern Apennines (Italy), in the Nure river basin, 30 km north of the city of Piacenza (Fig. 1a). According to regional landslide maps (Regione Emilia-Romagna 2015), it extends in elevation from 900 m to 330 m a.s.l., over an area of approximately 2 km² and a length of about 3.5 km (Fig. 1b). The landslide involves Cretaceous rocks such as sandstone turbidites of the “Scabiazza sandstones” Formation (SCB), marlstone-dominated turbidites of the “Bettola Flysch” Formation (BET), and, limitedly, calcarenitic turbidites of the “Monte Cassio Flysch” Formation (MCS) (Di Dio et al. 2005). Landslide deposits are constituted of grayish clays with included gravels to blocks of marlstones, sandstones, and calcarenites. On a geomorphic basis, the landslide exhibits two main convex source areas (up to 900 m a.s.l.), a system of coalescent convex lobes making up the main landslide body (between 850 and 450 m a.s.l.) and a large broadly fan-shaped accumulation toe (extending from the hamlet “Creda” at 450 m a.s.l. down to a group of houses known as “la Pergalla” and the river Nure at 330 m a.s.l.).

The 26 March 2016 reactivation event took place after a rainfall period cumulating 280 mm in 40 days. The reactivation event affected, essentially, only the large toe zone of the landslide. Roto-translational movements extended 500 m in length and 300 m in width, for an area of 2.1×10^5 m² (Fig. 1). Houses in the locality “la Pergalla” and the province road SP10 were severely

Recent Landslides

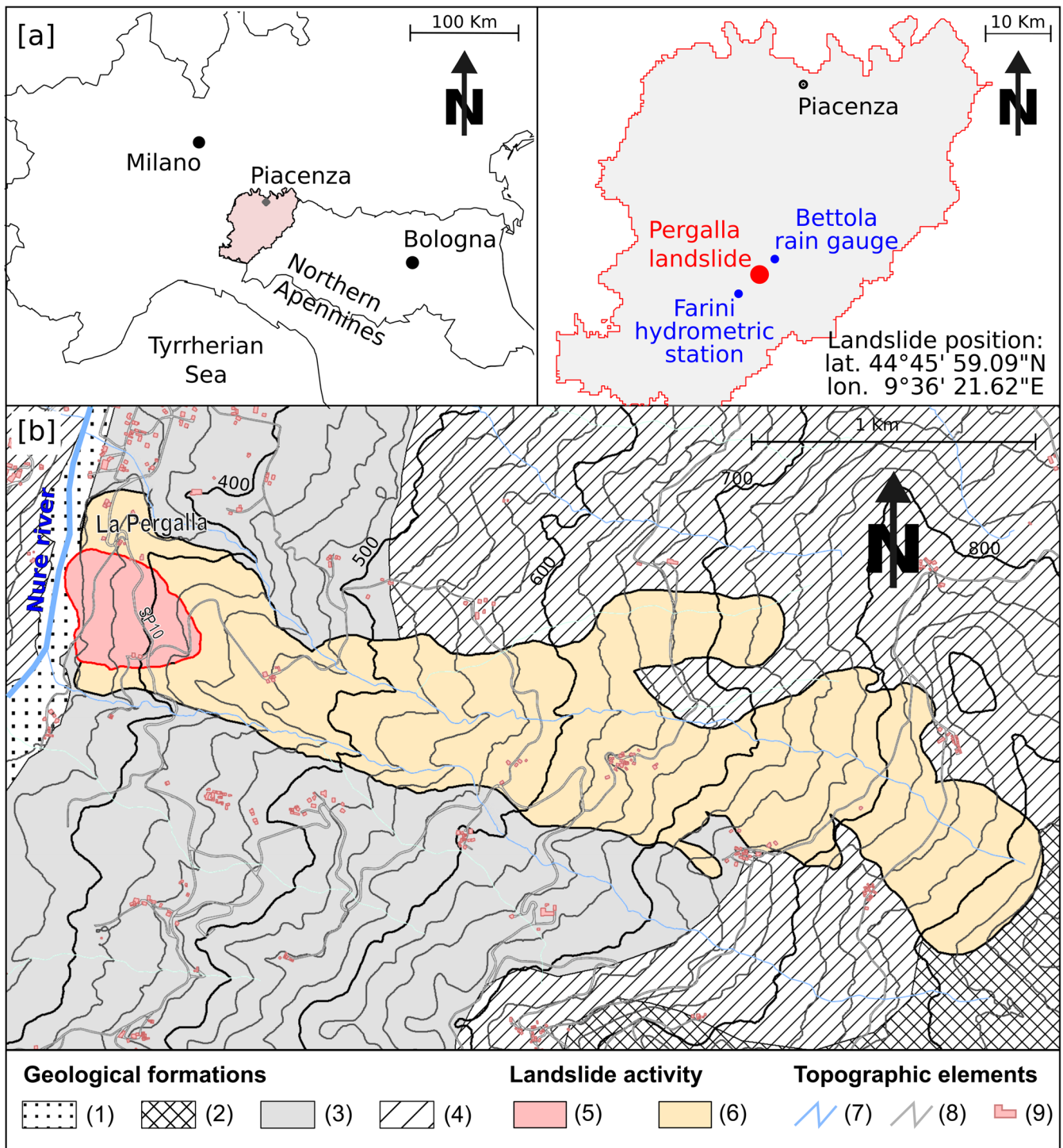


Fig. 1 a Location of the Pergalla landslide. b Geologic and geomorphic setting of the Pergalla landslide. (1) Alluvial deposits; (2) MCS, calcarenite turbidites; (3) BET, marlstone turbidites; (4) SCB, sandstone turbidites; (5) landslide area reactivated in March 2016; (6) dormant landslide; (7) river and streams; (8) road; and (9) building

damaged, forcing emergency evacuation of residents and interruption of traffic (Fig. 2(a–d)). At the same time, an almost 3-m uplift of the fluvial deposits of Nure river took place (Fig. 2(e)). This caused the impelling formation of a dam lake, which required the prompt intervention of excavation machines to be avoided. The comparison of post-event orthophotos of April 2016 with pre-

event orthophotos of 2015 (specifically the offset of the road SP10) highlights that during the March 2016 event, the maximum total displacement was in the order of 8 m (Fig. 3a). Most of such movement occurred during the first couple of days after reactivation. Fortunately, from the third day after reactivation, slope movements significantly slowed down. Noticeably, by 11 days after



Fig. 2 Field evidences and damages to human infrastructures caused by the reactivation of March 2016: (a–d) evidences of movements occurred within the mobilized area and at its borders; (e, f) evidences of the streambed uplift

the reactivation (when a robotic total station was installed to monitor the post-failure evolution), the velocity of the landslide was already reduced to less than 1 cm day^{-1} . The landslide remained in slow motion for the next 6 months, at velocities progressively decreasing to less than $0.5 \text{ cm month}^{-1}$.

On the basis of field surveys and the analysis of post-event aerial orthoimages, five orders of coalescent retrogressive rotational slide units can be outlined inside the area affected by the 2016 reactivation (i.e., units I to V in Fig. 3a). These units are delimited by rotational scarps and are internally affected by a network of tension cracks (Fig. 3b). Considering these units together with the results of underground investigation performed during summer 2016 (i.e., boreholes, inclinometers, P-wave refraction seismic tomography, and DC resistivity tomography), a longitudinal cross section of the reactivated landslide has been reconstructed (Fig. 3c). Specifically, inclinometer measures between May 2016 and January 2018 indicate that the main sliding zone is located at 19 m depth at borehole BET1 and at 35 m depth at borehole BET2. This is consistent with the results of geophysical surveys, indicating relatively low P-wave velocity and resistivity values down to 30 m in depth, and sliding surfaces extending beneath the Nure river streambed (Fig. 3d).

Discussion of concurrent causes of the 26 March 2016 reactivation

Taken for granted the fact that the existence of dormant landslide deposits is undoubtedly a predisposing causal factor for slope movements, the analysis of possible causes of the 26 March 2016 reactivation has been directed toward the following factors: antecedent rainfall and hydrometric level of the Nure river at the time of failure (derived by the ARPAE meteo-hydro monitoring network); slope undercutting related to active river channel migration (assessed by multi-temporal orthoimages analysis); pre- and post-failure landslide dynamics (measured by satellite radar interferometry and robotic total station).

Antecedent rainfall distribution at time of reactivation can be assessed using data from the Bettola ARPAE rain gauge, sited 1 km from the Pergalla landslide (see Fig. 1a for location). The record indicates that the landslide was triggered about 1 week after the termination of a prolonged rainfall period cumulating 280 mm precipitation in 40 days (“Event 1” in Fig. 4(a)). In 2016, at the Bettola rain gauge, the total annual rainfall was 844.8 mm, in line with the mean annual rainfall in the period 1950–2017 of 867 mm/year. The rainfall event before the March 2016 reactivation is not particularly uncommon in the area, as it corresponds roughly with a return period of 5 years. For instance, a similar rainfall event occurred as recently as fall

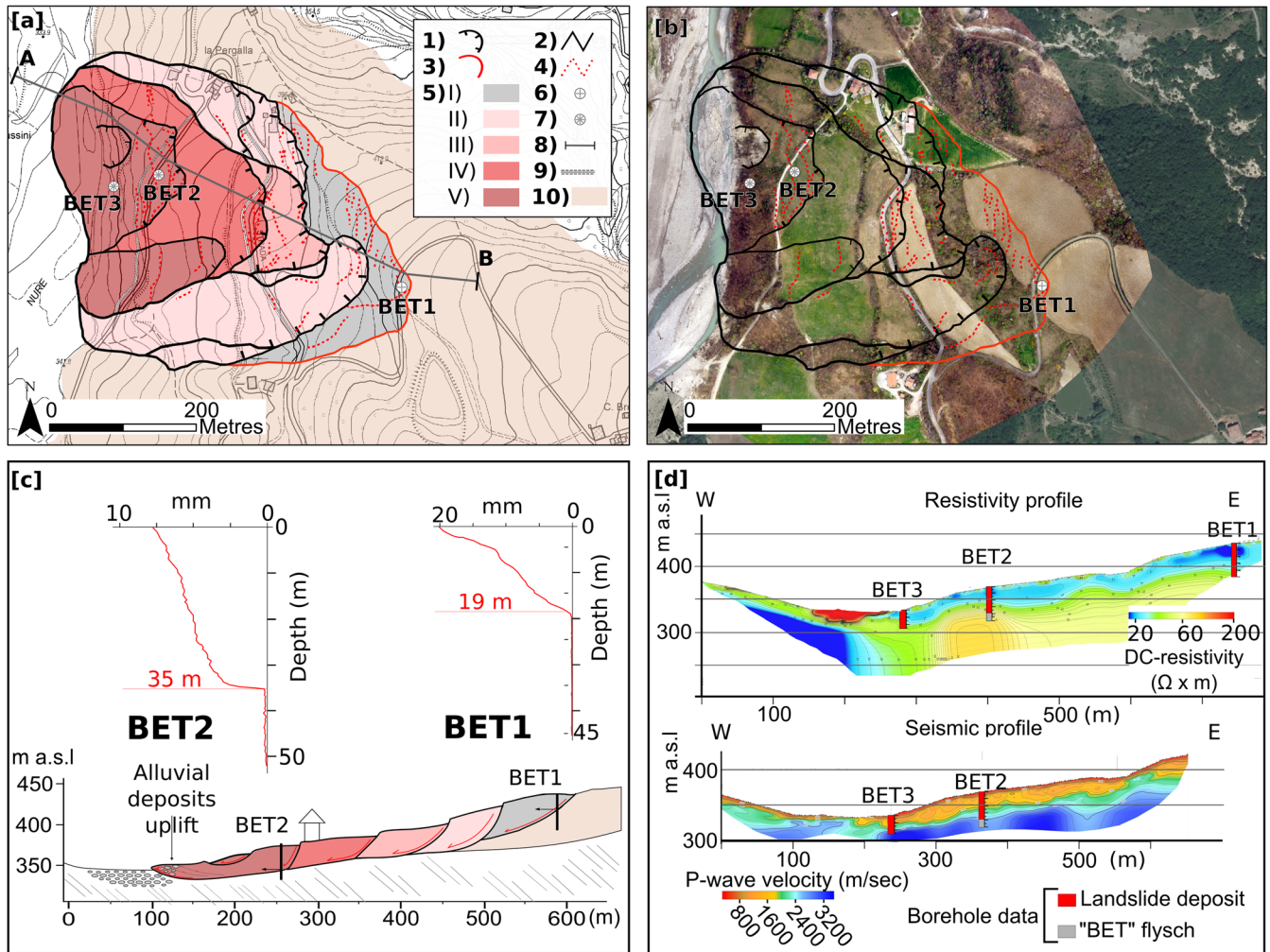


Fig. 3 a Geomorphological map of the failure event of 28th March 2016. (1) Rotational scarp; (2) geomorphic sub-unit outlines; (3) de-tensioned area limit; (4) tensional cracks; (5) coalescent rotational slide units and related hierarchical order I to IV; (6) inclinometer; (7) open-pipe piezometer; (8) seismic and resistivity tomography profiles; (9) post-activation road offset; (10) dormant landslide. b Post-event orthophoto gathered on 02/04/2016. c Cross section of the 2016 Pergalla landslide and inclinometers readings (May 2016 to Jan. 2018). d Results of geophysical surveys (DC resistivity and P-wave refraction seismic)

2014, but it did not determine any reactivation of the landslide (“Event 2” in Fig. 4(a)). The main difference between the two events is that in 2016, rainfall intensity increased toward the end of the event, while in 2014, it was mostly concentrated at the beginning of the event. The hydrometric level of Nure river is available from the Farini ARPAE gauge, sited 7 km uphill the Pergalla landslide (see Fig. 1a for location). This is the nearest upstream gauge existing. The record indicates an hydrometric level 2 to 3 m above the base level both during the 2016 and 2014 rainfall events (Fig. 4(b)). Given the rather flat morphology of the riverbed at the Pergalla landslide, these hydrometric levels are capable to determine side-bank erosion if the active stream channel meanders toward the slope.

Regarding slope undercutting, the analysis of multi-temporal orthoimages shows a progressive migration of the active channel toward the toe of the landslide from 2011 to October 2015 (Fig. 4(c)). Specifically, the active channel started undercutting the landslide toe only after the flooding event that occurred in the Nure river basin in September 2015. Such event caused widespread debris flows and

variations of streambed morphology over the whole Nure basin (Ciccarese et al. 2016; Scorpio et al. 2018). It can be speculated that river undercutting of the landslide toe, disregarding its volumetric consistence, could have been a factor in determining slope failure in 2016, also because the landslide toe was already slowly moving before the 2016 and it was thus, supposedly, already close to limit equilibrium.

Specifically, the existence of slow active movements prior to the 2016 reactivation can be assessed on the basis of publically available satellite interferometry datasets based on Persistent Scatterers (PS) processing of Cosmo-SkyMed X-band SAR data in ascending orbit (PST-A 2002). Data show that in the period 2011–2014, a cluster of moving PS can be identified in the area affected by the March 2016 reactivation (Fig. 5a). These points, corresponding to some of the houses that have been severely damaged by the 2016 reactivation, moved in the 2011–2014 period at a semi-constant velocity of about 1.5 cm year^{-1} (on the satellite’s line of sight, Fig. 5b). On the other hand, other PS located in the Pergalla landslide, but outside the area involved

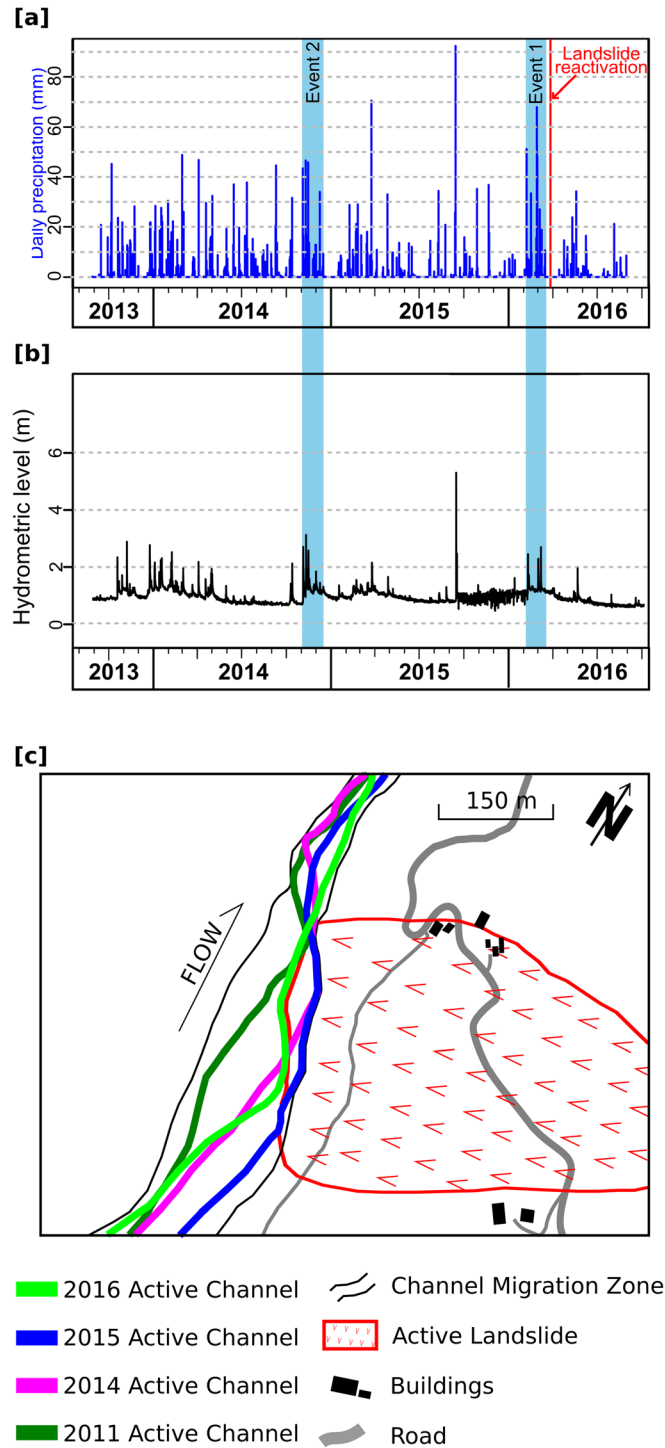


Fig. 4 (a) Daily precipitation record at the Bettola meteorological station (ARPAE network from September 2013 to September 2016). (b) Hydrometric level of the Nure river recorded at the Farini station (ARPAE network). (c) Nure river active channel migration reconstructed using orthoimages of Jun. 2011, Oct. 2014, Oct. 2015, and Apr. 2016

in the 2016 reactivation, show substantially no movement during the same period.

Furthermore, if the post-failure dynamic of the 2016 Pergalla landslide is considered, it is remarkable that already by 11 days after the paroxysmal reactivation (when a robotic total station monitoring 12 prisms on the landslide with duty cycles of 1 h was

installed), the landslide velocity was already decreased to less than 1 cm day^{-1} (Fig. 5c, d). This indicates that the changes in slope geometry induced by the slope movements, including the emersion of the landslide tip that uplifted the streambed, allowed the landslide to rapidly resume a condition close to limit equilibrium. The time series from the robotic total station (Fig. 5c, d)

Recent Landslides

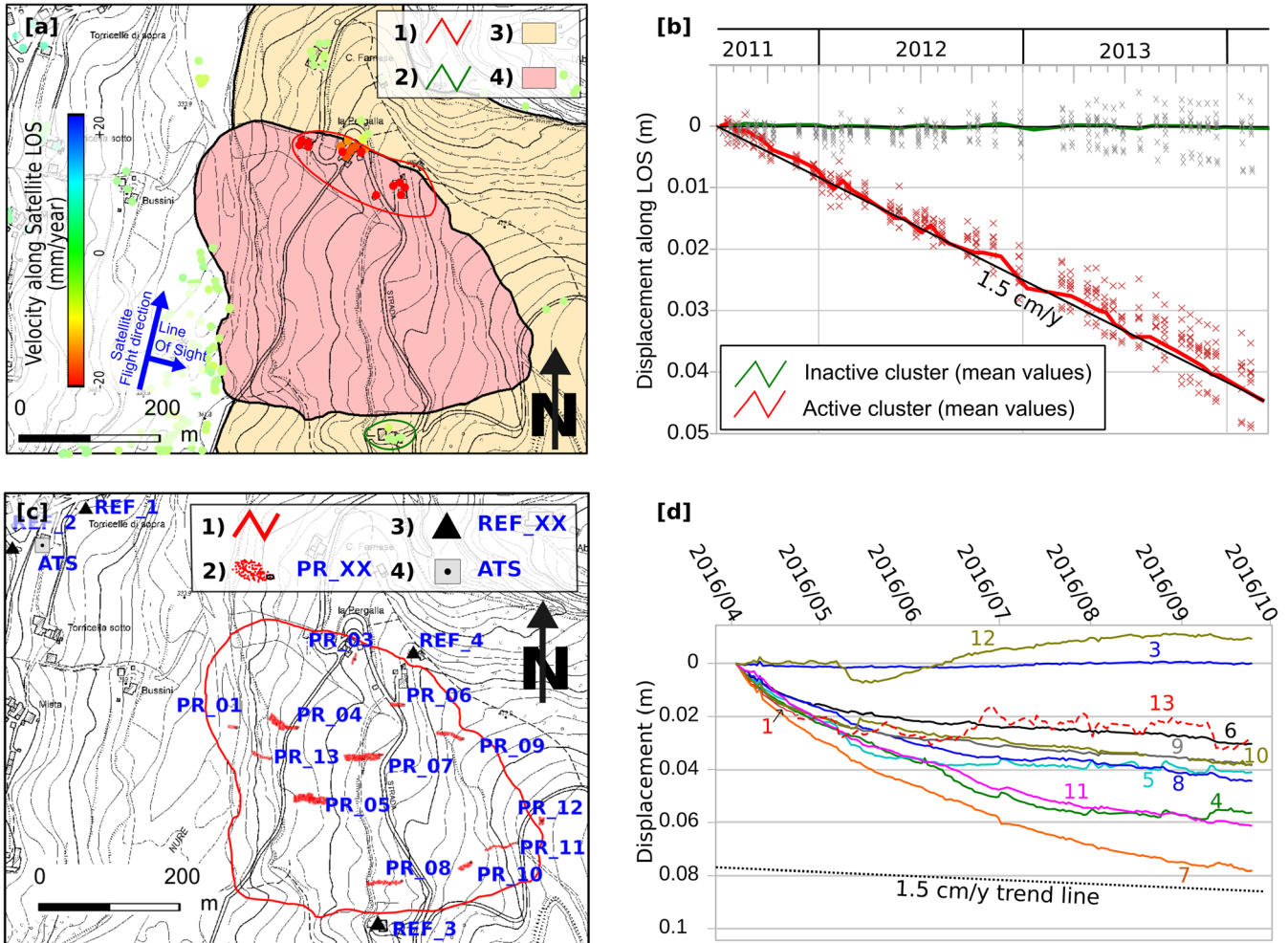


Fig. 5 a PS in the Pergalla landslide retrieved by Cosmo-SkyMed in ascending orbit. (1) Active PS cluster with time series plotted in b; (2) inactive PS cluster with time series plotted in b; (3) dormant landslide; (4) landslide-area reactivated in March 2016. b PS time series. c Robotic total station-based monitoring network active in the Pergalla landslide (April to October 2016). (1) Landslide area reactivated in March 2016; (2) monitoring prism position at each monitoring cycle (displacements are $\times 1000$ magnified); (3) position of reference prisms; (4) position of the robotic total station. d Displacement time series retrieved by robotic total station

show average velocities ranging from 0.5 to $1.3 \text{ cm month}^{-1}$, with the largest post-failure cumulated displacements (up to 8 cm) on the central part of the landslide (prisms 4, 7, and 11, from the bottom to the top). Nonetheless, it is to be pinpointed that the landslide deceleration down to velocity values similar to the pre-event conditions (i.e., 1.5 cm year^{-1}) took about 6 months to complete.

Conclusions

The Pergalla landslide reactivation in March 2016 appears to have been determined by a series of concurrent causes such as significant (but not exceptional) cumulated rainfall in the previous 40 days and high hydrometric level in the Nure river in the previous weeks; slope undercutting due to the active river channel migration toward the landslide toe during the 2015 to 2016 period; and mid-term ongoing pre-existing slow movements (at least in the 2011 to 2014 period) indicating that the landslide toe was already perilously close to limit equilibrium. During the reactivation, streambed uplift was caused by roto-translational sliding surfaces extending beneath riverbed.

In a broader perspective, it can be argued that some of these predisposing causes could have been preventively detected and, somehow, the Pergalla landslide was to be expected sooner or later. For instance, the evolution of active river channels can be assessed by multi-temporal remote sensing (Bollati et al. 2014) and the long-term trends of movements can be assessed by satellite radar interferometry both at a regional scale and at site scale (Corsini et al. 2006; Iasio et al. 2012; Cigna et al. 2013; Scaioni et al. 2014; Mulas et al. 2015; Bayer et al. 2018; Zhang et al. 2018). At the same time, the presence of sliding surfaces extending beneath the valley bottom can be presupposed on the basis of landslide features and dimension (Bertolini et al. 2017). In principle, these predisposing factors can be systematically analyzed at regional scale in order to assess sites where damming due to riverbed uplift has potential to occur. Doing this for the hundreds of landslides in the Northern Apennines that are indeed very similar to the Pergalla landslide could complement the existing maps and catalogs of landslides and support the planning of preventive measures.

References

- Bartarya SK, Sah MP (1995) Landslide induced river bed uplift in the Tal valley of Garhwal Himalaya, India. *Geomorphology* 12:109–121
- Bayer B, Simoni A, Mulas M, Corsini A, Schmidt D (2018) Deformation responses of slow moving landslides to seasonal rainfall in the Northern Apennines, measured by InSAR. *Geomorphology* 308:293–306. <https://doi.org/10.1016/j.geomorph.2018.02.020>
- Berti M, Simoni A (2012) Observation and analysis of near-surface pore-pressure measurements in clay-shales slopes. *Hydrol Process* 26:2187–2205
- Bertolini G, Pizziolo M (2008) Risk assessment strategies for the reactivation of earth flows in the Northern Apennines (Italy). *Eng Geol* 102:178–192. <https://doi.org/10.1016/j.enggeo.2008.03.017>
- Bertolini G, Guida M, Pizziolo M (2005) Landslides in Emilia-Romagna region (Italy): strategies for hazard assessment and risk management. *Landslides* 2:302–312. <https://doi.org/10.1007/s10346-005-0020-1>
- Bertolini G, Corsini A, Tellini C (2017) Fingerprints of large-scale landslides in the landscape of the Emilia Apennines. In: *Landscapes and Landforms of Italy*. Springer International Publishing AG, Cham (ZG), pp. 215–224. <https://doi.org/10.1007/978-3-319-26194-2>
- Bollati IM, Pellegrini L, Rinaldi M, Duci G, Pelfini M (2014) Reach-scale morphological adjustments and stages of channel evolution: the case of the Trebbia River (northern Italy). *Geomorphology* 221:176–186
- Borgatti L, Corsini A, Barbieri M, Sartini G, Truffelli G, Caputo G, Puglisi C (2006) Large reactivated landslides in weak rock masses: a case study from the Northern Apennines (Italy). *Landslides* 3:115–124. <https://doi.org/10.1007/s10346-005-0033-9>
- Casagli N, Ermini L (1999) Geomorphic analysis of landslide dams in the Northern Apennine. *Trans Jpn Geomorphol* 20(3):219–249
- Ciccarese G, Corsini A, Pizziolo M, Truffelli G (2016) Debris flows in Val Nure and Val Trebbia (Northern Apennines) during the September 2015 alluvial event in Piacenza Province (Italy). *Rend Online Soc Geol Ital* 41:127–130. <https://doi.org/10.33017/ROL2016.110>
- Cigna F, Bianchini S, Casagli N (2013) How to assess landslide activity and intensity with Persistent Scatterer Interferometry (PSI): the PSI-based matrix approach. *Landslides* 10:267–283. <https://doi.org/10.1007/s10346-012-0335-7>
- Corsini A, Farina P, Antonello G (2006) Space-borne and ground-based SAR interferometry as tools for landslide hazard management in civil protection. *Int J Remote Sens* 27(June):2351–2369. <https://doi.org/10.1080/01431160600554405>
- Costa JE, Schuster RL (1988) The formation and failure of natural dams. *Geol Soc Am Bull* 100:1054–1068. [https://doi.org/10.1130/0016-7606\(1988\)100<1054:TFAPON>2.3.CO;2](https://doi.org/10.1130/0016-7606(1988)100<1054:TFAPON>2.3.CO;2)
- Di Dio G, Piccin A, Vercesi PL (2005) Note illustrative della Carta Geologica d'Italia alla scala 1:50.000, foglio 179 “Ponte dell’Olio”. APAT—Agenzia per la protezione dell’ambiente ed i servizi tecnici, Dipartimento Difesa del Suolo, Servizio Geologico d’Italia. http://www.isprambiente.gov.it/Media/carg/note_illustrative/179_PontedellOlio.pdf
- Ermini L, Casagli N (2003) Prediction of the behaviour of landslide dams using a geomorphological dimensionless index. *Earth Surf Process Landf* 28:31–47. <https://doi.org/10.1002/esp.424>
- lasio C, Novali F, Corsini A, Mulas M, Branzanti M, Benedetti E, Giannico C, Tamburini A, Mair V (2012) COSMO SkyMed high frequency - high resolution monitoring of an alpine slow landslide, Corvara in Badia, Northern Italy. In: *2012 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, pp. 7577–7580. <https://doi.org/10.1109/IGARSS.2012.6351908>
- Micu M, Bălteanu D (2013) A deep-seated landslide dam in the Siriu Reservoir (Curvature Carpathians, Romania). *Landslides* 10(3):323–329. <https://doi.org/10.1007/s10346-013-0382-8>
- Mulas M, Petitta M, Corsini A, Schneiderbauer S, Mair V, lasio C (2015) Long-term monitoring of a deep-seated, slow-moving landslide by mean of C-band and X-band advanced interferometric products: the Corvara in Badia case study (Dolomites, Italy). *ISPRS Int Arch Photogramm Remote Sens Spat Inf Sci XL-7/W3:827–829*. <https://doi.org/10.5194/isprsarchives-XL-7-W3-827-2015>
- Piacentini D, Troiani F, Daniele G, Pizziolo M (2018) Historical geospatial database for landslide analysis: the Catalogue of Landslide Occurrences in the Emilia-Romagna Region (CLOCKER). *Landslides* 15:811–822. <https://doi.org/10.1007/s10346-018-0962-8>
- PST-A (2002) Piano Straordinario di Telerilevamento Ambientale. Website: <http://www.pcn.minambiente.it/GN/progetti/piano-straordinario-di-telerilevamento> Consulted on the 09/07/2018
- Regione Emilia-Romagna (2015) Carta Inventario delle frane e Archivio storico delle frane. Website: <http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/cartografia-dissesto-idrogeologico#accedi-alle-carte-inventario-delle-frane-nbsp-e-archivio-storico-delle-frane>. Consulted on the 09/07/2018
- Ronchetti F, Borgatti L, Cervi F, Lucente CC, Veneziano M, Corsini A (2007) The Valoria landslide reactivation in 2005–2006 (Northern Apennines, Italy). *Landslides* 4:189–195. <https://doi.org/10.1007/s10346-006-0073-9>
- Ronchetti F, Borgatti L, Cervi F, Gorgoni C, Piccinini L, Vincenzi V, Corsini A (2009) Groundwater processes in a complex landslide, northern Apennines, Italy. *Nat Hazards Earth Syst Sci* 9:895–904. <https://doi.org/10.5194/nhess-9-895-2009>
- Scaioni M, Longoni L, Melillo V, Papini M (2014) Remote sensing for landslide investigations: an overview of recent achievements and perspectives. *Remote Sens* 6:9600–9652. <https://doi.org/10.3390/rs6109600>
- Scorpio V, Crema S, Marra F, Righini M, Ciccarese G, Borga M, Cavalli M, Corsini A, Marchi L, Surian N, Comiti F (2018) Basin-scale analysis of the geomorphic effectiveness of flash floods: a study in the northern Apennines (Italy). *Sci Total Environ* 640–641:337–351. <https://doi.org/10.1016/j.scitotenv.2018.05.252>
- Tacconi Stefanelli C, Catani F, Casagli N (2015) Geomorphological investigations on landslide dams. *Geoenviron Disasters* 2:21–15. <https://doi.org/10.1186/s40677-015-0030-9>
- Wang F, Zhang Y, Huo Z, Peng X, Wang S, Yamasaki S (2008) Mechanism for the rapid motion of the Qianjiangping landslide during reactivation by the first impoundment of the Three Gorges dam reservoir, China. *Landslides* 5(4):379–386. <https://doi.org/10.1007/s10346-008-0130-7>
- Zhang Y, Meng X, Jordan C, Novellino A, Dijkstra T, Chen G (2018) Investigating slow-moving landslides in the Zhouqu region of China using InSAR time series. *Landslides* 15:1299–1315. <https://doi.org/10.1007/s10346-018-0954-8>

M. Mulas (✉) · G. Ciccarese · F. Ronchetti · A. Corsini

Dipartimento di Scienze Chimiche e Geologiche,
Università degli Studi di Modena e Reggio Emilia,
41125, Modena, Italy
Email: marco.mulas@unimore.it

G. Truffelli

Emilia Romagna Region—Regional Agency for Civil Protection and
Territorial Security—Po River Affluent Service,
Via Garibaldi 75, Parma, 43121, Italy