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Original Citation:
Geomorphology of the Rotolon landslide (Veneto Region, Italy) / Frodella W.; Morelli S.; Fidolini F.; Pazzi V.; Fanti R.. - In: JOURNAL OF MAPS. - ISSN 1744-5647. - ELETTRONICO. - 10(3):(2014), pp. 394-401. [10.1080/17445647.2013.869666]

Availability:
This version is available at: 2158/826340 since: 2016-01-12T14:40:38Z

Published version:
DOI: 10.1080/17445647.2013.869666

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Journal of Maps
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tjom20

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Published online: 11 Dec 2013.

To cite this article: William Frodella, Stefano Morelli, Francesco Fidolini, Veronica Pazzi & Riccardo Fanti (2014) Geomorphology of the Rotolon landslide (Veneto Region, Italy), Journal of Maps, 10:3, 394-401, DOI: 10.1080/17445647.2013.869666

To link to this article: http://dx.doi.org/10.1080/17445647.2013.869666

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Journal of Maps, 2014
Vol. 10, No. 3, 394–401, http://dx.doi.org/10.1080/17445647.2013.869666

SCIENCE

Geomorphology of the Rotolon landslide (Veneto Region, Italy)

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(*Received 28 June 2013; resubmitted 18 November 2013; accepted 23 November 2013*)

In this paper a geomorphological map of the Rotolon landslide is presented. This cartographic product was obtained using a combination of accurate field surveys together with airborne Lidar analysis, aerial photo interpretation and thermographic field surveys within a GIS. The map was prepared in order to analyze the morphological features of the landslide and therefore improve interpretation of the GB-InSAR data. This monitoring device was installed on the site after the detachment of a debris mass of 225,000 m^3 on 4 November 2010. The main purpose of the post-event activities, including the geomorphological characterization, was to detect the processes acting on the landslide, evaluate the hazard related to each phenomenon, understand the landslide kinematics and define the residual risk for the area.

The geomorphological map suggests that debris production and detachment are hazardous phenomena that involve the surficial detrital cover of a bigger and more complex landslide. The latter has the typical characteristics of a deep-seated gravitational slope deformation. The distinction between secondary processes, which appear to be the most hazardous in the short-term, and deep seated ones, demonstrates that accurate mapping provides important information for local administrations and decision makers, allowing them to prepare landslide susceptibility and hazard models.

Keywords: landslide; geomorphological survey; DSGSD; debris flow; photo interpretation

1. Introduction

Between 31 October 2010 and 2 November 2010 the whole Veneto region of north-eastern Italy (Figure 1) was hit by heavy and persistent rainfall that triggered floods and numerous slope failures. The south western part of the region, in particular Verona, Vicenza and Padova provinces, suffered the most damage, resulting in three fatalities, about 3500 evacuated people, and heavy economic losses for agricultural, livestock and industrial activities. Damage due to landslides was extensive and particularly severe in the western mountains of Vicenza Province. On 4 November 2010, after 480 mm of rainfall fell in the previous three days, part of detrital cover of the ancient Rotolon landslide, in the Recoaro Terme municipality (Upper Agno Valley; Figure 1), suffered the detachment of a mass of approximately 225,000 m^3, which was channeled in to the

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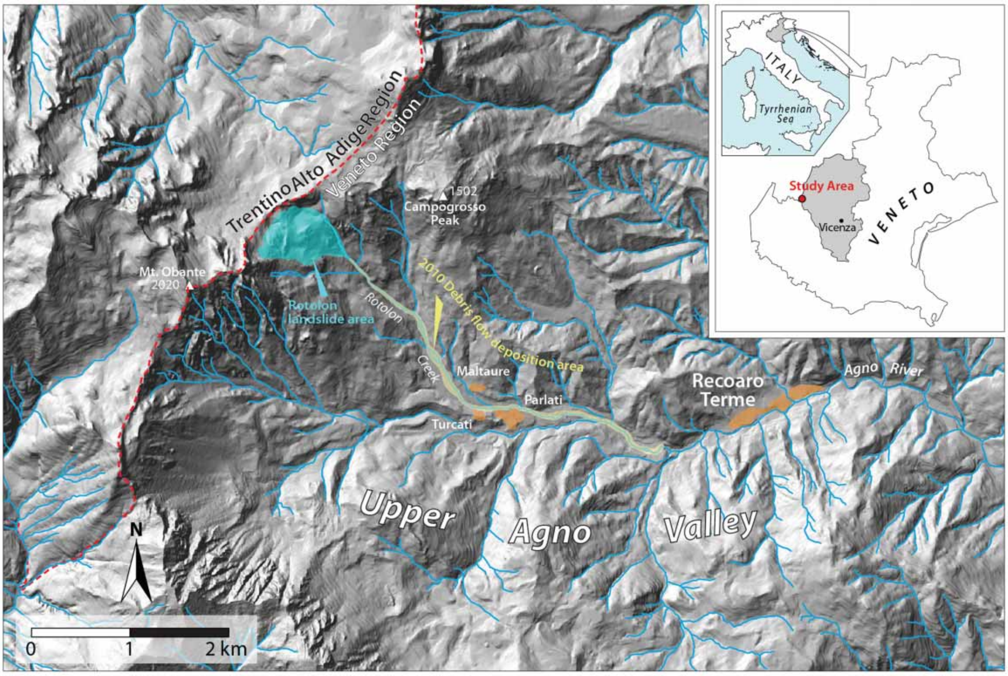

Figure 1. Location of the Rotolon landslide within the Upper Agno Valley. The three villages threatened by the 2010 debris flow are shown.

Rotolon Creek causing a debris flow. This flow had more than three kilometers of run-out distance, putting the population of three villages at high risk (Maltaure, Turcati and Parlati, Figure 1), and also damaging infrastructure such as check dams, bridges, roads and houses.

In order to manage the emergency and evaluate the residual risk, the Department of Earth Sciences of the University of Firenze (DST-UNIFI), on behalf of the National Department of Civil Protection (DPCN), from 8 December 2010 began monitoring the Rotolon landslide by means of a GB-InSAR radar interferometer (Antonello et al., 2004; Del Ventisette, Casagli, Fortuny-Guasch, & Tarchi, 2012; Gigli, Fanti, Canuti, & Casagli, 2011; Rudolf, Leva, Tarchi, & Sieber, 1999; Tarchi et al., 2003). During this phase accurate field surveys of the whole landslide area (Figure 1) were carried out, in order to analyze morphological features of the landslide, understand the debris flow triggering mechanisms, and improve radar data interpretation.

A detailed 1:3000 scale geomorphological Main Map was prepared showing: (i) the landslide upper limit;(ii) the morphological linear elements within the landslide area (minor crowns, morphological and lithostructural scarps, crests, trenches, counterslope surfaces); (iii) detrital bodies accumulated by transport and depositional processes acting along the main slopes (colluvial fans, colluvial aprons, rockfall and rock avalanche deposits); (iv) hydrographic elements (creeks, canals); (v) erosional landforms (channels, erosional surfaces).

2. Study area

The Rotolon landslide is in the Vicentine Prealps, on the south-eastern flank of the Little Dolomites chain, in the uppermost Agno river valley (Figure 1). Instability processes, such as slope failures and debris flows induced as secondary phenomena by the Rotolon landslide, have threatened the Upper Agno valley for centuries. The first recorded damages due to failures

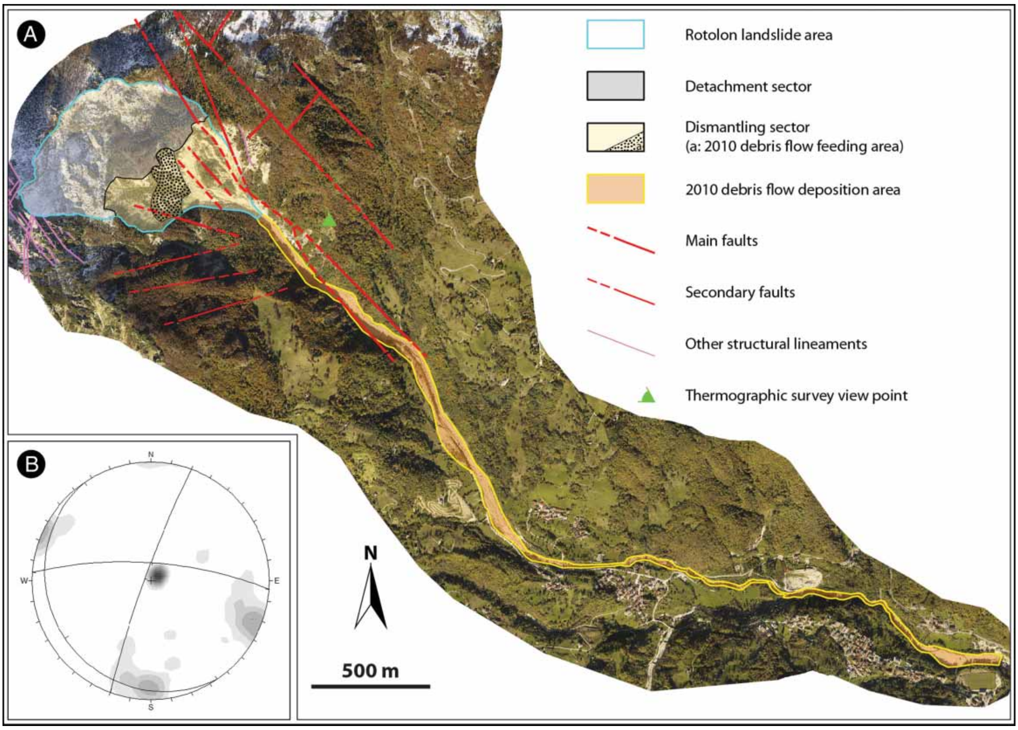

Figure 2. (A) The Rotolon creek valley and main structural lineaments controlling the geometry of the Rotolon landslide in its different sectors. (B) Plot diagram showing the horizontal attitude of bedding (central pole) and the geometry of two joints systems (J1 and J2), NNE-SSW and E-W oriented respectively. Data were collected along the ridge above the landslide crown.

and flooding connected to the landslide activity date back to the sixteenth century; other catastrophic events were reported by the local population in 1789, 1882 and 1985 (Trivelli, 1991).

From a geologic perspective the landslide is developed in the uppermost portion of a sub-horizontally bedded (Figure 2), intensively fractured, mainly dolomitic limestone stratigraphic succession belonging to the South Alpine Domain (Barbieri et al., 1980; Castellarin et al., 1968a, 1968b; De Zanche & Mietto, 1981), from middle Triassic to lower Jurassic in age. The geological formations are, from bottom to top: Mt. Spitz Limestone (massive, locally layered limestones); Raibl Formation (a sequence of conglomerates, sandstones, marls and dolomitic evaporates, showing at the bottom a discontinuous level of riolitic-dacitic phorphyrites); Dolomia Principale (dolostones and dolomitic limestones). The area is intersected by two main fault systems (Figure 2), one NE-SW oriented and one NNW-SSE oriented (Barbieri et al., 1980; Castellarin et al., 1968a, 1968b; De Zanche & Mietto, 1981). An E-W-oriented fault system is also reported.

The landslide is delimited on the NW by the ridge of the Mount Obante group and covers an area of 448,000 m^2 from about 1700 m a.s.l. to the point where minor tributaries converge forming the Rotolon Creek (at about 1100 m a.s.l.), for a total elevation drop of about 600 m.

3. Methods

The Rotolon landslide geomorphological Main Map was prepared using a detailed topographic reference map (1:3000 scale), obtained from post-debris flow event aerial Light Detection and

Ranging (LiDAR) data. Detailed geomorphological field surveys were performed and integrated with interpretation, of pre- and post-debris flow event aerial photographs (resolution of 0.2 m). For this latter purpose analysis using a geographical information system (GIS; hillshade, slope and aspect thematic layers; Figure 3) was performed on digital terrain models (DTMs; 2 m resolution) retrieved from the Lidar data acquired on 21 October and 23 November 2010, preceding and following the debris flow event respectively. A ground-based thermographic field survey (Adorno & Rizzo, 2011; Baroň, Bečkovský, & Míča, in press) of the lowermost part of the landslide area was also conducted from a fixed installation point (Figure 2). Data concerning the geometry of joints and fractures that intersect the rock mass were collected along the ridge above the landslide upper limit (Figure 2).

The map legend was arranged based on the guidelines of the Geomorphological Map of Italy (VV.AA., 1994), adapted to the aims of this work and according to the variety of landforms present in the study area.

4. Results and discussion

The Rotolon landslide is characterized by a complex activity (Cruden & Varnes, 1996) that leads to a rough physiography. Moreover the landslide geometry appears to be strongly influenced by structural features, such as joints, tension cracks and faults that involve the rock mass and control the lateral boundaries of the landslide itself (Figure 2).

Two distinct sectors were identified within the Rotolon landslide, and reported in the map (see also Figure 2): (i) an upper 'Detachment sector', followed downstream by a (ii) 'Dismantling sector'. This latter represents the slope sector supplying materials for the debris flows.

The Detachment sector, with a mean slope of 30°, develops downstream of the landslide upper limit. It is dominated by extensional deformation that leads to the development of tensional fractures, resulting in alternate trenches and crests, therefore creating a very rough, stepped topographic surface. This area is affected both by gravitational and water-related erosional processes and by debuttressing (Holm et al., 2004) and disaggregation of the rock mass, which cause the accumulation of various depositional elements (colluvial fans, colluvial aprons, rock fall and rock avalanche deposits) formed by very coarse clasts, ranging from cobbles to boulders with scattered blocks (10 s to 100 s of mm in size) in a coarse sandy matrix.

The Dismantling sector has a mean slope of 34°. It is characterized by a compressional stress field, highlighted by toe bulging and by common anti-dip fractures in its uppermost part. Nevertheless the area is apparently dominated by surficial processes (e.g. concentrated and diffuse erosion, slope waste deposition due to gravity and detrital cover failures) that partially mask the evidence of deep deformation. This is also the source area for debris flows, as confirmed by the thermographic analysis, which revealed cold anomalies connected to moisture zones representing springs from ephemeral creeks. Downstream from this area debris flows the deposit materials in the Rotolon Creek bed (Figures 1 and 2).

The following landforms related to gravity were mapped and characterized within the landslide:

Linear landforms related to gravity:

(i) Landslide upper limit: high-angle perimeter escarpment related to the main fracture delimiting the landslide; the sliding surface locally shows striae dipping along the main movement direction;
(ii) Crowns: active and inactive escarpments bounding minor surficial detachments;
(iii) Lithostructural scarps: scarps occurring on stepped-profile rock walls corresponding to bedding strike;

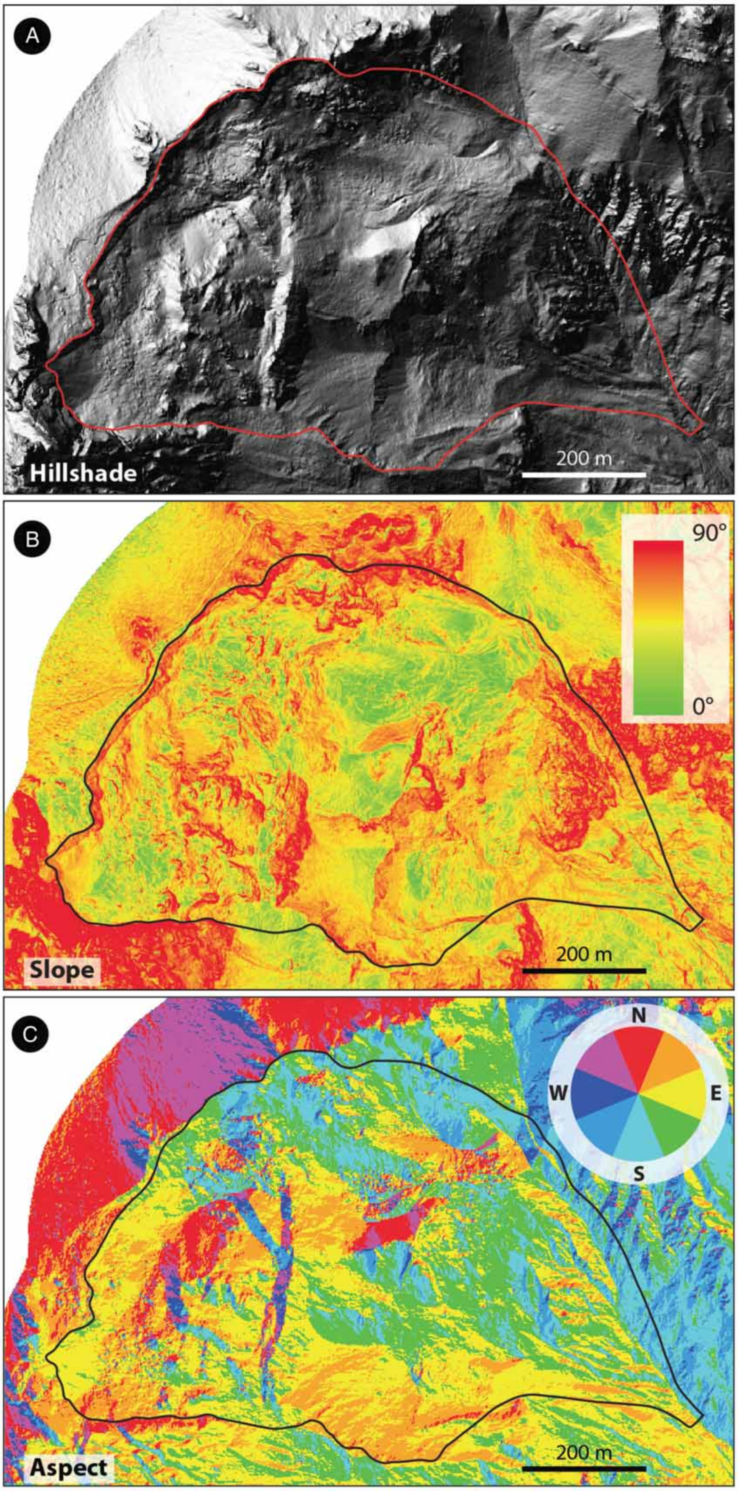

Figure 3. Thematic maps obtained by DTM analysis. (A) Hillshade; (B) Slope; (C) Aspect.

(iv) Morphological scarps: slope breaks related to gravitational processes;
(v) Counterscarps: morphological slope breaks facing the direction opposite to the landslide main movement direction;
(vi) Crests: linear, narrow top of a ridge;
(vii) Trenches: linear, narrow depression, locally filled by debris, related to tensional cracks and deep-seated processes;
(viii) Counterslope surfaces: slope surfaces dipping in the opposite direction with respect to the main slope and related to slump failures and/or dislocations of large rock masses;

Depositional landforms accumulated by transport/depositional processes along the main slopes:

(ix) Colluvial fans (active and inactive): fan-shaped depositional bodies accumulated by mass movements at the foot of a topographic escarpment and consisting of angular clast-supported gravel (pebble- to cobble-sized, with scattered boulders);
(x) Colluvial aprons: coalescing, wedge-shaped colluvial deposits draping the base of escarpments or steep slopes and consisting of clast-supported pebble- to cobble-sized gravel;
(xi) Rockfall deposits: debris cones due to episodic local rockfalls and consisting of matrix free blocks ranging from centimeters to meters in size;
(xii) Rock avalanche deposits: tongue-shaped accumulation of rocky blocks (up to several meters in diameter) due to episodes of large rock wall failures and consisting of matrix-free blocks ranging from centimeters to meters in size;
(xiii) Surface affected by water erosion: surface denuded by diffuse and concentrated erosional processes due to runoff and affecting the soil cover;
(xiv) Channels: linear depressions created by concentrated water erosion along which debris flows may flow.

Main hydrographical landforms:

(xv) Creeks;
(xvi) Canals: artificial channels built in the 1920s to enhance the surficial drainage in order to mitigate the risk related to instability processes.

Elements i, iv, v, vi, vii, viii can typically be explained by slow movements related to deep-seated gravitational processes (Agliardi, Crosta, & Zanchi, 2001; Crosta, 1996; Crosta, Frattini, & Agliardi, 2013; Cruden & Varnes, 1996; Dramis, 1984; Dramis & Sorriso-Valvo, 1994; Hutchinson, 1995; Oyagi, Sorriso-Valvo, & Voight, 1994; Soldati, 2013) commonly known as deep-seated gravitational slope deformations (DSGSD, *sensu* Dramis & Sorriso-Valvo, 1994). The strong influence of the structural and geological setting on the landslide geometry supports this hypothesis (Guzzetti, Cardinali, & Reichenbach, 1996). Moreover, the evidence of extensional and compressive processes in the uppermost and lowermost parts of the landslide respectively suggest a particular type of DSGSD, known as ‘sackung’ (Agliardi, Crosta, & Zanchi, 2001; Ambrosi & Crosta, 2006; Bisci, Dramis, & Sorriso-Valvo, 1996; Savage & Varnes, 1987; Varnes, Radbruch-Hall, & Savage, 1989; Zischinsky, 1966, 1969).

Nevertheless in the dismantling sector the large amount of debris supplied results in an apparent dominance of short-term surficial processes over long-term deep-seated ones, because the former appear to be the more effective phenomena in modifying the slope morphology. Because of the coexistence of these different movement mechanisms in different parts of the slope, the Rotolon landslide can be classified as a composite landslide (*sensu* Cruden & Varnes, 1996).

5. Conclusions

The Rotolon landslide geomorphological Main Map was prepared at 1:3000 scale by a combination of detailed geomorphological field surveys, pre- and post-debris flow event aerial Lidar surveys and aerial photography, GIS analysis of DTMs (hillshade, slope, aspect thematic layers) and ground-based thermographic field surveys. The combination of these data proved to be fundamental for the accuracy of the Main Map. The acquired data suggest a complex nature for the Rotolon landslide, which is characterized by a very rough topography (e.g. stepped profile in the upper part, showing scarps, counterscarps, ridges, trenches and counterslope surfaces; toe bulging, high average steepness and against-dip fractures in the lower part), documenting the activity of long-term deep-seated processes, and a wide range of short-term secondary processes (e.g. secondary slope failures, rock falls, rock avalanches, debris accumulation and debris flow triggering). Although the latter represent, at the moment, the most hazardous phenomena for the inhabited areas along the Rotolon Creek valley, they are considered to be only the surficial and secondary expression of a more complex system.

The map was fundamental for detecting the areal extent of the processes acting on the landslide and, thus, to understanding the kinematic mechanisms involving the whole rock and debris mass. This allowed distinguishing between dominant/secondary phenomena and long-term/short-term hazardous phenomena. In this study secondary processes appear to be the most dangerous from a short-term perspective, demonstrating that accurate mapping provides important information for local administrations and decision makers, allowing them to prepare landslide susceptibility and hazard models.

Software

ESRI ArcMap 9.2 was used for the production of shaded relief, slope gradient visualizations and other 3D analyses, for digitizing landforms recognized by means of field surveys and aerial photo-interpretation and for cartographic work. Map layout and final editing were performed using Adobe Illustrator CS5.

Supplemental data

Supplemental data for this article can be accessed at http://dx.doi.org/10.1080/17445647.2013.869666

Acknowledgements

The map was prepared within the framework of activities arranged after the November 2010 event post-emergency management coordinated by the Italian Civil Protection Department. We also would like to thank the Veneto Soil Defense Regional Directorate for providing Lidar and aerial photo data. We are grateful to Federico Di Traglia for reviewing an early version of the manuscript.

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