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GEOMORPHOLOGICAL ANALYSIS APPLIED TO ROCK FALLS IN ITALY: THE CASE OF THE SAN VENANZIO GORGES (ATERNO RIVER, ABRUZZO, ITALY)

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ABSTRACT

Among the types of instability, which vary in terms of typology, evolution and dimension, rock falls represent a constant hazard for structures, buildings and the population, because of their extreme speed.

Rock falls in central Italy (Abruzzo Region) occur within the chain area, at the junction between the chain area and the piedmont and between piedmont hills and coastal sectors with wide coastal cliffs.

This work focuses on the multidisciplinary analysis of rock falls affecting fault homocline ridges and, particularly, on the case of the San Venzanzio gorges (Aterno river) well known for rock falls particularly after the 2009 L'Aquila eartquake. The gorges are located along the Aterno river within the central Apennines, between L'Aquila and Sulmona, in a geological and geomorphological context typical of the Apennines chain.

The analysis is based on 1:5.000-1.10.000 field geological and geomorphological mapping integrated with reported events analysis, photogeological analysis, laser scanning and geomechanical investigations. This approach is considered vital for a correct investigation of rock fall hazard and susceptibility, particularly on large slopes where topographical, geological, tectonic, geomechanical and geomorphological variation control rock fall development. In these cases, only a complete geological, morphostructural and geomechanical data set allows to achieve effective results when applying deterministic and probabilistic methods for rock falls investigation.

INTRODUCTION

Among the types of instability, which vary in terms of typology, evolution and dimension, rock falls represent a constant hazard for structures, buildings and the population, because of their extreme speed (Keefer, 2003; Scarascia Mugnozza *et alii*, 2006). Rock falls have been studied all over the world in several geographical and morphostructural settings, from huge mountain escarpments to small cliffs, with different approaches (from standard geomorphological analysis to multidisciplinary analyses including geology, geomorphology, geomechanics, geophysics, modeling/ software simulation, laser scanning, etc.) (Evans & Hungr, 1993; De Gregorio *et alii,* 1994; Baillifard *et alii*, 2003; Del Maschio *et alii*, 2003; Bianchi Fasani *et alii*, 2004, 2006; Budetta, 2004; Reichenbach *et alii*, 2005; Bianchi Fasani *et alii,* 2006; Di Crescenzo & Santo, 2007; Leuratti *et alii,* 2007; Calista *et alii*, 2008; Piacentini & Soldati, 2008; Paronuzzi, 2006; Chiessi *et alii,* 2010).

Rock falls in central Italy (Abruzzo Region) occur within the chain area, at the junction between the chain area and the piedmont and between piedmont hills and coastal sectors with wide coastal cliffs. This type of landslide occurs mostly in different main morphostructural settings, such as: faulted homoclinal ridges on marine Meso-Cenozoic carbonate rocks, calcareous rock slopes of karst landforms, structural scarps on marine Neogene arenaceous, gypsum and conglomerate deposits, structural scarps on conglomerates and breccias of Quaternary continental deposits (Miccadei *et alii*, 2013).

This work focuses on the multidisciplinary analysis of rock falls affecting fault homocline ridges and particularly, on the case of the San Venzanzio gorges. The gorges are located along the Aterno river within the central Apennines, between L'Aquila and Sulmona, in a geological and geomorphological context typical of the Apennines chain.

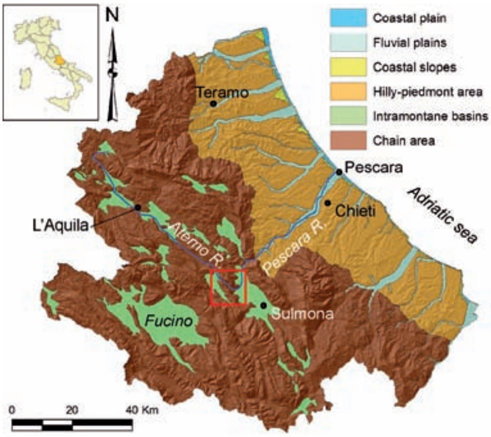

Fig. 1 - Physiographic scheme of the Abruzzo region and location map of the study area (red box)

The area has been studied since the 1990s through field surveys, focusing on the morphotectonic setting and Neogene-Quaternary tectonic evolution, which is difficult to understand due to high bedrock fracturation and cover deposits (Miccadei *et alii*, 1999a,b). Over the last few decades this area has been involved in the new Geological Map of Italy, scale 1:50.000 (APAT, 2006; ISPRA, 2010).

This study stemmed from the consideration that rock falls accounted for 67% of the mass movements triggered by the 2009 L'Aquila earthquake in the mountain area (some of them in the San Venanzio gorges >40 km from the epicenter area) (Miccadei *et alii,* 2010) and other episodes were recorded during extreme weather events that caused floods in the piedmont and coastal areas. The analysis of rock falls is mostly based on field data and has been carried out through: a historical analysis of past events, a multitemporal and multiscale analysis of aerial photos, geological and geomorphological field mapping, a geomechanical analysis of rock masses, and laser scanner imaging (Bianchi Fasani *et alii,* 2006; Calista *et alii,* 2008; Miccadei *et alii*, 2012b).

This methodological approach is vital for a complete and effective analysis of rock fall hazard

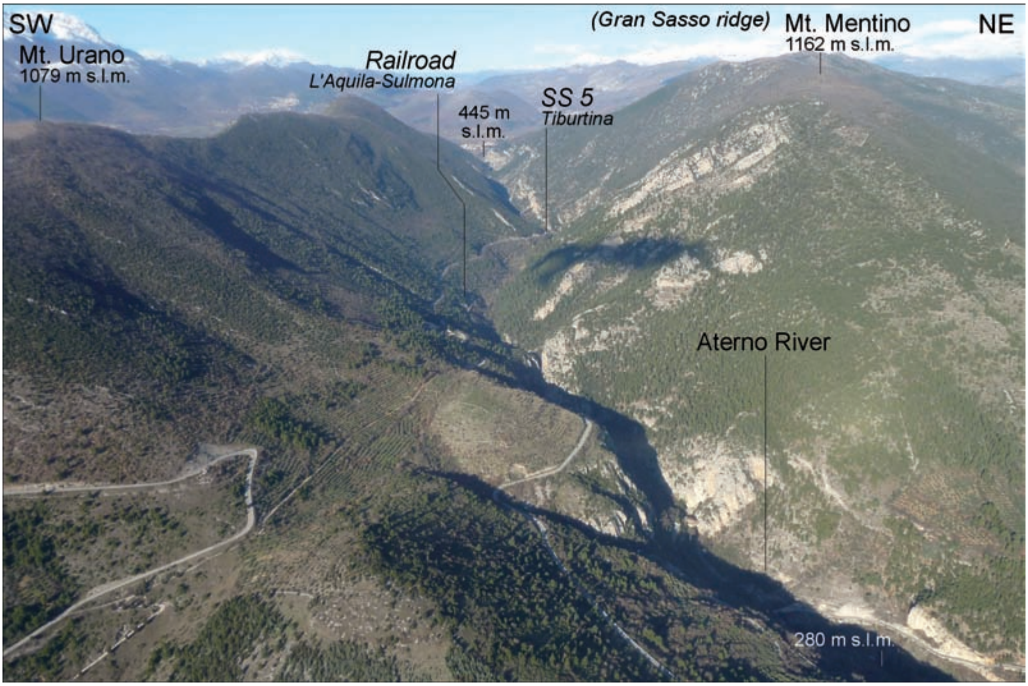

Fig. 2 - Panoramic view of the San Venanzio gorges, along the Aterno river valley

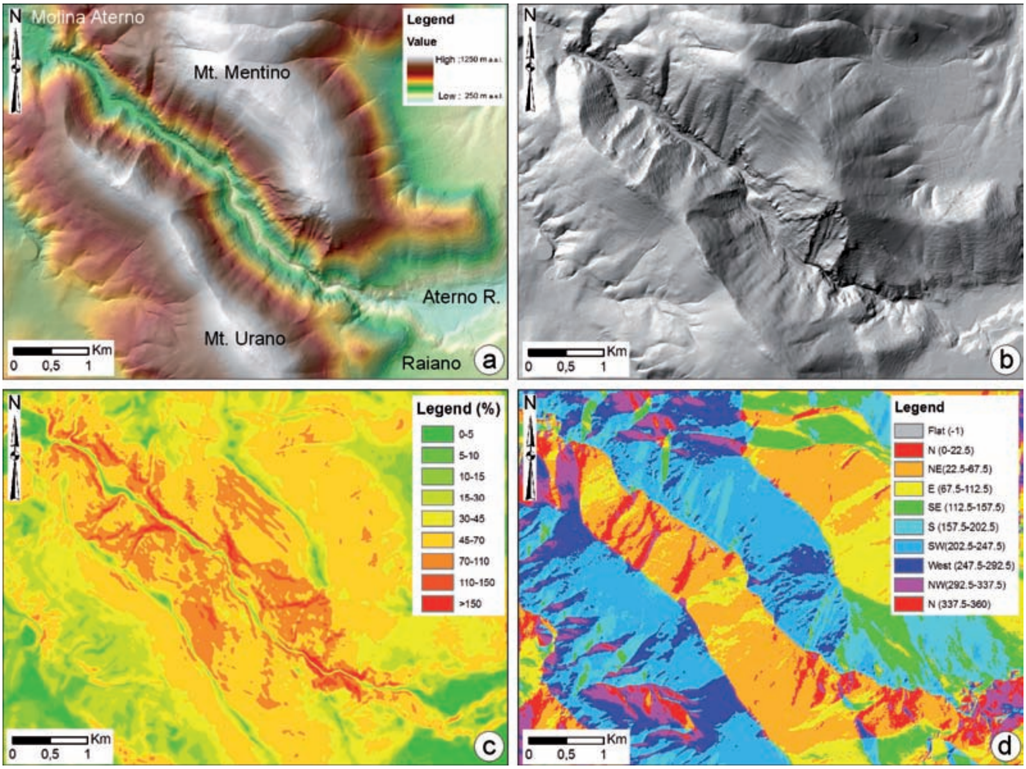

Fig. 3 - San Venanzio gorge physiography: a) Elevation map; b) shaded relief image; c) slope map; d) aspect map

and susceptibility including kinematics, deterministic and probabilistic methods. Moreover, this kind of studies is required at various levels: on a regional scale to prevent instability phenomena and reduce the risk of rock fall; on a local scale for correct land management as well as a tool for predicting the scene of a disaster and its impact on the anthropized landscape.

The relief features of the Central Apennines are consist of N-S, NW-SE or E-W carbonate ridges (2000-3000 m high), with intervening narrow valleys parallel to the ridges and cut in either terrigenous or carbonate rocks, or by wide intermontane tectonic (and or karst) basins, in most cases, partially filled with continental Quaternary deposits (Fig. 1). Ridges have steep slopes and are incised, both longitudinally and transversally, by deep cuts and gorges.

The development and deepening of the drainage system in opposition to the tectonic activity and regional uplift has meant that fluvial and slope-landslide processes have dominated the evolution of the chain landscape (D'Alessandro *et alii*, 2003).

STUDY AREA

The San Venanzio gorges are located along the Aterno river valley, between the L'Aquila basin and the Sulmona basin (Fig. 2). They are 9 km long, within an asymmetric valley with NW-SE orientation, between the Mt. Mentino ridge (1164 m a.s.l.) towards NE and the Mt. Urano-Le Spugne ridge (1080-1046 m a.s.l.) towards SW. The elevation of the Aterno river bed decreases from >400 m (at Molina Aterno) to <270 m a.s.l. (at Raiano in the Sulmona basin). The transversal profile is asymmetric, with a steep NE slope with > 200 m high rock scarps, and a moderately steep SW slope with a transversal steps-like morphology.

MORPHOMETRY

Within the gorges elevation ranges from 1164 m a.s.l. on the NE side (Mt. Mentino) to 270-400 m along the incision, to 1080-1046 m a.s.l. on the SW side (Mt. Urano-Le Spugne) (Fig. 3a,b,d). The main rock scarps are 20-50 m high on the SW slope and up to >200 m high on the NE one.

The slope is very high on both sides (60-150%)

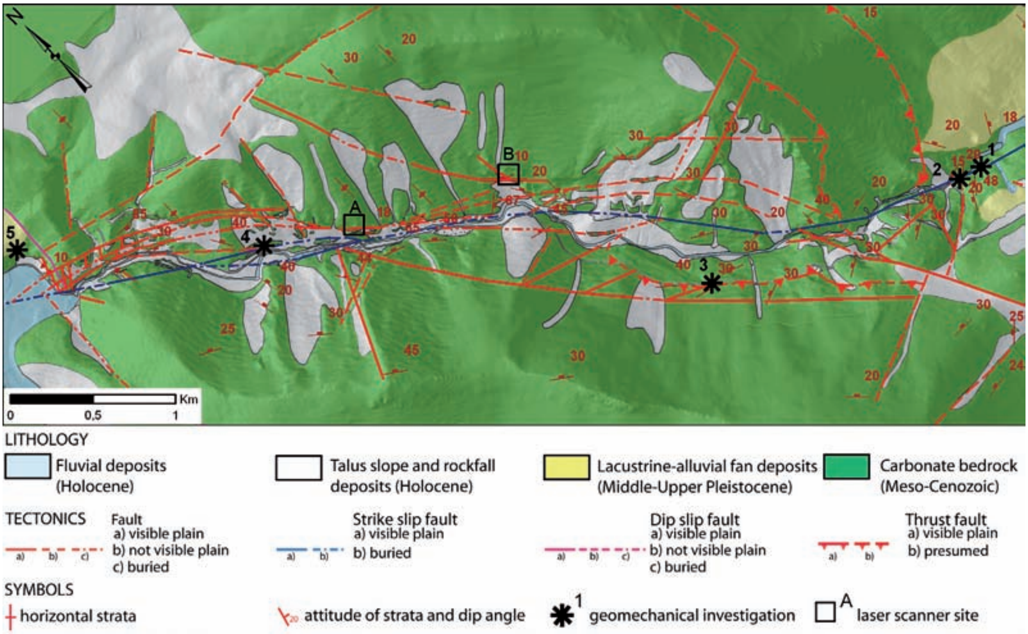

Fig. 4 - Geological map of the San Venanzio gorges

(Fig. 3c). However the NE slope is step-like with steep subvertical scarps and gentler intervening slopes (45-110%), while the SW one is more regular (45-110%) and is broken only by minor transversal scarps. The overall features outline an asymmetric NW-SE valley.

The two main scarps analyzed in this work are located on the NE slope. The highest one is in the SE part of the gorge. It consists of at least three overlapping 50-100 m scarps oblique to the slope, with an overall elevation up to >200 m. The second scarp is in the NW part of the slope. It is a single rectilinear or slightly sinuous scarp, parallel to the valley, 30-100 m high, with a secondary 30-60 m scarp at the base, in the NW termination.

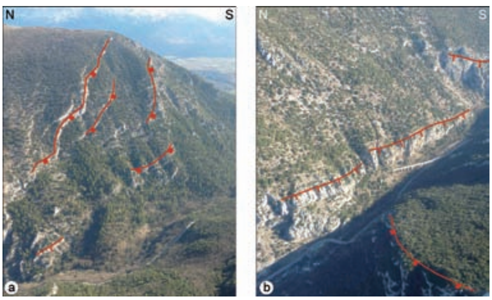

Fig. 5 - Steps-like slopes with structural scarps and fault scarps on the NE slope of the San Venanzio gorges (for scarp legend see Fig. 6): a) SE part; b) central part

GEOLOGY

The ridges surrounding the gorges consist of slope-basin marine Meso-Cenozoic carbonate successions, made up of interbedded micritic limestones, calcarenites and calcirudites (Miccadei *et alii,* 1999b; Centamore *et alii*, 2006; Miccadei *et alii,* 2012 a and references therein).

The structural setting results from a polyphasic Neogene-Quaternary tectonics with strike slip tectonics followed by an extensional one. Tectonic activity developed since at least the Early Pleistocene and has caused a vertical displacement of the bedrock in the order of several hundreds of metres along the main fault system. A series of secondary faults and transfer elements is linked to the main ones.

The San Venanzio gorges are located between two main NW-SE oriented and NE dipping calcareous homoclines (Fig. 4). Mt. Urano is a ~35° NE dipping NW-SE homocline made up of a slope-to-basin calcareous succession. Mt. Mentino is a faulted NW-SE to N-S homocline passing towards E to an overturned thrusted anticline. Along the gorge, however, the calcareous strata are mostly 30-40° ENE dipping. This structure is cut also by E-W vertical strike slip and dip slip faults.

These homoclines are separated by a complex tectonic fault zone along the Aterno river, which is incorporated in the main fault system of the Aterno

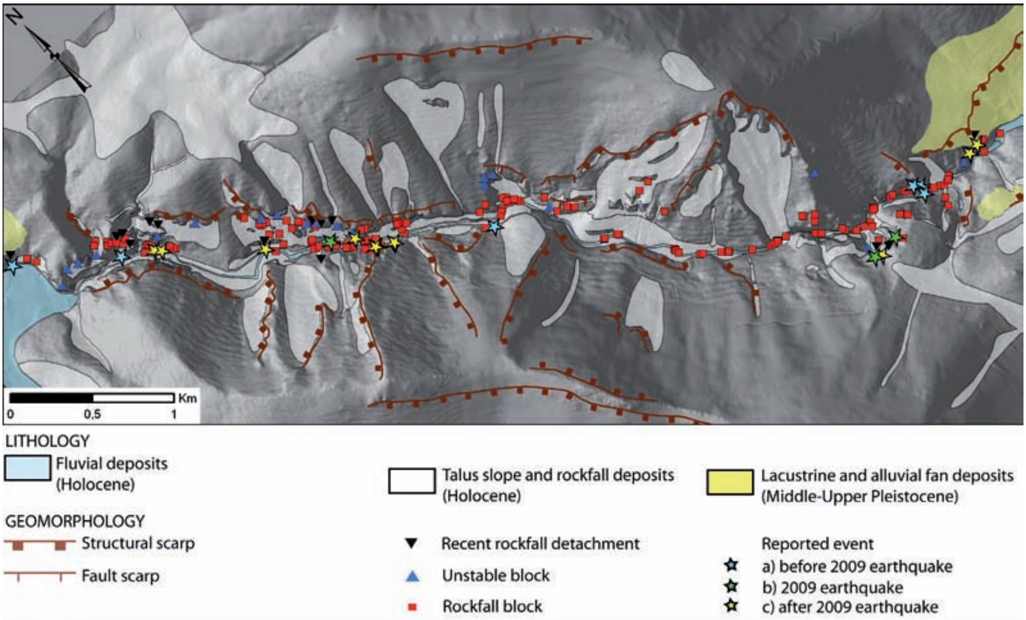

Fig. 6 - Geomorphological and rock fall map of the San Venanzio gorge from reported events and field survey

valley (Bosi & Bertini, 1970; Miccadei *et alii*, 1999b; APAT, 2006; Falcucci *et alii,* 2011). This is affected by a polyphasic tectonic with strike slip and dip slip movements displacing previous thrust faults with a complex interference geometry.

On the gorges' slopes cover Quaternary deposits are poorly present. They are mainly made up of talus slope deposits and rock fall deposits in the NE slope and of talus slope and thin colluvial deposits in the SE slope. Only at the outlet of the gorge into the Sulmona basin, can a thick complex Middle Pleistocene to Holocene succession of cover Quaternary deposits be found, mostly related to alluvial, lacustrine and slope environments, forming active, inactive and relict landforms (Bagnaia *et alii*, 1989; Miccadei *et alii,* 1999a; APAT, 2006).

GEOMORPHOLOGY

The ongoing uplift of the area and the local tectonic effects induced the valley and gorge incision controlled by the high fracturation of the rock masses along different directions (main faults NW-SE secondary ones NE-SW, N-S, E-W). The morphostructural features are well defined by faulted homocline ridges separated by a deep tectonic asymmetric valley with a dip slope on the SW side (Mt. Urano homocline) and a fault slope on the NE side (Mt. Mentino homocline) (Demangeot, 1965; Miccadei *et alii,* 1999b; D'Alessandro *et alii*, 2003).

The landform distribution is strongly controlled by the morphotectonic setting of the area, which induced variable slopes with scarps and step-like slopes (Fig. 5). The step-like slopes are related to the strata attitude (on the dip slope side) and to tectonic elements (on the fault slope).

The main landforms within the gorges include the following (Fig. 6): structural landforms, slope landforms and mass movement, fluvial landforms (along the main gorge). Karst landforms are widespread along the calcareous slopes and on top of the ridges.

Structural scarps occur along the main banks and strata on the SW side of the valley; these landforms edge wide dip slopes, 30-40° NE-dipping; fault scarps occur on the NE side of the valley along the main faults, with an up–to-100m height, from vertical to high angle SW-dipping; ridges are present on top of the main homoclines, straight and NW-SE oriented. Slope landforms and mass movements include the following: talus slopes, which are mainly active in the NE slope and mainly inactive or dormant in the SW slope; locally talus cones occurring at the slope base and rock falls at the base of the main scarps all along the valley and within the gorge; several debris channels incising the NE slope and feeding the talus slopes and cones. Fluvial landforms are mainly gorges incised in the bottom of the valley. Karst landforms affect all the calcareous ridges; large landforms (i.e. dolines) are present on the summit of the Mt. Mentino ridge but mostly outside the study area; small landforms (i.e. karren, lapiez, underground channels and fissures) affect all the rock scarps of the valley, opening and enlarging tectonic joints and faults and inducing a strong weathering of the rocks.

DATA AND RESULTS

Rock falls affect all the scarps within the gorges. Some of them are inactive, outlined by rock fall deposits; most are active, affecting the main bare rock scarps. Active rock falls have involved the road and railroads running into the gorge several times, as documented by reported events and field mapping.

The San Venanzio gorge has been known for decades for rock fall damages, which required the installation of several protections (barriers, netting) along a road (SS 5 Tiburtina) and a railroad (L'Aquila-Sulmona).

AVI Project data (CNR-GNDCI, 1998), technical reports, newspapers, and civic committees allowed us 17 main reported events have been collected based on AVI Project data (CNR, 1998), technical reports, newspapers, and the documents owned by civic committees (Tab. 1). These events resulted in moderate to severe damages. The largest event occurred after the 2009 L'Aquila earthquake, which triggered multiple rock falls on a >150 m long scarp, requiring traffic blockage for several months. Minor events not affecting infrastructures are frequent all along the main scarps.

Municipality	Location	Data	Source
Raiuno	San Venanzio hermitage	19/11/1986	Project AVI (CNR - GNDCI, 1998), SICI, http://sici.irpi.cnr.it
Raiuno	San Venanzio hermitage	1987	Project AVI (CNR - GNDCI, 1998), SICI, http://sici.irpi.cnr.it
Raiuno	San Venanzio hermitage	1993	Project AVI (CNR - GNDCI, 1998), SICI, http://sici.irpi.cnr.it
Castelvecchio Subequo	SS 5 Tiburtina	02/1994	Project AVI (CNR - GNDCI, 1998), SICI, http://sici.irpi.cnr.it
Raiuno	SS 5 Tiburtina	01/1997	Project AVI (CNR - GNDCI, 1998), SICI, http://sici.irpi.cnr.it
Raiuno	SS 5 km 164+250	17/11/2007	Pro Valle Subequana civic commettee
Molina Aterno	SS 5 km 161+900	12/02/2008	Pro Valle Subequana civic commettee - Doglioni & Salti (2009)
Molina Aterno	SS 5 km 161+100	09/10/2008	Pro Valle Subequana civic commettee - Doglioni & Salti (2009)
Raiuno	SS 5 km 163+550	05/01/2009	Pro Valle Subequana civic commettee
Molina Aterno	SS 5 km163+250	06/04/2009	Pro Valle Subequana civic commettee - IRPI CNR Survey, 13/04/2009
Raiuno	SS 5 km 166+850	06/04/2009	Pro Valle Subequana civic commettee - IRPI CNR Survey, 13/04/2009
Raiuno	SS 5 km 167+00	06/04/2009	Pro Valle Subequana civic commettee - IRPI CNR Survey, 13/04/2009
Molina Aterno	SS 5 km 162+850	13/10/2010	Pro Valle Subequana civic commettee
Raiuno	SS 5 km 163+650	23/11/2010	Pro Valle Subequana civic commettee
Castelvecchio	SS 5	08/2011	Abruzzo local newspaper Il Centro
Molina Aterno	SS 5 km 162+100	13/10/2011	Pro Valle Subequana civic commettee
Molina Aterno	SS 5 km 162+150	05/03/2012	Pro Valle Subequana civic commettee
Raiuno	SS 5 km 166+900	04/07/2012	Pro Valle Subequana civic commettee
Raiuno	SS 5 km 163+550	06/09/2012	Pro Valle Subequana civic commettee
Molina Aterno	SS 5 km 163+400	14/09/2012	Pro Valle Subequana civic commettee

Tab. 1 - Rock fall events reported from AVI Project, technical reports, newspapers and local inventories

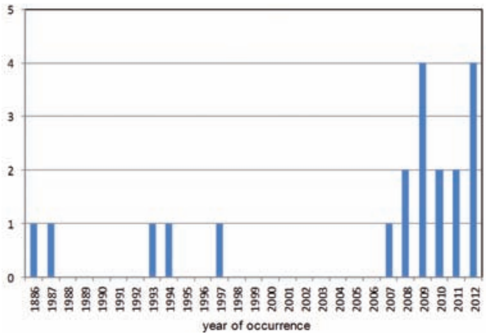

Fig. 7 - Rock falls reported events time distribution

The reported event time distribution (Fig. 7) shows, on average, one event every 1-10 years before 2009, four multiple events on 6 April 2009 (L'Aquila earthquake main shock) and 2-4 events per year after 2009.

FIELD SURVEY

Field survey allowed for the mapping of the following rock falls features (Fig. 6): a) recent rock fall detachment scars, b) rock fall bodies or single blocks, and c) unstable blocks, which in two sites were investigated with laser scanning, together with d) reported events pre-, sin-, and post-2009 earthquake.

Rock falls affect steep to vertical to overhanging scarps mostly on the NE side of the gorges. Detachment areas are controlled by strata attitudes parallel to the slope or inclined less than the scarps (SW side of the gorges), inducing slide mechanisms, or by antidip strata intersecting joints parallel to the scarps (NE side of the gorges), inducing toppling mechanisms, or by oblique joint intersection, inducing toppling or wedge sliding (locally on the NE side). Fall mechanisms are related to rock quality, jointing, discontinuity orientations compared to slope orientation and roughness, block size. Fall paths, followed by rebound and rolling, run several hundreds metres along the slopes and usually reach the gorge bottom or are stopped by roads, railroads or other obstacles. The biggest blocks usually get break during rebound.

Field survey outlined variable jointing along the main scarps, isolating unstable blocks having a moderate (<1 m^3) to large size (>2-3 m^3) (Fig. 8a,b,c,d). The main unstable blocks are due to: 1) large rock slices surrounded by edge joints from which large blocks could slide or topple, 2) highly jointed rock peaks and pinnacles, from which moderate size rock volumes could fall, 3) multiple blocks along the main joints, from which multiple falls could occur.

Rock fall deposits at the base of slopes and scarps show an irregular (locally progressive) size distribution along the slope profile due to rock jointing and slope angle. The deposits are made up of small to moderate size

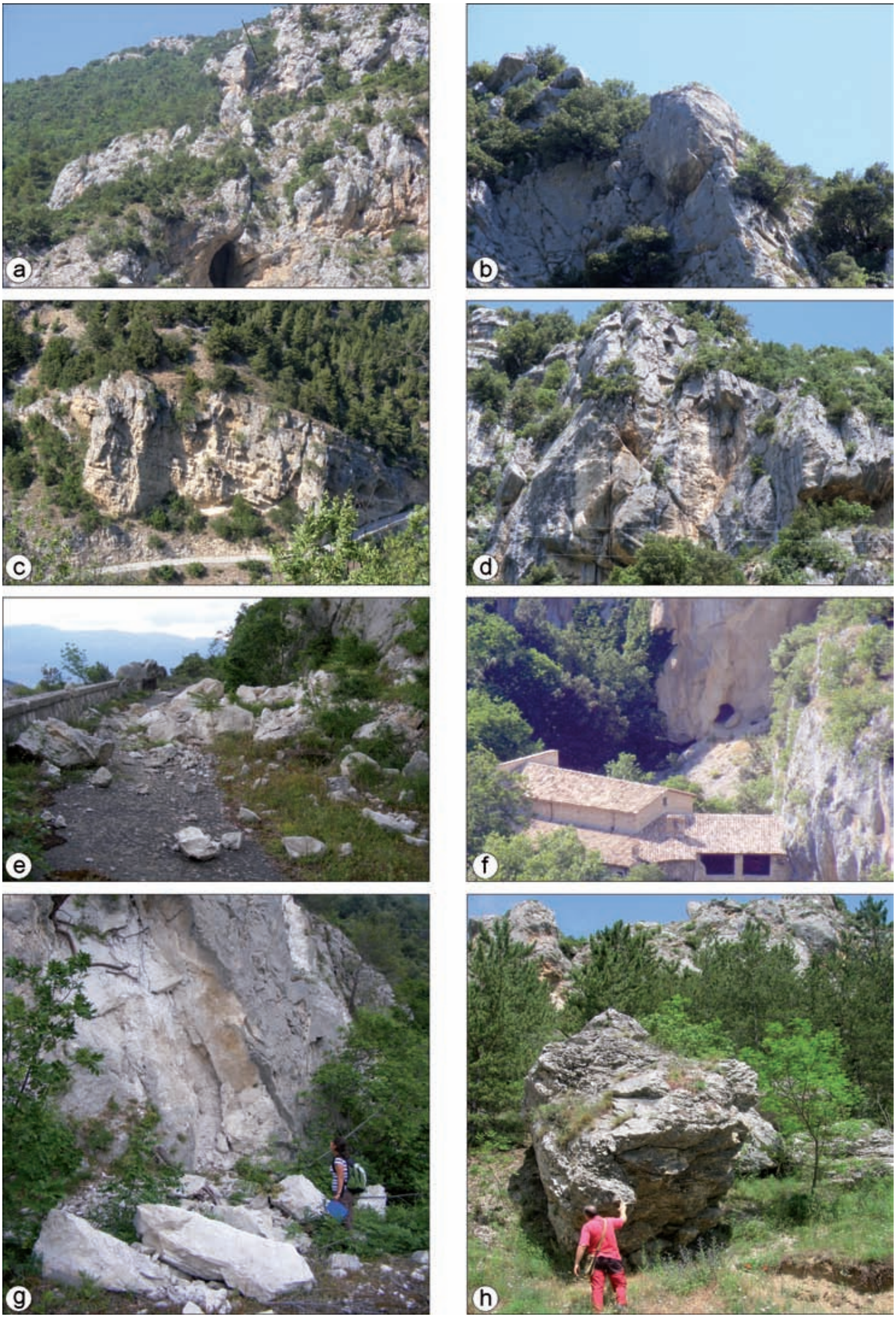

Fig. 8 - Unstable blocks and rock falls occurred in the San Venanzio gorges (Aterno river): a) central sector NE slope, unstable blocks along a N-S vertical joint; b) SE sector NE slope, prismatic unstable blocks with possible sliding on strata; c) outlet of the gorges NE side, unstable blocks and scars on conglomerates and breccias of the Quaternary continental deposits; d) NW sector NE slope, unstable blocks with possible wedge sliding; e) SW sector SW slope, multiple rock falls; f) San Venanzio hermitage, rock fall scar and deposit; g) NW sector NE slope, rock falls on N140 open joints; h) central sector NE slope, large rock fall blocks

calcareous blocks within a pebble to cobble matrix, with size generally increasing down slope. The large blocks (>1 m^3) are scattered along the slope, mostly in the lower part and occasionally in the intermediate part (stopped by natural or anthropic obstacles) (Fig. 8e,f,g,h).

On two of the main scarps in the middle part of the gorges (along the SS5 road; location in Fig. 4) laser scanner imaging has been performed (acquisition with Topcon GLS 1000, Long Range terrestrial Laser Scanner; processing with ScanMaster) in order to analyze in detail the scarp morphology and geometry as well as the size of unstable blocks. The first site (SS5 at km 163,400, NE slope of the gorges; A in Fig. 4) is a 150 m high and 200 m wide scarp showing a clear step-like morphology, directly overhanging the SS 5 road. The laser scanner allowed to outline vertical segments up to 20 m high and overhanging segments up to 5 m high and 2 m deep; unstable blocks are up to >3-5 m^3 (Fig. 9a).

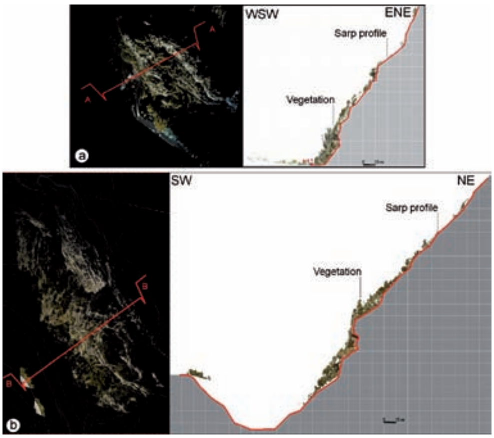

Fig. 9 - Detailed morphometric cross section from laser scanner imaging: a) site A; b) site B (location in Fig. 4)

The second site (SS5 at km 164,500, NE slope of the gorges, B in Fig. 4) is 200 m high and 300 m wide, showing again a step-like morphology. In this case vertical segments are up to 30 m high and overhanging segments are up to 15 m high and >5 m thick; unstable rock volumes are up to 30-50 m^3 (Fig. 9b).

GEOMECHANICAL INVESTIGATIONS

Susceptibility of the slopes to rock falls was analyzed by investigating the geomechanical features of the slopes (I.S.M.R., 1978) and outlining possible movement mechanisms and block dimensions. Investigations were carried out on the main rock scarps affected by rock falls along the SS 5 road. Litology, joint density and weathering and discontinuity sets were analyzed together with their relationship with the rock scarp attitude and main fault planes, in order to define blocks susceptible to fall. The five investigation sites are located all along the gorges from SW to NE and were selected according to their geological and geomorphological features and their position along the SS 5 road. In all the sites open or closed pervasive joints are present, with a high to very low joint density and variable attitude. The statistical analysis of discontinuity orientation and spacing and their relationship with slope orientation allowed to define the main discontinuity sets and the fall mechanism (Tab. 2; Fig. 10).

Joint spacing is from high (joint spacing >100 cm) to very low (6 cm); along the main faults cataclasite belts are present. This allows to infer the size of possible unstable blocks from medium-sized to small (>1 m^3 to 0.01 m^3). Bigger blocks are locally present (Fig. 7) and smaller ones fall with a high frequency and are responsible for talus slopes and cone formation. According to these data the rock quality is from moderate to very poor (along the main cataclasite belts).

Area	Slope	S0	F1	F2	F3	F4	Jv
1) Mulino	N260/80	N220/20 (30-80 cm)	N345/65 (50 cm)	N180/75 (10 cm)	N030/70 (50 cm)	N225/80 (40 cm)	17
2) Eremo	N345/65	N250/35 (50-80 cm)	N290/75 (100 cm)	N070/60 (6 cm)	N030/75 (50 cm)	N270/80 (15 cm)	20-25
3) SS5 km 165,700	N270/70	N280/30 (30-80 cm)	N115/50 (50 cm)	N165/70 (35 cm)	N140/60 (35 cm)	N260/50 (40 cm)	11
4) Galleria Claudia	N145/77	N330/15 (~150 cm)	N030/75 (40 cm)	N060/80 (60 cm)	N100/65 (40 cm)	N230/85 (60 cm)	8
5) SS5 Km 162	N150/68	N310/20 (50-100 cm)	N140/70 (25 cm)	N160/72 (25 cm)	N200/55 (18 cm)	N342/80 (100 cm)	16

Tab. 2 - Geomechanical investigations data. Orientation of slopes, strata (S0) and main joints (F1,2,3,4) analyzed along the San Venanzio gorges; in brackets is the spacing of discontinuity (ISMR, 1978); estimated Jv for each site

The stability analysis of the slopes is based on the analysis of the discontinuity set orientations: Strata (S0) are the first and most important discontinuity sets: a) N200-230/20-30 on the SW side of the SE part of the gorges; b) N280-290/30-40 on the SW side of the central part of the gorges; c) highly variable on the NE side of the gorge, from horizontal to N310-330/15-20 in the NW part, to low angle and high angle (10-20° to 85°) S dipping in the central part, to 160-200/25-35 in the SE part of the gorges.

In the SE part of the gorges on the SW side of the valley (1 in Fig. 10) the intersection of strata attitude (S0-N220/20) and scattered joint sets (N345/65, N30/70, N180/75, N225/80) induces the instability of small-medium size wedge blocks (<1 m^3) with slide and topple mechanisms.

On the SW side of the gorges, again in the SE part (2 in Fig. 10), strata attitude (S0-N250/35) and joints (N270-290/75-80 and N30-70/75-60) define oblique wedge blocks susceptible to toppling and fall on NW-SE, NE dipping slopes (N345/65). The physical and karst weathering of rock and joints weaken the rock masses and increase, together with shrub and tree roots, rock fall susceptibility.

In the central sector (3 in Fig. 10) on the SW side of the valley, parallel strata (S0-N280/30) and slope orientation (N270/70), with strata dip angle less than slope angle, enable the development of sliding. Sliding and fall are also controlled by N140-160/70 joints (several metres long, 5-20 cm open, low roughness, 20-30 cm spaced) that cut strata transversally.

In the NW part of the gorges on the NE slope (4 in Fig. 10) the intersection of several high angle discontinuity sets (N30-60/75-80 and N230/85) and strata (S0-N330/15) enables wedge sliding along NW-SE slopes SW dipping (N145/77) and locally toppling.

In the extreme NW part of the gorges, again on the NE slope (5 in Fig. 10) the most critical discontinuity set (N140-160/70-72) is parallel to the main slope (N150/68) and enables toppling mechanisms.

CONCLUSIONS

The San Venanzio gorges are a peculiar site for the analysis of rock falls. They are permanently under study and monitoring due to the high frequency of rock falls triggered by high present and past seismicity of the area or by heavy rainfall events and controlled by the deep incision of the gorges and the evolution of fault slopes and dip slopes of the Aterno asymmetric tectonic valley between Mt. Mentino and Mt. Urano faulted homocline ridges.

The analysis of morphostructural control on rock falls as presented in this work is based on 1:5.000-1.10.000 field geological and geomorphological mapping integrated with reported events analysis, photogeological analysis, laser scanning and geomechanical investigations. This approach is considered vital for a correct investigation of rock fall hazard and susceptibility, particularly on large slopes where topographical, geological, tectonic, geomechanical and geomorphological variation control rock fall development. In these cases, only a complete geological, mor-

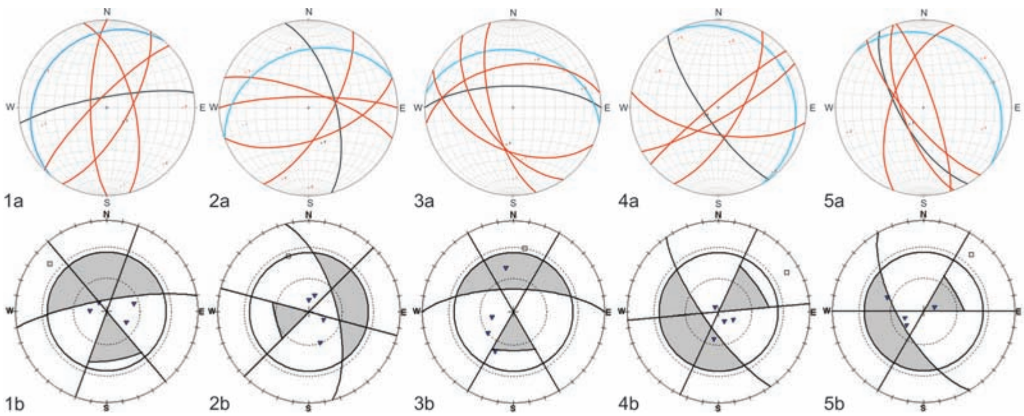

Fig. 10 - Geomechanical investigations data. a) Plots of the main discontinuity sets (strata and joints; lower hemisphere projection) along the San Venanzio gorges from SE to NW (for investigation sites' location see Fig. 4); black line: slope orientation; blue line: strata attitude (S0); red line: joints (F1,2,3,4). b) Markland test plot: quadrangle: strata; triangle: joints

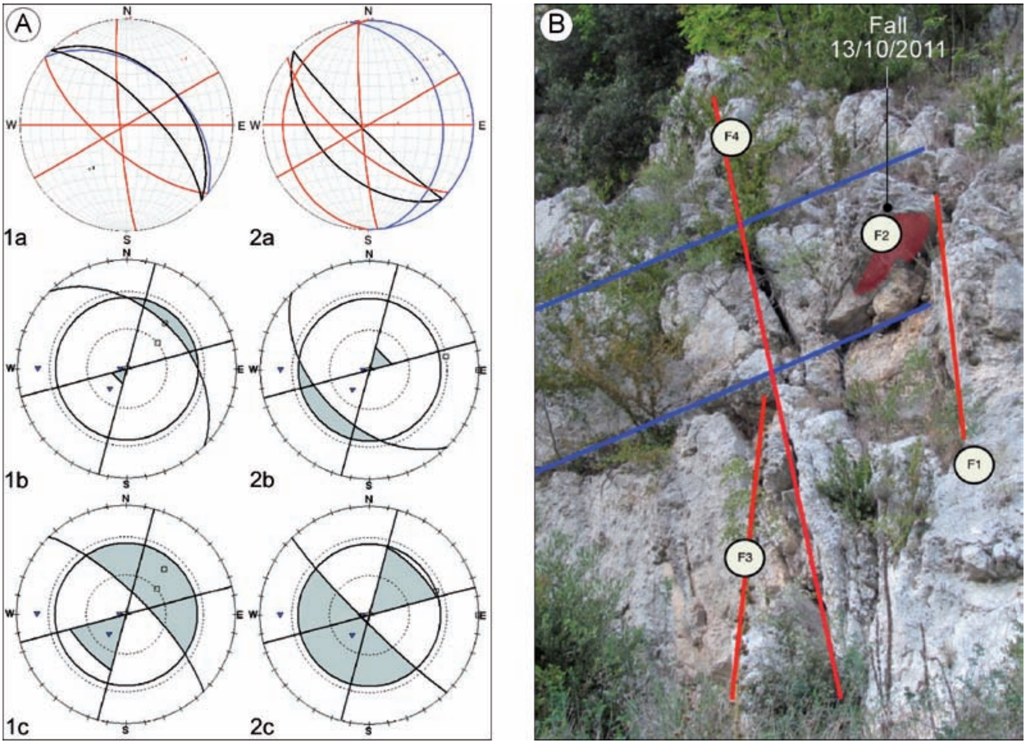

Fig. 11 - A) Plots summarizing the stability conditions: 1) on the SW slope (a: main discontinuity sets; b: Markland test for medium angle slopes; c: Markland test for high angle scarps); 2) on the NE slope (a: main discontinuity sets; b: Markland test for medium angle slopes; c: Markland test for high angle scarps). B) Rock scarps summarizing the main discontinuity set affecting the San Venanzio gorges area: S0-N330/15; F1-N120/80; F2= N220/65; F3-N120/90; F4-N270/80. At the intersection of the main joints and strata a rock fall occurred on 13 October 2011 involving the block outlined in the image

phostructural and geomechanical data set allows to achieve effective results when applying deterministic and probabilistic methods for rock falls investigation.

The complex and variable features of the San Venanzio gorges are outlined by geological and geomorphological mapping. The faulted homocline ridges of Mt. Mentino and Mt. Urano have been affected by a strong polyphasyc tectonics that developed since the Neogene time and throughout the Quaternary (Miccadei *et alii,* 1999 b; APAT, 2006; Miccadei *et alii,* 2012 a), in relation to: a) N-S thrusting (Upper Messinian - Lower Pliocene); b) strike slip tectonics along NW-SE high angle faults (including the San Venanzio gorges faults) (possibly Middle Pliocene); c) dip slip faulting again along NW-SE high angle faults (in some cases reactivation of previous faults, i.e. San Venanzio gorges faults) (Pleistocene-Holocene). The intersection and interference of these features, activated on different times and with different movements, are responsible for the complex geological and morphostructural setting and for the high jointing of rocks. The San Venanzio gorges were incised after the Pleistocene uplift along an asymmetric tectonic valley between Mt. Mentino and Mt. Urano faulted homocline ridges.

Within the valley several high angle faults affect the calcareous bedrock (N120-150; N40-60; N70-110) intersecting previous thrust faults (N180/10-30) and are characterized by fault breccias and cataclasite belts. Rock falls within the San Venanzio gorges occur on vertical, step-like or overhanging slopes (structural scarps or fault scarps) due to sudden detachments from rock scarps. They occur more in the NE side of the valley than in the SW one due to the morphostructural setting of the slopes and vegetation (SW: heavy tree canopy on dip slope, NE: bare, shrubby or sparse trees, step-like fault slope). The rock falls frequency seems to have strongly increased after the 2009 L'Aquila earthquake (during which two multiple events occurred) from 1 event every 1-5 years before 2009, to 2-4 events per year after 2009. This could be due to increased care by people and governmental and local public bodies to rock falls in this area after the 2009 L'Aquila earthquake, but also to increased rock fall susceptibility of the rock scarps induced by the seismic shaking and the related mechanical weathering.

Geomechanical investigations allowed to outline the main discontinuity sets, strata and joints (mostly parallel or controlled by the main tectonic elements) and to infer the size of possible unstable blocks (from ~1 m^3 to 0,01 m^3). The rock quality is from moderate to very poor. The poorest rocks are those along strike slip faults and related cataclasite belts, and at the intersection with thrust faults; the scarps of these areas are affected by high frequency falls of small blocks (usually <0,01 m^3) that feed talus slopes and cones. Moreover karst weathering affect the rock scarps with a double effects: a) small karst landforms induce a heavy weathering of the rock masses worsening the rock quality conditions, while b) locally karst precipitation and carbonate concretion formation induce the sealing of joints and the strengthening of rock masses.

The geomechanical investigation and the comparison with main tectonic features outline that instability mostly affects N300-350 NE dipping strata (S0), intersected by N175 vertical and N130/70 discontinuities, on the SW side of the valley on high angle slopes, inducing slide mechanisms. On the NE side of the valley instability mostly affects N330-350 NE dipping strata (S0), intersected by N175 vertical and N130/70 discontinuities a) with a slide mechanism when the dip angle is less than the slope, b) with a topple mechanism when the dip angle is more than the slope, c) with wedge sliding when intersecting N060/90 and N090/90 discontinuities transversal to the slopes (Fig. 11).

The geomorphologic surveys carried out in the gorges area before and after the April 2009 earthquake were compared to previous studies on landslides in the

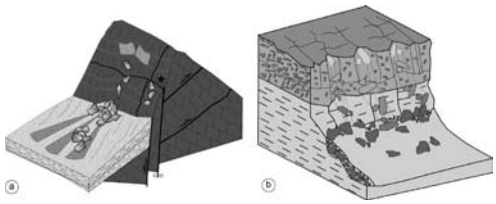

Fig. 12 - Morphostructural scheme of rock falls: a) on calcareous faulted homocline ridges forming talus slopes and cones (NE slope of the San Venanzio gorges, asterisk indicates the discontinuity intersection and the related scarps as in Fig. 5b and 11b); b) on structural scarps on faulted breccias and conglomerates of Quaternary continental deposits (NE slope of the San Venanzio gorges at the outlet into the Sulmona basin, see also Fig. 8c)

Abruzzo Region and analyzed at the light of the relationship between landslide distribution and morphostructural setting, resulting from the regional landslide inventory. In the San Venanzio gorges rock falls occur on: a) calcareous faulted homocline ridges; b) structural scarps on faulted breccias and conglomerates of Quaternary continental deposits (Fig. 12).

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