

The 27 February 2014 San Leo landslide (northern Italy)

Abstract The report describes a recent landslide occurred in San Leo (northern Italy), an outstanding village from the historical, architectural and landscape point of view. On February 27, 2014, around 6PM local time, about 0.30 Mm³ of rock detached from a sub-vertical cliff and fell into the facing valley, producing a roar and a shake, which was initially perceived by the inhabitants as an earthquake, then followed by a dust cloud produced by the fragmentation of material during the collapse. Fortunately, nobody was injured, neither the landslide damaged any relevant structure; anyhow, it is still posing a severe threat to the village and, above all, to the fortress that represents an architectural masterpiece dating back to the middle ages. An outlook of the event will be given, along with the description of the peculiar geological and geomorphological features driving the slope instability phenomena, which indeed are widely diffused in the entire region. Lastly, an overview of the landslides, which historically affected the village, is also given, showing how natural hazards can influence the history of a site.

Keywords Northern Italy · Rock fall–topple · Earth flow · Clay shales · Limestone slab

The most beautiful village in Italy? San Leo: a fortress and two churches.

(Umberto Eco, author of the novel “The Name of the Rose”)

Introduction

San Leo is located in the heart of the Montefeltro countryside in north-eastern Italy and lies on a hilltop approximately 660 m above sea level inhabited since the Roman times. The former name of the village was Mons Feretri from a temple dedicated to Jupiter Feretrus (literally “striking Jupiter”) erected by Romans, hence the modern term Montefeltro of the region. Later, it was renamed San Leo for Saint Lion, a bishop who founded a place of Christian worship there during the fourth century AD.

San Leo is renowned as one of the “most beautiful villages in Italy” and also has the Orange Flag award for sustainable tourism. It even impressed Dante Alighieri (the author of the “Divine Comedy”), who based on this site the description of the ascent to the Purgatory. The highlight of San Leo is the stunning castle located on a large craggy rock above a precipitous cliff, along with two well-preserved Romanesque style churches dating back to the twelfth century. The fortress housed many people of great importance, including Dante Alighieri himself (in 1306), Saint Francis of Assisi (in 1213), Alexander the Count of Cagliostro (1743–1795), a famous alchemist who was here imprisoned by order of Pope Pio VI from 1791 to 1795, when he died. The beautiful landscape of Montefeltro inspired also many painters (Borchia and Nesci 2012), like Piero della Francesca (1412/17–1492) and perhaps Leonardo da Vinci himself (1452–1519).

The citadel gained great fame first as an impregnable military fortress and later as an extraordinary prison, due to the morphological features of the site. In fact, the village of San Leo rises at the top of a limestone and sandstone slab of approximately 0.5 km², bordered by vertical and overhanging cliffs up to 100 m high, above clayey gentle slopes. Indeed, the morphology looks like a “cuesta”, with the highest altitude towards east, where the fortress is built, and then sloping toward west, where the historical downtown developed (Fig. 1).

The peculiar geological and morphological features give rise to different landslide hazards, including the opening of ground cracks, local subsidence and slope failures. The rock slab is subject to lateral spreads and related rock falls, rock slides and topples, whereas the underlying clay shales undergo to earth slides and flows. Therefore, the site is particularly significant because it combines unique geological and geomorphological features with outstanding historical and artistic assets, which are exposed to a relevant landslide risk (Ribacchi and Tommasi 1988).

This report outlines the main features of a recent landslide, which occurred on February 27, 2014 along the northeast side of the rock cliff, seriously threatening the village, and which is now continuously monitored for possible further retreats of the main scarp. Furthermore, the description of the geologic setting is given along with a brief summary of the historical landslides, which affected the rock slab in the past, as a commentary showing how history can be also driven by environmental factors.

Geologic setting

San Leo rock plate is located on the south side of the Marecchia River Basin. The structural setting is characterised by alloctonous geological units belonging to the so-called “Val Marecchia Sheet”, a nappe overlying the autoctonous geological units of the “Umbria-Marche-Romagna” geological sequence (Fig. 2). The “Val Marecchia” Nappe encompasses several geologic units, from the older—*stratigraphically lower*—Ligurian units to the younger—*stratigraphically upper*—Epiligurian units, dating back to Oligocene and Pliocene. Epiligurian units are formed by hard rocks and are well differentiated from the Ligurian units that are characterized by a dominant clayey fraction.

The “Val Marecchia” Nappe displays many landforms of geomorphologic relevance, strongly controlled by the litho-structural arrangement of the Nappe and by differential erosion of the outcropping rock masses. Indeed, the presence of resistant rocks embedded in clay-rich terrains promotes the process of selective erosion responsible for shaping of steep cliffs and spurs. The clayey substratum, in turn, leads to the progressive undermining of the resistant rocks, which implies the cliff retreat and contributes to shaping hillsides through progressive mass wasting and soil erosion. Accordingly, the San Leo rock slab can be considered a typical example of rock plate belonging to the “Val Marecchia” Epi-Ligurian Basal Complex (Conti and Tosatti 1996).

Fig. 1 South view of San Leo (Emilia-Romagna Region, northern Italy). The photo shows the rock slab lying over a hilly landscape, with the village in the middle and the fortress on the east side, where the rock cliff reaches the maximum height (photo O. Nesci, April 2005)



The rock plate is made of limestone belonging to the “San Marino” geologic formation at the base and glauconitic arenaceous–calcareous sediments of the “Monte Fumaiolo” geologic formation at the top (Fig. 3). The lower part of the “San Marino” geologic formation is composed of thick weakly bedded calcirudite layers, whereas a strongly bedded calcarenitic facies outcrops in the upper part.

The overlapping “Monte Fumaiolo” geologic formation is mainly composed of sandstones. Looking upward, coarse-grained sandstone with pelitic interbedded layers can be observed, turning into coarse-grained pelitic arenaceous strata.

The whole cliff lies above the varicoloured clays named “Argille Varicolori”. The contact between the rock mass and the underlying clays was clearly visible along the south wall; at present, it is covered by the thick debris of the recent landslide.

The structural setting drives the morphology, with rock slabs generally verging toward east and northeast, according to the main direction of fault and fold axes (Fig. 2). Bedding layers in the rock slab are mainly WSW dipping. At the north-western edge the bedding dip is chaotic, while at the south-eastern cliff edge the bedding dip direction quickly turns to WNW. On the west side, vertically bedding, parallel to the cliff wall, can be observed, but local variations can be observed owing to prolapsed bedding. The structural features are mainly influenced by discontinuities such as faults and joints of tectonic origin (Spreafico et al. 2013).

As a matter of fact, the rock slab is bordered by subvertical and overhanging cliffs up to 100 m high, overlying clayey gentle slopes and badlands. Owing to squeezing phenomena at the rock slab foot, in some places the clayey material rises vertically and is injected for some meters into open fractures formed by tensile stresses in the overlapping rock. Moreover, due to their lithological and mineralogical composition, varicoloured clays undergo swelling and are subjected to rapid erosion and unloading phenomena; thus, landslide processes, such as slumping and earth flows, concentrate both at the foot of the rock plate and in the surrounding badlands. As a consequence, the cliff base is progressively undermined and the stability of the rock plate is compromised by rock falls and topples, so that periodic and expensive maintenance and consolidation works are requested to avoid damages to the old town and the castle (Caturani et al. 1991).

The landslide of 27 February, 2014

On February 27, 2014, 16:56':37" (UTC), a rock mass initially estimated to be between 0.45 and 0.50 Mm³, detached from the NE cliff of San Leo rock slab and collapsed onto the facing valley (Fig. 4).

Local inhabitants reported to have heard a loud roar, followed by ground shaking; then, a dust cloud rose from the valley toward the sky. Some of them reported seeing the trees getting up and then the cliff collapsing. Many people reported strange noises, like

Fig. 2 Geological sketch of Montefeltro area. Legend: 1 continental Quaternary deposits; 2 Ligurian, Subligurian and Epiligurian units; 3 Tuscan units. Umbria–Marche–Romagna sequence and post-evaporitic sequence of Apenninic–Padanian border; 4 marine Quaternary deposits; 5 Messinian–Pliocene sequence; 6 secondary basins sequence; 7 principal basin sequence. The main fold axes are also shown

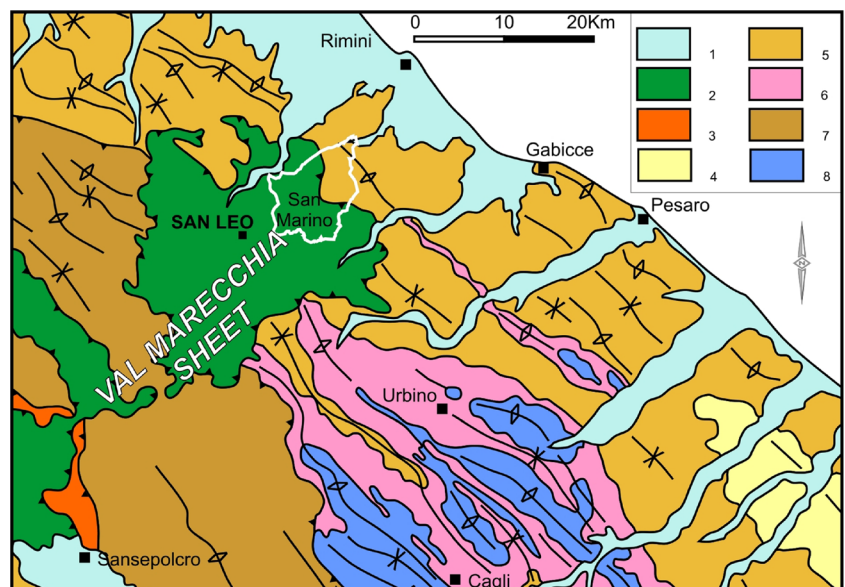
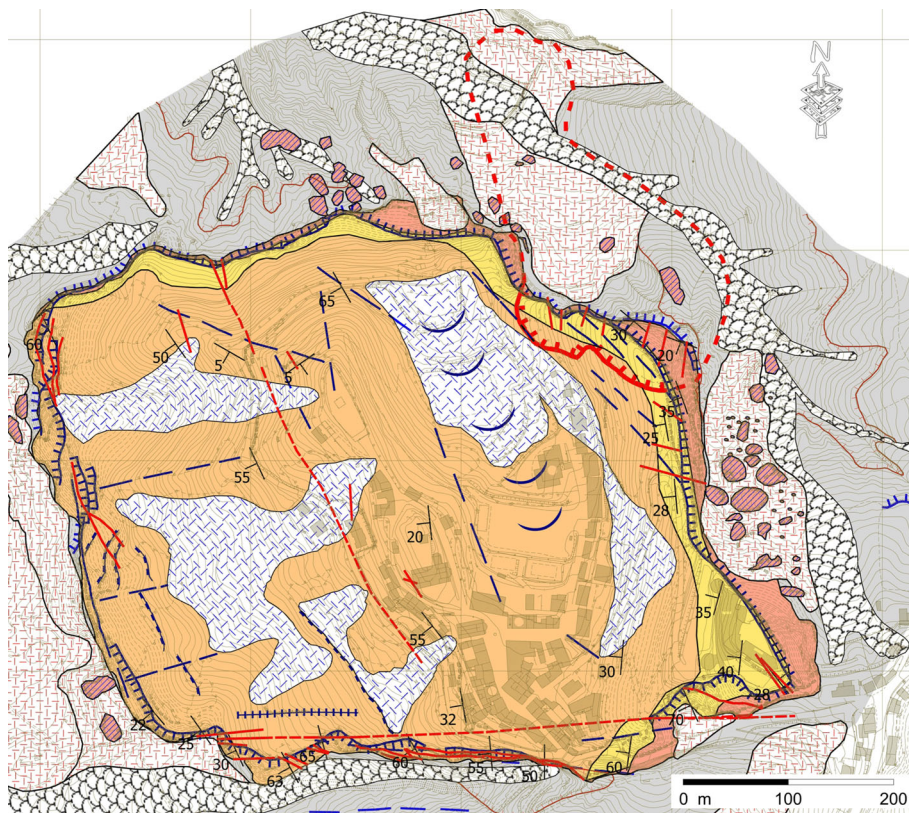


Fig. 3 Geomorphologic map of San Leo rock slab



Geological and structural elements

Epiligurian Units

- Monte Fumaiolo Fm. upper member
- Monte Fumaiolo Fm. lower member
- San Marino Formation
- Argille Varicolori Formation
- Indifferentiated fault

Lineation

- Lineation
- Attitude of strata (dip in degrees)

Quaternary continental deposits and landforms

- Slope debris and colluvium

- Earth flow

- Landslide body

- Boulder

- 2014 landslide body

- 2014 landslide crown

- Landslide crown

- Trench

- Edge of polygenetic scarp

- Edge of badlands

- Though-shaped valley

thunders, coming from the cliff during the night between Wednesday 26 and Thursday 27.

An eyewitness (a woman living downtown) describes the event as follows: “I will never forget it. I heard a loud roar and I believed it was an earthquake, so I ran out. I saw first a cloud dust then a big crack propagating slowly into the cliff. In a few seconds a big portion of the cliff moved and then collapsed in front of my eyes. A surreal scene, like a movie, but it was real”. Minor rock falls continued until the evening of Friday, 28.

Fortunately, the collapse occurred in an unpopulated area and far from the rock slab portion underlying the fortress, which remained undamaged and reopened few days after the event with the only limitation of a pedestrian access. As a precautionary measure, ten houses located close to the landslide scarp were evacuated, along with the police station (“Carabinieri”, military

policemen) and the elementary school, and a secondary road was closed.

The rock debris buried an aqueduct and truncated an electric line, which resulted in a blackout, promptly restored by the electric power company the morning after.

A strong-motion seismic station managed by the National Institute of Geophysics and Volcanology (INGV) recorded the ground shaking produced by the landslide (Fig. 5). Two main events occurred within approximately 1.5 min, the second being larger than the first. This is in agreement with the eyewitness description of the event: a first failure accompanied by the dust cloud, followed by the main collapse of the cliff. Minor cracks propagation can be inferred from the seismic record around 30 s before the first event, as well as in between the two events.

Fig. 4 East view of the landslide occurred on February 27, 2014. On top of the rock slab, the downtown village is visible, along with the fortress on east face (*left side*). The photo shows the contact between the rock slab and the underlying clay shales and the oxidation of the main scarp



A tentative reconstruction of the temporal evolution of the whole process is shown in Fig. 6, based on the reports of witnesses and on the seismic record. The kinematics of the movement seems to recall a progressive detachment of the cliff, followed by a toppling of the whole block and then the collapse. Just after the failure, the movement evolved into a rock and debris avalanche with boulders up to 10,000 m³. The landslide debris and mud spray went up the opposite side of the valley up to 30 m above the valley bottom. In the days after, the bigger boulders moved at a speed up to 30 cm/day along vectors in agreement with the possible reactivation of the earth flow in the varicoloured clays outcropping at the valley bottom, due to a mechanism of undrained loading.

The landslide crown extends for about 200 m, and the scarp shows a retrogression of approximately 40 m. Just after the event, the landslide debris covered an area of around 60,000 m²,

stretching for about 400 m along the river valley. An aerial view (Fig. 7) shows the master joints visible in the upper crest, now approaching the first houses of the village. The oxidation of the landslide main scarp is also clearly visible (as in Fig. 4, too), indicating the infiltration of water through open fractures; certainly, the exceptional snowfall of February 2012 when the snow cover reached a thickness of 2.25 m and lasted for some weeks, greatly contributed to the progressive opening of the fractures.

Immediately after the landslide, terrestrial laser scanner and photogrammetric surveys were carried out by the Emilia-Romagna Region's Technical Services, complemented by the installation of a ground-based SAR. The surveys allowed a reduction of the volume of the landslide, now better estimated to be around 0.30 Mm³. Then, an integrated monitoring system was installed. It consists of 13 wire crackmeters, 4 jointmeters, 2 borehole rod extensometers and 2 vibrometers (1 installed in free field and 1 located inside a

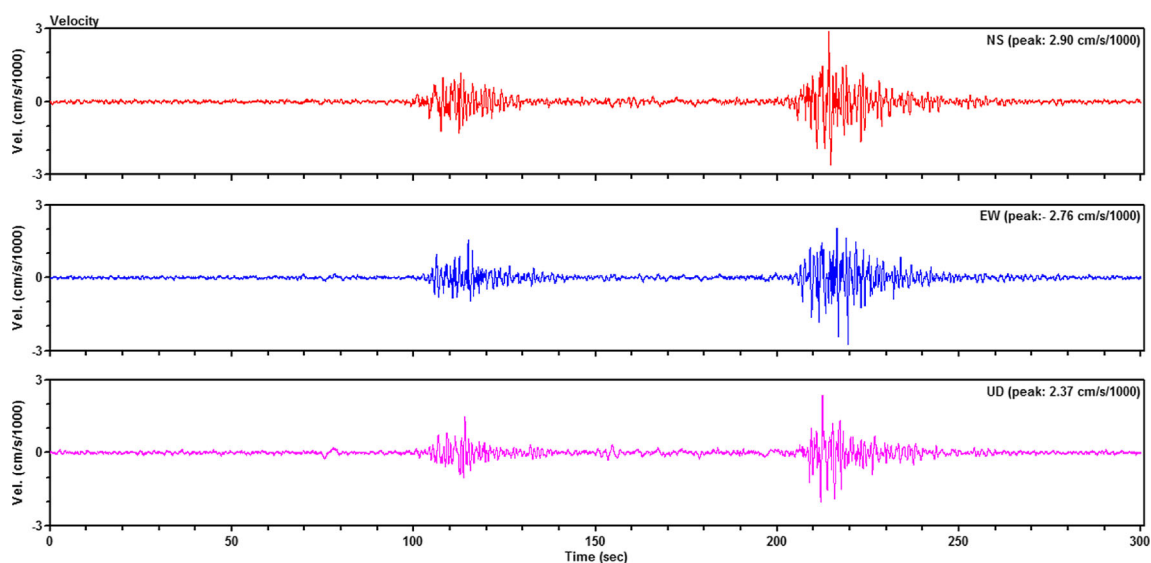


Fig. 5 Ground shaking due to the landslide event, recorded by the seismic station of Mount Carpegna, 11 km far from San Leo. Time axis starts at 16:55:00" UTC. A band-pass filter between 0.5 and 25 Hz has been applied to isolate signal coming from the landslide rather than from ambient noise or larger scale perturbations (Allstadt 2013)

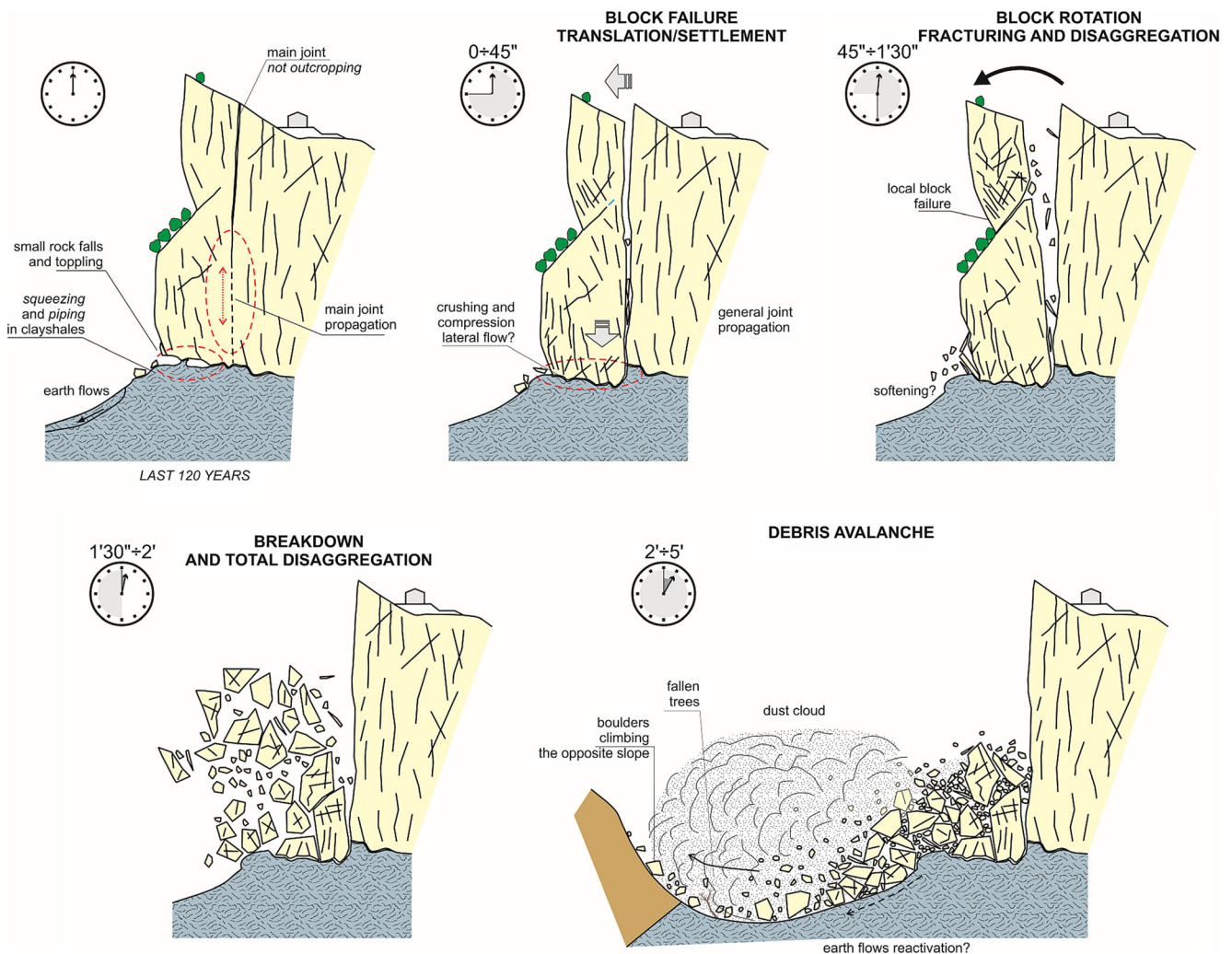


Fig. 6 Tentative reconstruction of the time evolution of the landslide event

building located near the landslide crown). The instruments are monitoring the main fractures (master joints), as identified by a geomechanical field survey. The instruments are redundant in number, in order to have more data collected on the same fracture. The system was switched on April 18, 2014, and from August, it serves to activate the civil protection emergency plan by sending an alert if strain-rate and displacement thresholds are exceeded.

The data collected from April to October 2014 show opening and closing of major fractures in relation to daily and seasonal temperature changes. The thermal effect is noticeable in the wire crackmeters and jointmeters data, while the records of borehole rod extensometers are essentially constant with respect to the temperature variations. The vibrometers measured a number of earthquake events related to the regional natural seismicity.

As far as the residual risk is concerned, two scenarios were considered, both with potentially rapid evolution:

- Metric and/or decametric blocks can fall from the main scarp. This scenario threatens the main scarp, some portions close to the edge and the underlying area.
- Generalized retrogression of the main scarp can occur, due to the presence of pervasive sets of unfavourably oriented and

well-developed master joints, showing weathered surfaces. In this scenario, an event of the same magnitude of the February 2014 is considered possible, also as a consequence of the stress state change in the rock mass. For this reason, four buildings and the public school were initially evacuated.

Following the first results of the studies and the installation of the monitoring system, two buildings and the school were declared provisionally functional. The risk assessments of the remaining two buildings is still ongoing, as well as the design of possible countermeasure works.

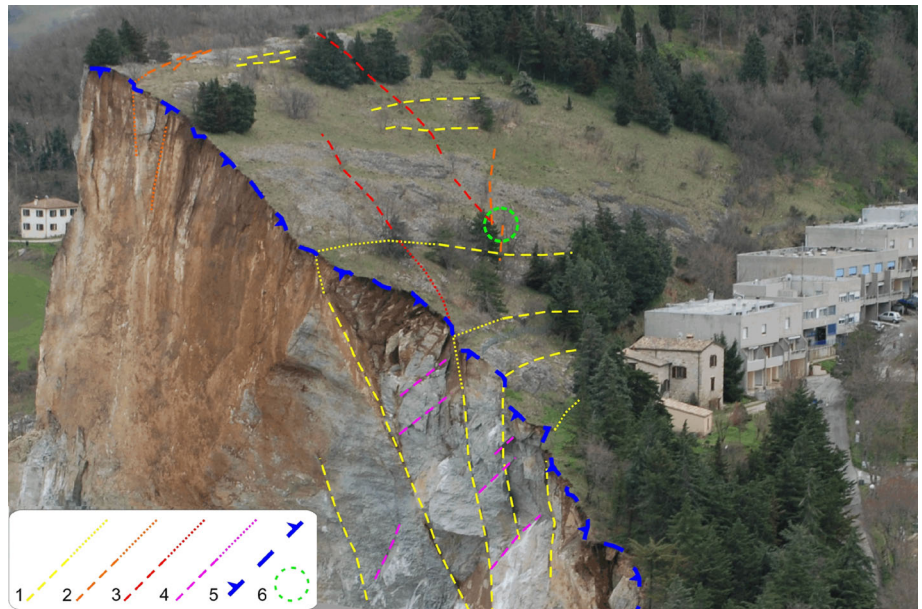
Past landslides

Many historical documents, such as chronicles, letters, paintings and, more recently, vintage photos, witness the history of San Leo coexistence with landslide hazards (Benedetti et al. 2011).

One of the most outstanding documents is the watercolour by Francesco Mingucci, which dates back to 1626, where the eastern face of the cliff is portrayed (Fig. 8, top).

Comparing the watercolour with present day pictures of the rock cliff (Fig. 8, middle and bottom), it can be observed that large

Fig. 7 Prospective view of the main scarp and the crest of the landslide, which is now very close to the nearest houses of the village. 1–4 main joint sets, 5 present landslide scarp, 6 sinkhole related to fracture intersections



volumes of rock along the cliff face are now completely missing, as well as the lack of a massive prism just beneath the fortress where the present cliff edge has retreated reaching the north tower. The

neighbourhood visible in the watercolour at the top of the cliff edge completely disappeared due to the landslides that affected the cliff in the first half of 1600 and destroyed also the old access to the

Fig. 8 Comparative pictures showing the evolution of the north-eastern cliff face of San Leo village. *Top* Watercolour by the painter Francesco Mingucci, 1626AD; most of the blocks visible along the rock cliff face are now missing due to a number of landslides that occurred since the seventeenth century. *Middle* the same cliff face portrayed in the watercolour as it appeared at the end of twentieth century. *Bottom* present view of the cliff face after the landslide of February 27, 2014. On the *right side of bottom figure* is visible the cliff face produced by the 2006 landslide, best pictured in Fig. 9

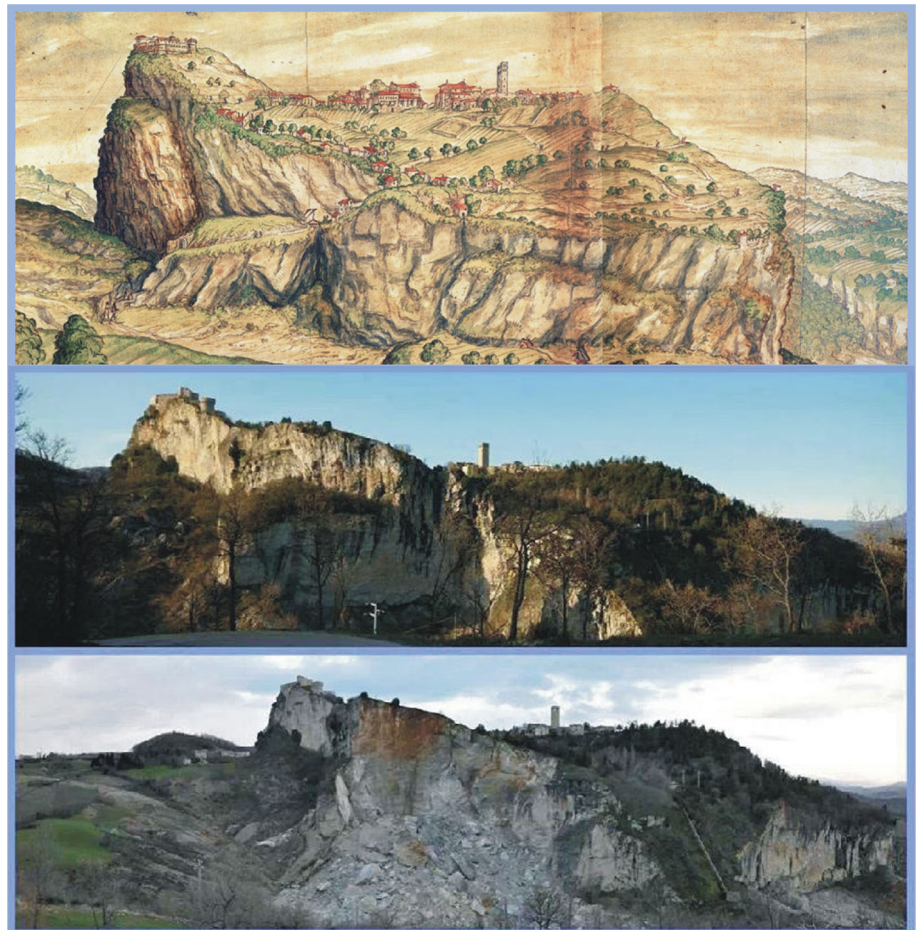




Fig. 9 On the foreground, the 2006 landslide that affected the northern cliff face; clearly visible, at the toe, the landslide debris. On the background, Maiolo hill, similar to San Leo, where the night of May 29th, 1700 a landslide buried an entire village, remarking the diffusion of such phenomena in the whole Montefeltro area

village. Moreover, while in the watercolour no badlands are depicted, they appear now to be widespread, affecting the clay shales since, at least, a century ago.

In another document, a letter from a notable man, it is reported that between 1700 and 1800 a great number of landslides occurred, to the point that “the village is now completely surrounded by them”, wrote the notable man in his letter. In this regard, a strong increase in the occurrence of landslide phenomena has been observed in the whole region since the second half of the second millennium, probably related to the Little Ice Age (Mann 2002) whose peak was reached at the end of the seventeenth century and whose effects on the stability conditions of the region has been well ascertained and documented (Piastra et al. 2005). As a matter of fact, the night of May 29th, 1700, a nearby village (Maiolo, visible on the background of Fig. 9) was completely buried by



Fig. 10 Detail of the east-facing rock cliff beneath the fortress’ north tower. The vertical fracture developing below the tower is already open, as clearly shown by the presence of vegetation and debris in the upper part

a landslide, which affected the hill where the village was built. A manuscript dated 1737AD reports that, after 40 h of continuous rainfall, the Maiolo cliff collapsed burying the village and killing more than 100 people (some tens according to more reliable sources). The chronicle, apart from the legendary interpretation that attributed the catastrophe at a divine punishment (the 40 h continuous rain is a clear reference to the biblical Deluge) for the libertine behaviour of its inhabitants (like Sodom and Gomorrah), refers to a period of intense rainfalls followed by floods and landslides that affected all the region at the end of the seventeenth century, clearly related to the end of the Little Ice Age cited above.

From the available historical documents, periods of dormancy up to 100 years followed by periods of activity of varying duration can be inferred, with the last relevant phase of instability dating back to the beginning of the twentieth century. This poses the problem for the potential of a new slope stability crisis starting from the beginning of the present millennium.

As a matter of fact, a significant landslide occurred on May 11th, 2006 along the north face of the cliff (Fig. 9). A volume of approximately 50,000 m³ detached from the cliff, and some inhabitants reported to have perceived the movement like an earthquake followed by a dust cloud and a strong wind due to the sudden movement of the landslide mass. Successively, the rock debris fallen onto the underlying clay shales, reactivated an earth flow that moved at a speed of about 1 m/day, which activated, in turn, other landslides downstream. A number of countermeasures were adopted in different sites since the 1970s to control both the rock falls along the cliff and the earth flows at the valley bottom, such as, respectively, rock bolts and retaining walls (D’Ambra et al. 2004), none of them seeming to have been resolute.

Conclusions

The 27 February 2014 landslide is one of the numerous slope instability phenomena, which repeatedly affect the San Leo cliffs. Its geomorphic features are typical of Montefeltro area, where many villages are placed on the top of rock slabs overlying clay shales. This geologic conformation triggers a vicious circle, which can be described as follows: The clay shales, whose mechanical properties are poor (very low cohesion and residual friction angle around 12°), are involved in slow earth flows; the progressive retrogression of the earth flow scarps causes the undermining of the overlying rock walls; this process is furthermore worsened by piping erosion due to the percolation of water through the rock mass; once the toe is progressively removed, the rock cliff undergoes to sudden rock falls and topples; the rocky blocks act as an overburden on the underlying clays and landslide deposits contributing to increase the rate of movement of the earth flows; then, the process alimts itself continuously. Perhaps, the most important evidence from the present landslide seems that the control of the water infiltration through the rock joints and fractures in the upper slab—*reducing the lubrication of the joints surface and the softening of the basal clay shales*—could be the solution for the mitigation of rock falls and topples along the cliff face.

Finally, what is notable today is the temporal and spatial trend of the slope instability phenomena, which appear to be propagating from north to south in clockwise direction (2006 north face, 2014 northeast face). This poses a crucial question: if the trend continues, could the fortress be the next asset to be seriously threatened in the near future (Fig. 10)?

Acknowledgements

The authors thank the National Institute of Geophysics and Volcanology (INGV, Italy), which provided the seismic record of Mount Carpegna station (<http://ismd.mi.ingv.it/>). The support and encouragement by the municipal administration is also acknowledged. Finally, we thank the anonymous reviewers who provided useful insights, which improved the original manuscript.

References

- Allstadt K (2013) Extracting source characteristics and dynamics of the August 2010 Mount Meager landslide from broadband seismograms. *J Geophys Res* 118:1472–1490
- Benedetti G, Bernardi M, Borgatti L, Continelli F, Ghirotti M, Guerra C, Landuzzi A, Lucente CC, Marchi G (2011) San Leo: centuries of coexistence with landslides. In: Margottini C, Canuti P, Sassa K (eds) *Landslide science and practice*. Springer, Berlin, 6, pp 529–537
- Borchia R, Nesci O (2012) The invisible landscape. A fascinating hunt for the real landscapes of Piero della Francesca among Montefeltro Hills. In: *Il Lavoro Editoriale* (ed) Ancona, Italy 144p
- Caturani A, Ribacchi R, Tommasi P (1991) The San Leo Cliff (Italy): stability conditions and remedial measures. VII ISRM Int. Congr. on Rock Mechanics, Aachen, 2, pp 853–858
- Conti S, Tosatti G (1996) Tectonic vs gravitational processes affecting Ligurian and Epiligurian units in the Marecchia valley (Northern Apennines). *Mem Sci Geol* 48:107–142
- D'Ambra S, Giglio G, Lembo-Fazio A (2004) Interventi di sistemazione e stabilizzazione della Rupe di San Leo. 10° Congress INTERPRAEVENT 2004, Riva del Garda 2:IV/103-114
- Mann ME (2002) The Earth system: physical and chemical dimensions of global environmental change. In: MacCracken MC, Perry JS (eds) *Encyclopedia of global environmental change*. John Wiley & Sons, Ltd, Chichester, pp 504–509
- Piastra S, Landuzzi A, Cencini C (2005) Historical landslides (XVII–XIX centuries) from Romagna Apennines, Northern Italy. A cultural approach. 6th Int. Congress on Geomorphology, Zaragoza, Spain, 410p
- Ribacchi R, Tommasi P (1988) Preservation and protection of the historical town of San Leo (Italy). I.AEG Int. Symp. on Engineering Geology of Ancient Works, Monuments and Historical Sites, Athens, 1:55–64
- Sprefaico MC, Bacenetti M, Borgatti L, Cignetti M, Giardino M, Perotti L (2013) Structural analysis of San Leo (RN, Italy) east and north cliffs using 3D point clouds. *Rend Online Soc Geol Ital* 24:304–306

L. Borgatti · C. Guerra · A. Landuzzi · G. Benedetti · G. Marchi

Department of Civil, Chemical Environmental and Materials Engineering (DICAM), University of Bologna, Bologna, Italy

C. Guerra

ITS Associates, San Marino, Republic of San Marino

O. Nesci · R. W. Romeo (✉) · F. Veneri

Department of Earth, Life and Environment Sciences (DiTeVA), University of Urbino, Scientific Campus, 61029, Urbino, Italy
e-mail: roberto.romeo@uniurb.it

G. Benedetti · G. Marchi

ENSER Co., Faenza, Italy

C. C. Lucente

Technical Service of Romagna Basin, Emilia-Romagna Region, Rimini, Italy