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ONE OF THE HAZARDOUS NEIGHBOURS OF THE VAJONT LANDSLIDE: THE HISTORICAL M. SALTA ROCK-BLOCK SLIDE-ROCK FALL.

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ABSTRACT: In the Vajont Valley (north-eastern Alps), the everlasting interactions between endogenic (tectonic, seismic, isostatic) and exogenic (glacial, slope, anthropogenic) processes have resulted in a hazardous environment. The most striking geomorphological feature of the valley is the evidence of several landslide processes of different type, age, and size. The October 1963 catastrophic landslide is undoubtedly the most notorious one. However, the Pineda and Salta landslide events have left enduring signatures in the landscape of the valley. In particular, the wide landslide deposit upslope Casso, on the southern slope of M. Salta, derives from multiple overlapping events. Rock planar slides, topples, and rock falls occur since centuries, displaying a complex-composite style of activity. Nowadays, in this area, slope processes are still active and are threatening the village of Casso and the visitors of the 1963 disaster site.

Keywords: Complex historical landslide, kinematics, Vajont Valley, north-eastern Alps, Italy.

1. INTRODUCTION

The Vajont Valley, located in the Eastern Italian Alps in the buffer zone of the Dolomites UNESCO World Heritage Site, is a left-hand tributary of Piave Valley. It can be considered a typical Alpine valley displaying an assemblage of landforms and deposits originated mainly by glacial and fluvial processes. However, the most striking feature of the Vajont Valley is the diversity of landslide processes, in terms of types, sizes and ages. The valley has been prone to slope instability ever since, due to its geologic, tectonic and geomorphologic settings. Among the widespread active, inactive and dormant slope instability phenomena, the most relevant in terms of geomorphological risk, long-lasting evidence in the landscape and damage are the Salta, the Pineda and the Vajont landslides (Fig. 1, 2a). The most impressive one is certainly that related to the October 1963 catastrophic event (Rossato et al., 2020). Nevertheless, the southern Salta slope is still posing a residual risk to the downstream village of Casso. The main geomorphological features of these landslides are here briefly described, focusing on the Salta area for which some original geomorphological and historical data are provided.

2. GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

2.1. Geology

In the Vajont Valley the geological formations range in age from the Upper Triassic (Dolomia Principale) to the Middle Eocene (Flysch). The Erto basin is connected with the Tertiary formations outcropping in the core of the sinclyne: the steep slopes sourronding the valley are ascribed either to faults or mostly to hard rocks outrcopping in the syncline flanks. The local stratigraphic series is represented in the Legend of Fig. 2c. However, due to the presence of the M. Borgà Thrust (Fig. 2), in the section representative of the M. Salta landslide, only the following formations outcrop:

Scaglia Rossa (Upper Cretaceous-Lower Paleocene; ~300 m thick). It is a monotonous succession of marls and red marly limestones; the typical facies is completely lacking of resedimentation features.

Socchèr Limestone (Lower-Upper Cretaceous; 150 m thick). Alternation of microcrystalline limestones, calcarenites and bioclastic-intraclastic calcirudites with nodules and beds of chert.

Vajont Limestone (Dogger; 450 m thick). Oolitic calcarenites, massive or layered in thick beds, intercalated with decimetric layers of brown basinal micrites and intraformational breccias.

Igne Formation (Middle-Upper Lias; 0 - 150 m thick). Remarkable lithological heterogeneity, it consists of alternating marls and marly limestones, organic black shales, green and red nodular limestones.

Soverzene Formation (Lower-Middle Lias; 600 m thick). Monotonous succession of frequently dolomized grey or brown micrites, rhythmically alternating with centimetric layers of grey and yellow marls; black chert in nodules and beds.

Fig. 1 - View of the Vajont Valley seen from east, with its main landslide accumulations concentrated in a restricted area. Here, the landslides, and the geological bodies, can be viewed as elements of the Memory (Modified from Dolomiti Project srl).

2.2. Tectonics

The Vajont Valley follows the core of an Alpine Syncline (Erto Syncline) with an E-W to WNW-ESE trending axis (Riva et al., 1990) gently plunging towards the E. The Erto Syncline lies on the hanging wall of the Belluno Thrust, one of the main structures of the Venetian south-vergent Alps (Doglioni, 1992; Massironi et al., 2013) and it is paired with a frontal asymmetric structure, the Belluno Anticline. The northern limb of the Erto Syncline is reversed and stretched by the M. Borgà Thrust, an older thrust passively transported on the back of the Belluno Thrust. The regional M. Borgà Thrust

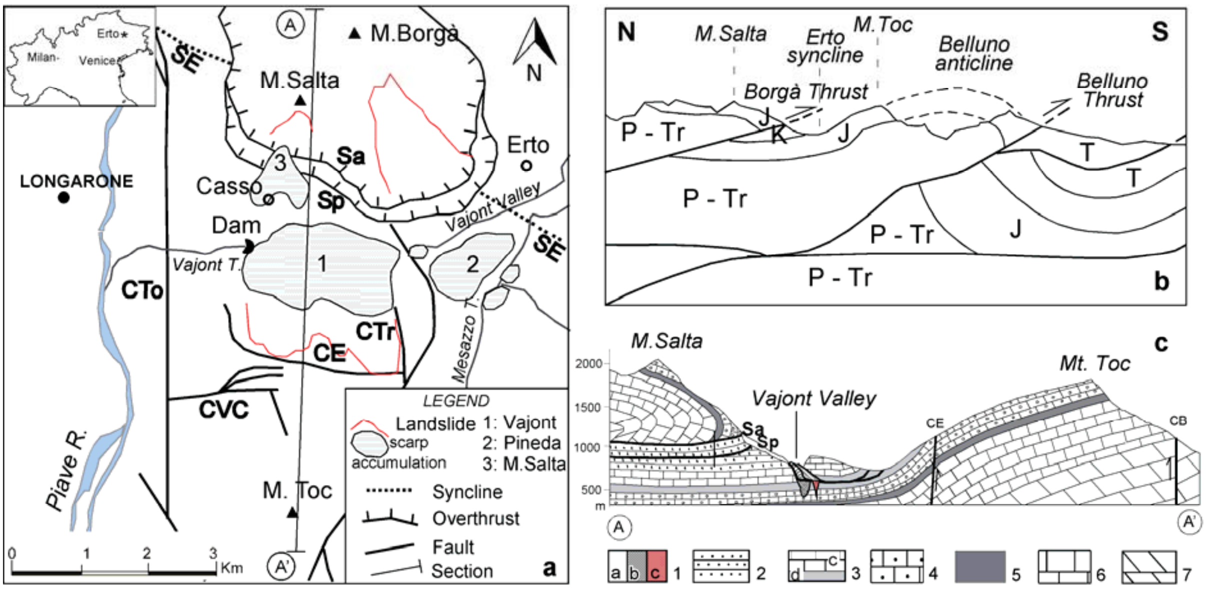

Fig. 2 - a) Tectonic map of the western part of the Vajont Valley and Vajont Valley landslides. Labels of symbols: CE: Col delle Erghene Fault; CTr: Col Tramontin Fault; Sa: M. Salta Overthrust; Sp: Le Spesse Overthrust; CVC: Costa Vasei- Calta Faults; CTo: Col delle Tosatte Fault; SE: Erto Syncline. b) Tectonic cross-section at a regional scale. Legend: P - Tr = Permian-Triassic; J = Jurassic; K = Cretaceous, T = Tertiary (modified after Doglioni, 1992); c) Geological section. 1a - Quaternary; 1b - fluvial gravels filling the Vajont epigenetic gorge; 1c - 1963 Vajont landslide deposit; 2 - Scaglia Rossa Fm. (Upper Cretaceous-Lower Paleocene); 3 - Cretaceous-Jurassic Fms. (Socchér Fm. sensu lato and coeval): 3c - Socchér Fm. sensu stricto, 3d - Ammonitico Rosso and Fonzaso Fms.; 4 - Vajont Limestone (Dogger); 5 - Igne Fm. (Upper Liassic); 6 - Soverzene Fm. (Lower and Middle Liassic); 7 - Dolomia Principale (Upper Triassic) (modified after Riva et al., 1990; Semenza & Ghirotti, 2000).

uplifts limestone Jurassic in age on top of the Scaglia Rossa Fm. The M. Borgà Thrust is limited to the east, south and west by the M. Salta Overthrust (**Sa** in Fig. 2), which separates the Jurassic formations of the thrust itself from the underlying Scaglia Rossa. The Le Spesse Overthrust (**Sp** in Fig.2) runs almost parallel to **Sa** and develops within the Scaglia Rossa unit for almost all its path. The tectonic element between these two lines has been interpreted as a reversed wedge of Scaglia Rossa, detached from the top of the series that was overtaken by the M. Borgà Thrust, and pushed forward during its motion.

2.3. Geomorphology

The main geomorphological feature of the Vajont Valley is the presence of several huge landslide deposits of different type, age and size, that will be described in the following sections. However, besides landslides, the valley is also rich in glacial and fluvial deposits and karst landforms (Pasuto, 2017). The glacial history of the region is poorly known, since related landforms have been dismantled by subsequent slope and karst processes, especially in Vajont Valley. During the Last Glacial Maximum (LGM), the hanging Vajont Valley was probably occupied by a local glacier merging into the main Piave Glacier. Afterwards, the valley has been dammed several times by landslides activated during or after deglaciation (Wolter et al., 2016). As a consequence, the Vajont Stream has been from time to time diverted northwards and southwards, probably cutting more than one persistent and deep epigenetic gorges prior to the catastrophic 1963 failure (Fig. 2c).

3. LANDSLIDE TYPES AND PROCESSES IN THE VAJONT VALLEY

3.1. The neighbouring landslides

The Vajont landslide (northern Italy) is one of the best known and most tragic examples of a natural disaster induced by human activity. The northern slope of M. Toc underwent nearly 3 years of intermittent, slow slope movements, beginning at the time of the first filling of the reservoir. On the 9th October 1963 at 22:39 local time, during the third reservoir emptying, a catastrophic landslide suddenly occurred on the southern slope of the Vajont dam reservoir and the whole mass collapsed into the reservoir itself. The failed mass (270 Mm^3 of rock) drove the water of the reservoir forward, giving rise to a wave, which overtopped the dam at a height of more than 100 m above the crest and hurtled down the Vajont gorge to the Piave Valley floor. The flood destroyed many villages and almost 2000 people lost their lives. The slide moved a 250 m thick mass of rock some 300 to 400 m horizontally with an estimated velocity of 20 to 30 m/s, before running up and stopping against the opposite side of the Vajont Valley. At present, the area affected by the 1963 landslide is subject to environmental and town planning restraints. Numerous initiatives have been carried out in order to keeping the memory of the catastrophic disaster alive (Rossato et al., 2020).

The pre-historic Pineda landslide, similarly to the Vajont landslide, has had a large impact on the morphology of the valley (Pasuto, 2017; Ghirotti et al., 2013). It has detached from the steep, bare slope on the north of M. Borgà (Fig. 2a). It can be defined as a translational landslide (Dykes et al., 2013) which turned into a rock avalanche (Esposito et al., 2015). The sliding surface is visible on the right side of the valley along a footpath that connects the villages of Casso and Erto, while the large accumulation is located at the base of the opposite slope. The landslide would have dammed the Vajont River and Mesazzo Stream, with implications for river course, erosion of the landslide dam, and evolution of the valley geomorphology (Esposito et al., 2015; Wolter et al., 2016). The source area is currently characterized by a debris cover which is often involved in debris flow phenomena. The Pineda landslide overlaps a delta sequence (topset, foreset, bottomset) of glaciofluvial origin, allowing its preservation. This delta entered an extinct glacial lake, as witnessed by laminite sequences with drop-stones. A diamictite, hypothesized to be a glacial till, locally covers the Pineda landslide body (Masè et al., 2004; Ghirotti et al., 2013). This would point to a pre-LGM age for the Pineda event.

3.2. The Salta landslides

The Salta area is located on the northern slope of the Vajont Valley. Active slope processes are severely threatening the small village of Casso, where some tens of people live. Rock and debris falls originating from the uppermost part of the southern slope of M. Salta, at an elevation of about 1500 m a.s.l., can be considered the most hazardous slope process still active in the valley. In the 1960s, large boulders reached the secondary road connecting the village of Casso to Regional Road 251. Since 1990, minor rock falls have been repeatedly reported on the same slope. The most recent rock fall event occurred in 2001, when five blocks detached at 1050 m a.s.l from the Scaglia Rossa Fm. cropping out above the village of Casso, fell for about 300 m and reached the outskirts of the village (Tagliavini et al., 2009). The steep accumulation of the Salta landslides covers a total area of about 250,000 m^2 stretching between 1250 and 850 m a.s.l. and has a volume of approximately 2.5 Mm^3. It is composed by abundant huge blocks, which can reach a volume of some hundreds of cubic meters. Marcato et al. (2007) based on the distribution of the blocks and their dimensions, suggest that the kinematics of major past events in the southern M. Salta slope can be described as rock avalanches (Evans & Hungr, 1993). Recently, a quarry has been opened east of Casso to exploit the debris materials for construction purposes- to set up a retaining zone to protect the village. Apart the most recent events, the wide landslide deposit upslope Casso appears to be the result of multiple overlapping events, but only one of these can be dated. In a written document dating back to 1688 a landslide event occurred 14 years before is referred to. Therefore, it can be dated back to 1674. Moreover, in a historical map dating back to 1747 found in the archive of Casso church, the two branches of the deposits are clearly visible (Fig. 3): one is called "*motta prima de sassi cascata dalla Croda di Salta*" (first landslide composed by stones fallen from the M. Salta), the other "*motta seconda*" (second landslide). The main scarp is

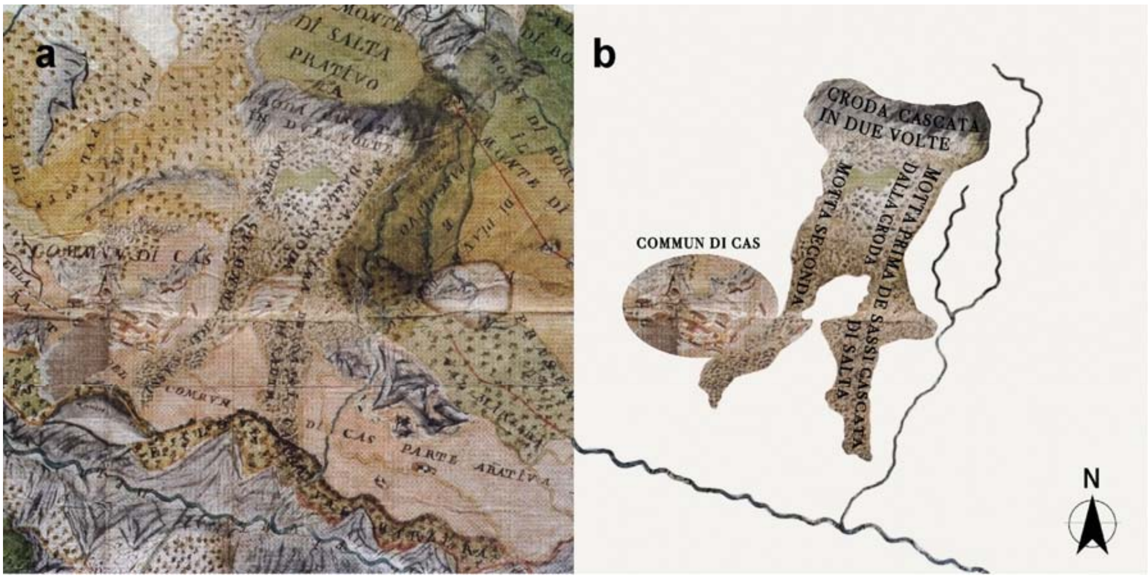

Fig. 3 - a) Historical map of the southern slope of M. Salta dating back to 1747; b) contour of the landslide body and crown areas.

labelled as “*Croda cascata in due volte*”, that is scarp fallen in two different moments. It can be deduced that two different events have occurred, spreading from East to West. The scarp and the accumulation zone of the 1674 event are still evident. The depicted deposit reaches the lower sector of the slope, as it can be observed even nowadays, with two distinct lobes which reach downwards altitudes between 950 and 800 m a.s.l. (Fig. 4). Two minor rock fall deposits, related to small scarps outcropping just north of Casso, are not represented in the historical map, meaning that they could have fallen after 1747 or that they were too small to be mapped.

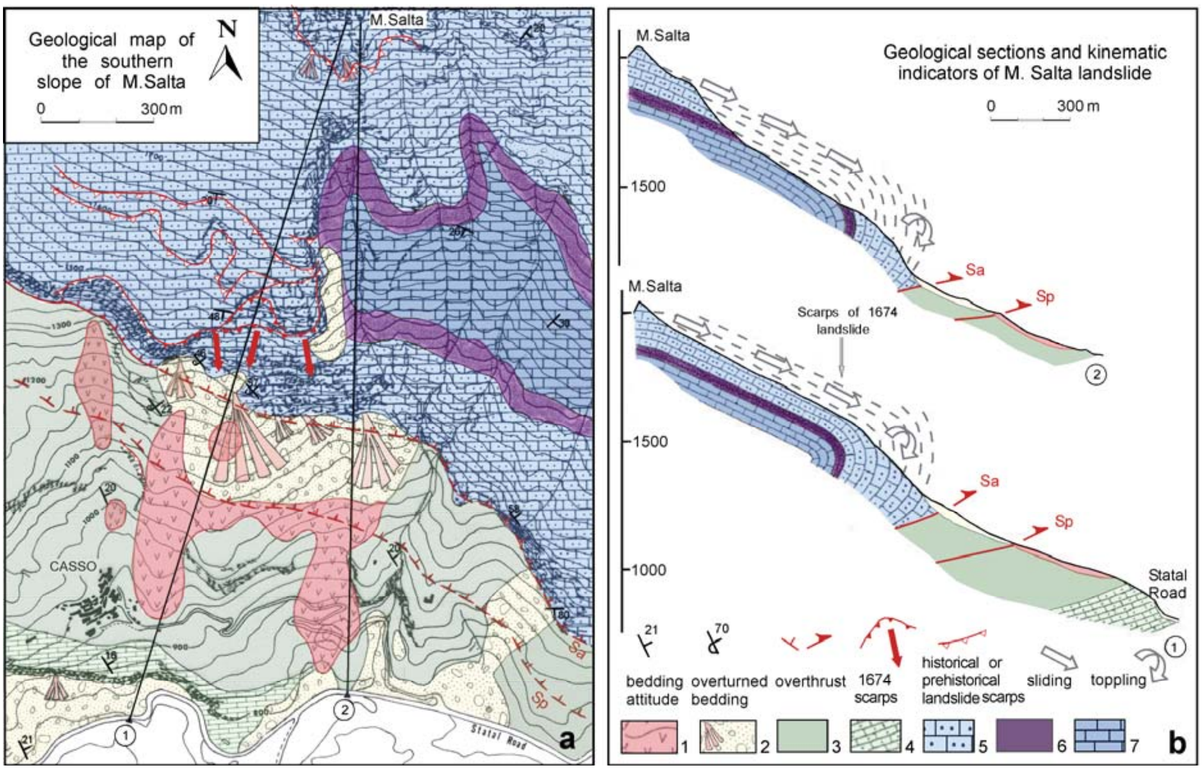

Fig. 4 - a) Geological map of the southern slope of M. Salta; b) geological sections and kinematic indicators of M. Salta landslides. Legend: 1 - M. Salta landslide deposits; 2 - undifferentiated Quaternary deposits; 3 - Scaglia Rossa Fm.; 4 - Socchèr Limestone Fm.; 5 - Vajont Limestone Fm.; 6 - Igne Fm.; 7 - Soverzene Fm.

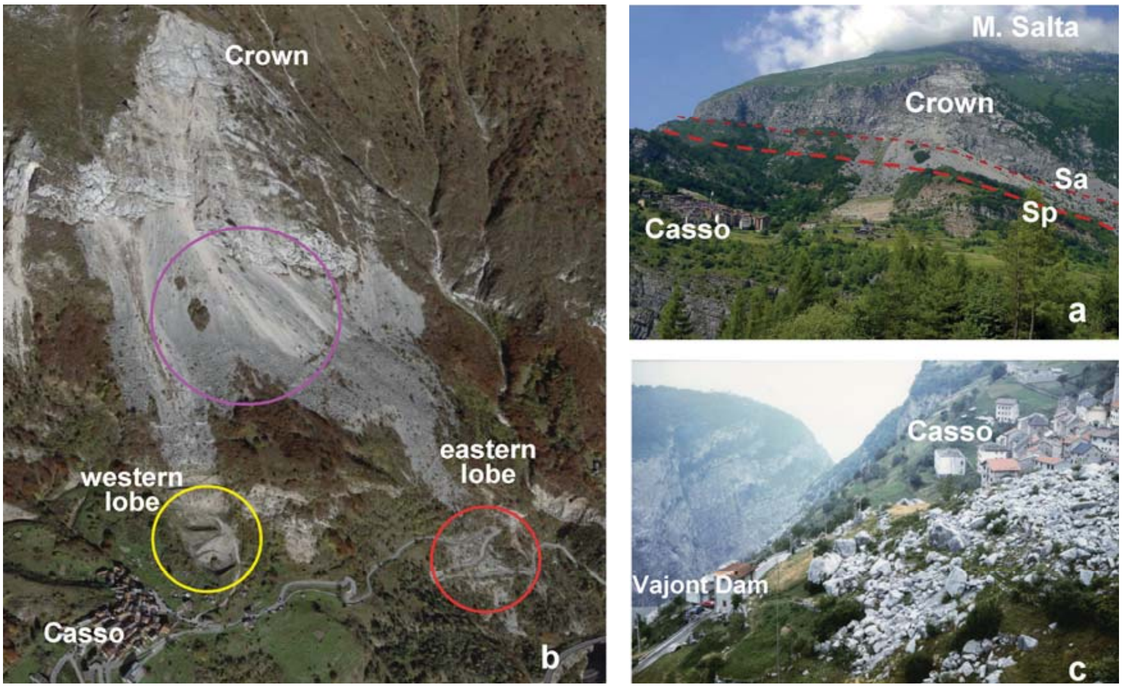

Fig. 5 - a) View of the 1674 M. Salta landslide, from South: Sa M. Salta overthrust; Sp Le Spesse overthrust; b) aerial view of the main geomorphological features of the landslide: the yellow circle indicates the toe of the western lobe, at present exploited by quarrying activity; the red circle shows the eastern lobe which affects the road connecting Casso to the Vajont Valley; in the purple circle active slope deposits cover the central part of the 1674 landslide body (Google Earth); c) picture of the toe of the western lobe taken in '80s, before the opening of the quarry: the blocks are heterometric, angular, subangular, and monolithologic (Vajont Limestone Fm.)

The geomorphological evolution of the slope appears to be mostly driven by the structural setting. In particular, the M. Borgà thrust is certainly the main conditioning structural element that has led to the weakening of the rock mass and has driven the subsequent slope failure (Fig. 4). The emplacement of the thrust has sheared the rock and has induced intensive and pervasive brittle fracturing processes (Stead et al., 2019).

Above the thrust zone, folded and faulted bedding planes dip steeply towards the slope free face, predisposing the rock mass to failure (Fig. 4). In particular, in the upper part of the slope (2050-1700 m a.s.l.) the Vajont limestones dip 30° downslope, whereas in the middle part (1700-1525 m a.s.l.) the slope is still homoclinal, but the dip increases up to 45°. In the lowermost part of the slope, the bedding is dipping into the slope.

The slope is characterized by the presence of different structural and landslide scarps, distributed along tectonic discontinuities. More in detail, the first series of scarps is located around 2000 m a.s.l. and it is supposed to be the remnant of even older events of the same type and style of activity as of the 1674 event.

From 1700 to 1425 m a.s.l. four orders of scarps can be found, and the latter corresponds to the crown of the 1674 landslide (Fig. 4a). It displays a semicircular shape and is delimited by steep walls, several meters high, carved in the Vajont Limestone Formation. Downslope, several minor scarps follow the strike of the bedding (from WNW-ESE to EW). The scarp located around 1430 m a.s.l. limits a recent landslide scarp to the south.

The main scarp of the 1647 landslide is characterized by a series of steps forming three orders of vertical scarps reaching 20-30 m height, merging in a single irregular scarp along the western flank of the landslide crown. The historical landslide accumulation covers an area of about 160,000 m^2, with a length of about 800 m and an estimated volume in the order of 1,5 Mm^3. Its head lies at about 300 m from the lowermost scarp and is composed by huge blocks up to 840 m^3 volume.

The blocks have a prismatic to cubic shape and the farthest one has reached 750 m a.s.l. At places, the landslide deposit is covered by slope deposits due to erosional processes following the XVII century event. A relatively small and recent landslide deposit is in turn covering the scree slope around 1150 m a.s.l., witnessing ongoing slope instability processes (Fig. 5).

The 1674 landslide might have displayed a complex style of activity. The movement started as a rock block slide in the homoclinal slope evolving in a rock toppling at the front of the overthrust, where the bedding planes are sub-vertical (Fig 4b, section 1). The movement continued along the slope as a rockfall. The same kinematics can be hypothesized also for landslides occurring in other sectors of the southern slope of M. Salta in historical or prehistorical times (Fig. 2b, section 2).

The scarps of the minor westernmost landslides are characterized by a stepped morphology. The main movement appears to be by toppling, followed by slides and falls. The maximum volume of the blocks is of about 70 m^3. These landslide events are supposed to be more recent since their body is not covered by any slope de-

Fig. 6 - a) General view of the main scarp of M. Salta landslide (red arrows mark the location of trenches and the extensometric net); b) a trench, more than 10 m wide and several tens of meters deep; c) outcrop of the Vajont Limestone Fm. Forming the main scarp at 1575 m a.s.l. in correspondence with the sliding surface; d) isolated rock wedges at critical stability condition, located at the eastern part of the main scarp. (Figures 6a, c and d courtesy of CNR-IRPI PD).

posits.

At the moment, the most hazardous sector appears to be the main scarp and its surroundings, along with the steep debris accumulation (Fig. 5b and 6a). This area stretches from 1250 m a.s.l. to 1475 m a.s.l. It displays a steep and rugged morphology, developed in an intensely fractured rock mass. Field surveys have revealed unstable rock blocks with volumes exceeding 1,000 m^3. These blocks are separated by fractures up to 2 m wide and 10-15 m deep (Fig. 6d). The shape of the scarp itself is due to the intersection of four joint sets: the main one is parallel to the bedding, and the secondary one is almost perpendicular to it. Here, huge blocks (volume in the order of 300 m^3) are isolated from the rest of the slope and have already undergone a back-tilting movement along the bedding plane (Fig. 6b). It is evident that those blocks represent a threat for the village of Casso (Fig. 6c).

A monitoring system, based on extensometers placed across some large and open fractures located north-west of the 1674 crown between 1500 and 1600 m a.s.l., provided data about their opening and closing trends for a few years (Ghirotti, 1995). Unfortunately, the monitoring system is presently out of order.

Being this region active from the seismic point of view, the effect of seismic acceleration on the stability of the rocky scarps and of the debris has been addressed. The results of numerical modelling (Marcato et al., 2007; Tagliavini et al., 2009) show that the village of Casso and the road could still be affected by rock falls detaching from the scarps and/or by remobilisation of debris deposits. The modelled scenarios could in principle be used for functional countermeasure works design and civil protection plans. For instance, as suggested by Marcato et al. (2007), a realistic mitigation of the residual risk posed to the village of Casso could foresee the continuation and progressive enlargement of the quarrying activity, in order to create a zone that could contain the debris possibly remobilised in case of co-seismic landslide events.

4. CONCLUSIONS

The Vajont Valley is a tectonically and geomorphologically active area, where many large mass movements have occurred in the recent and distant past. The instability of the M. Salta southern slope is certainly driven by the peculiar geologic and tectonic structure and in particular by the presence of a heavily fractured bedrock in the frontal band of the local thrust (Benko & Stead, 1998; Stead & Wolter, 2015). Other factors have played a role in the progressive decay of the frictional strengths of the joint surfaces, like alpine climate and climate changes and related erosional processes, groundwater flow and karst dissolution, along with seismicity. Glacial erosion and possible debuttressing have weakened the rock masses and changed stresses in the slope by unloading. The influence of past and current seismicity is not known, in terms of major co-seismic events, as only relatively small rock falls events have been recorded. Nevertheless, earthquakes may have affected the strength of steep and fractured rock slopes. In conclusion, the combination of individual predisposing factors appears to be more relevant than specific triggers in driving slope processes affecting the M. Salta southern slope.

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