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LANDSLIDES OF THE WESTERN DOLOMITES: CASE STUDIES FROM THE ADIGE AND SARCA VALLEYS (NE ITALY).

Silvana Martin [1], Susan Ivy-Ochs [2,3], Alfio Viganò [4], Paolo Campedel [4], Manuel Rigo [1,5], Christof Vockenhuber [3], Fabio Gabrieli [6], Volkmar Mair [7], Sandro Rossato [5]

[1] Department of Geosciences, University of Padova, Padova, Italy.
[2] Department of Earth Sciences, ETH Zürich, Zürich, Switzerland.
[3] Laboratory of Ion Beam Physics, ETH Hönggerberg, Zürich, Switzerland.
[4] Servizio Geologico, Provincia autonoma di Trento, Trento, Italy.
[5] Institute of Geosciences and Earth Resources, National Research Council of Italy, Padova, Italy.
[6] Department of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy.
[7] Ufficio geologia e prove materiali, Provincia autonoma di Bolzano, Cardano (BZ), Italy.

Corresponding author: S. Rossato <sandro.rossato@igg.cnr.it>

ABSTRACT: The Lavini di Marco, Marocche di Dro and Molveno rock avalanches in Trentino, and the Termeno landslide in South Tyrol are here presented as case studies for the western Dolomites (Adige and Sarca Valleys, NE Italy). Their structural predisposition, run-out and timing are discussed, also in consideration of other evidence for the Alpine region. The detailed geomorphological mapping of deposits and their release area, combined with regional and local structural analysis, isotopic dating, and numerical modelling, have led to updated interpretations of their mechanisms, timing, and triggering/driving forces. In particular, the major role of structural controls is investigated. Intense rock damage and rock fatigue, which are related to tectonic activity along the Southern Giudicarie and Schio-Vicenza fault systems, together with high topographic relief energy and local dip slope, all combine to promote detachment of huge rock volumes. Besides structural predisposition, other factors like glacial erosion/unloading and climate can exert a primary control.
Three large rock avalanches occurred between 5-3 ka ago: Lavini di Marco (200 Mm^3, 3.0±0.4 ka), Marocca Principale (1000 Mm^3, 5.3 ±0.9 ka) belonging to the Marocche di Dro complex, and Molveno (600 Mm^3, 4.8±0.5 ka). This period has been recognized as one of enhanced slope failure activity in the Alps, perhaps related to the climatic transition to cooler and wetter conditions at the beginning of the late Holocene. This is particularly valid for the close contemporaneity of the Marocca Principale and Molveno rock avalanches. Conversely, younger ages at the Kas rock avalanche (Marocche di Dro complex; 300 Mm^3, 1.1±0.2 ka) likely imply a close relation with seismic forcing.

Keywords: Landslides, rock avalanches, geomorphological mapping, tectonics, cosmogenic nuclide dating.

1. INTRODUCTION

The large landslides of the western Dolomites are mostly distributed along a narrow area stretching from the northern edge of Lake Garda to the Brenta Dolomites, between the Sarca and Adige Valleys (Fig. 1). These two valleys are adjacent to each other, running north-south across the Southern Alps. Pleistocene glaciations shaped their landscape entrenching deep glacial troughs and promoting rock instability on their steep flanks. Here, many slope failures are developed within the Mesozoic sedimentary successions, especially Jurassic limestones.

The Alps and the Trentino region are characterized by numerous post-glacial gravitational events (e.g., Taramelli, 1881; Penck & Brückner, 1909; Fuganti, 1969; Perna, 1974; Soldati et al., 2006), which have been interpreted as due to different causes, as climate and seismicity. In fact, strong tectonic events could have triggered landslides during the middle Holocene (Ambrosi & Crosta, 2006; Prager et al., 2008). The large landslide deposits of the Southern Alps mostly made of big boulders were called "Marocche". The name “Marocca” derives from “Mar”, which means stone. Perna & Sauro (1978) pointed out that this term was used to refer to a landslide that fell onto a glacier, which also transported and deposited the landslide debris.

These deposits are often impressive, as the Marocche di Dro in the Sarca Valley, and are interpreted as rock avalanche deposits (e.g., Ivy-Ochs et al., 2017b). According to various authors, a rock avalanche is defined as a large (volume >1 Mm^3) and very rapid (>40 m/s) rock mass where debris shows turbulent flow and is sometimes channelized (Heim, 1932; Hungr et al., 2014;

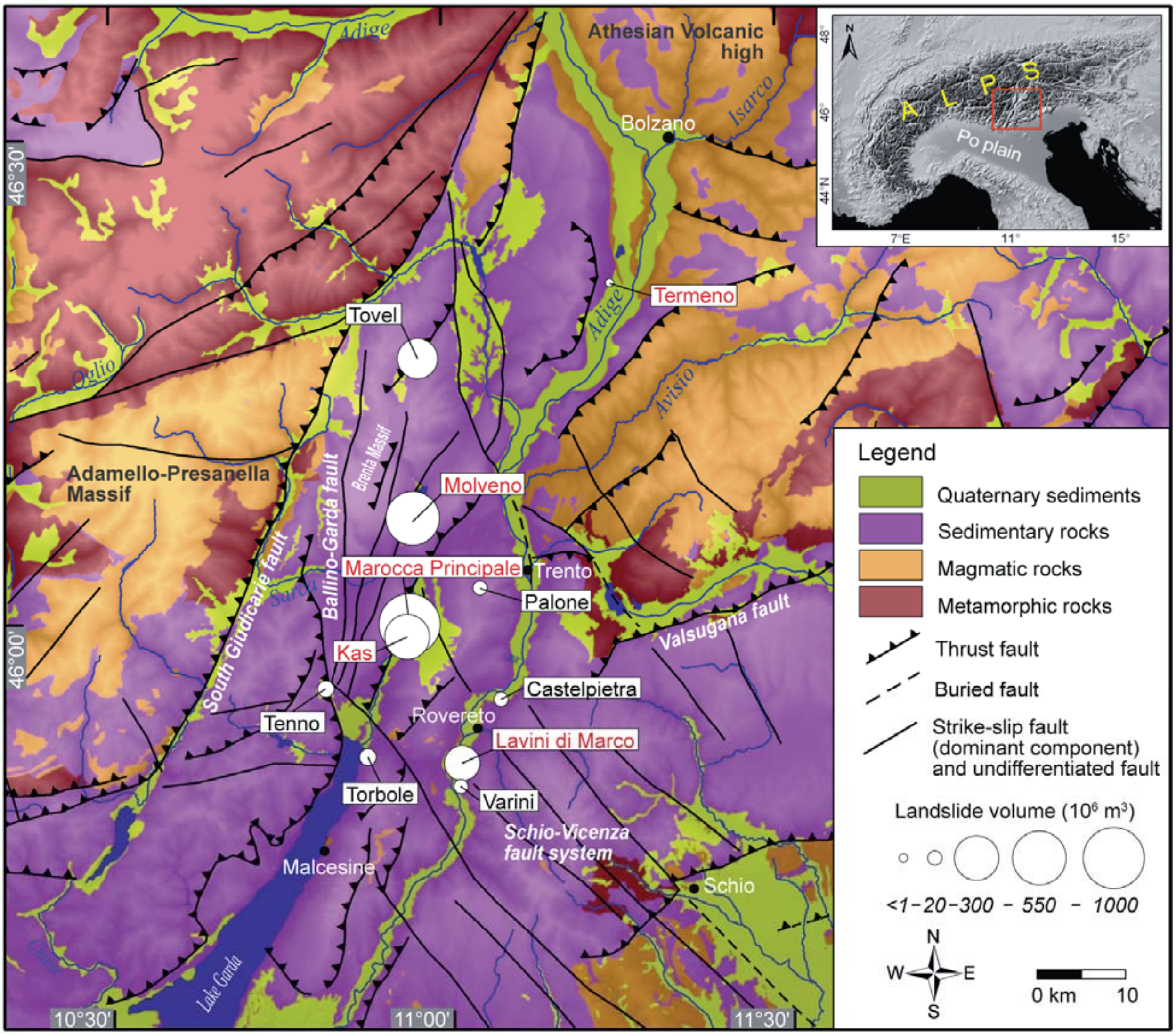

Fig. 1 - Simplified geological map of the Sarca and Adige Valleys (data from the Geological Survey of Trento, CARG project database). Circle size is proportional to landslide volume (modified from Ivy Ochs et al., 2017b; Elsevier used with permission). The Tovel deposits, with an estimated total volume of 300 Mm^3 (Oetheimer, 1989) and shown as a single circle, are due to multiple events. The names of the landslides studied in this work are in red.

Aaron & Hungr, 2016).

Here we present four landslide cases in the western Dolomites (Trentino & South Tyrol). Lavini di Marco and Termeno are in the Adige Valley, while Marocche di Dro and Molveno are located between Lake Garda and the Brenta Dolomites. The aim is to reexamine and discuss some data from literature, regarding the rock avalanches of this region, and to present original data on the Termeno rockfall study. The landslides discussed in this paper have been also presented in the framework of the sites visited in Trentino/South Tyrol during the Summer School on “Historic and prehistoric landslides in the NE Italian Alps - Implications for new hazard maps in mountainous areas”, hosted by the University of Padua in 2019. The other sites of the Veneto region visited during the summer school are presented in a companion paper of this volume (Rossato et al., 2020b).

2. LANDSLIDES OF THE WESTERN DOLOMITES

The map of Figure 1 shows the distribution of the largest landslide deposits of the western Dolomites. The Adige Valley includes, among others, the Lavini di Marco (200 Mm^3; Martin et al., 2014), Castelpietra (6 Mm^3; Ivy-Ochs et al., 2017a) and Termeno (related to several rockfall events) landslide deposits. The adjacent Sarca Valley and the Brenta Dolomites include the Marocche di Dro (>1300 Mm^3; Ivy-Ochs et al., 2017b), Molveno (600 Mm^3; von Wartburg et al., 2020) and Tovel (related to several landslide events with total volume of 300 Mm^3; Oetheimer, 1989) rock avalanche deposits.

The famous Lavini di Marco rock avalanche deposit is located near Rovereto, in the middle reach of the Adige Valley. It was mentioned by Dante Alighieri in the *Divina Commedia* (Alighieri, 1314) and was also studied

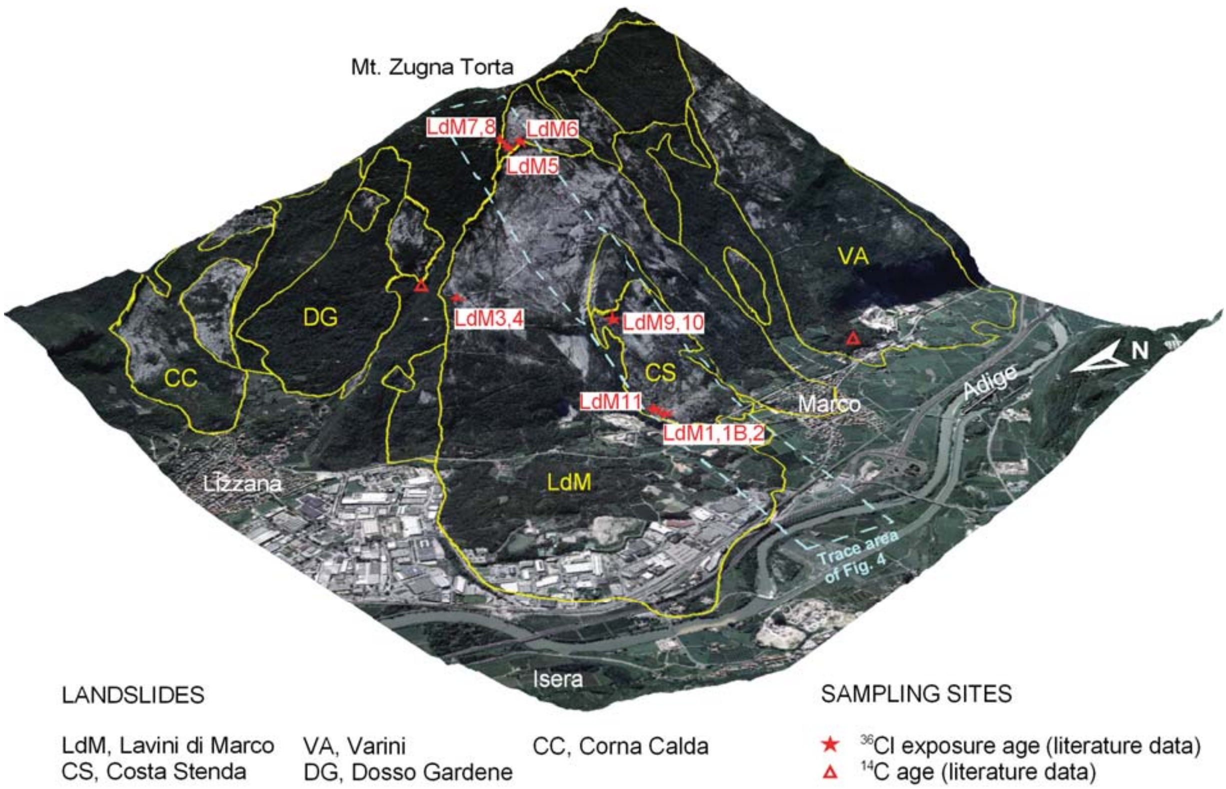

Fig. 2 - Landslide scarps and deposits along the western slope of Mt. Zugna Torta (from Martin et al. 2014; Elsevier used with permission). Stars mark the ^{36}Cl dated samples for Lavini di Marco (LdM) and Costa Stenda (CS). Red triangles mark sites of ^{14}C-dated samples (Orombelli & Sauro, 1988) (cf. Fig. 5).

by many naturalists in the XIX century (Noriller, 1871; Penck, 1886). The Termeno landslide is an historical event, located a few kilometers south of Bolzano, on the right side of the Adige River. It is characterized by isolated gigantic boulders (up to hundreds of cubic meters in volume) detached from the rock walls overhanging the Gewürztraminer vineyards. Between Lake Garda and the Brenta Dolomites, the Marocche di Dro and Molveno rock avalanche deposits are located within the Southern Giudicarie tectonic realm and have been studied for more than one century (Lepsius, 1878; Damian, 1890; Trener, 1924; Abele, 1974; Perna, 1974; 1975).

These rock failures are located close to the seismically active faults of the NNE-trending Southern Giudicarie and the NW-trending Schio-Vicenza fault systems, or at the junction of them (Castellarin et al., 2005; Viganò et al., 2015; 2018). The asymmetric valley configuration is generally characterized by west-dipping bedding planes on eastern valley slopes and tectonic scarps on the western ones. These are due to the regional setting of the Giudicarie fault system, which is also responsible of the NNE-trending synclines hosting Lake Garda, the Sarca Valley and the Molveno lake. The Lavini di Marco, Marocche di Dro and Molveno rock avalanches, as others in the Alpine region, were previously ascribed to stress release following downwasting of glaciers at the end of the Last Glacial Maximum, and were thought to have occurred between 18,000 and 12,000 years ago. However, these rock avalanches were much more recent, as shown by isotopic dating, historical records and updated geomorphological observations (Martin et al., 2014; Carton, 2017; Ivy-Ochs et al., 2017b; Rossato et al., 2020a; von Wartburg et al., 2020).

3. ROCK AVALANCHES AND ROCKFALLS OF THE ADIGE VALLEY

3.1 Lavini di Marco

The Lavini di Marco rock avalanche deposits consist of the main Lavini di Marco (LdM in Fig. 2) and the minor Costa Stenda deposits (CS in Fig. 2), separated by the Costa Stenda ridge. Other deposits are located on the same flank of the Mt. Zugna Torta (CC, DG, VA in Fig. 2). These two principal deposits cover a total area of 4.2 km^2, with a length of about 4.8 km and a width of about 1.8 km, yielding an estimated volume of 200 Mm^3 (Martin et al., 2014). Deposits are located between the Adige plain (at 170 m a.s.l.) and the head scarp (at 1260 m a.s.l.; Fig. 3). Based on an estimated run-out distance of ~4.8 km, Abele (1974) calculated a *fahrböschung* angle of 12°. The rock avalanche involved Jurassic carbonate rocks of the Calcari Grigi Group, including the Monte Zugna, Loppio and Rotzo Formations (see stratigraphic column in Fig. 4). Detachment occurred on dip-slope bedding planes, cut across by NW-trending faults belonging to the Schio-Vicenza system which (Fig. 4).

Combination of field survey, remote imagery analy-

Fig. 3 - The sliding surface and the 30 m-high head scarp of Lavini di Marco (photo by G. Griesmeier, 2019). The site is located near the LdM5 sampling site (cf. Fig. 2).

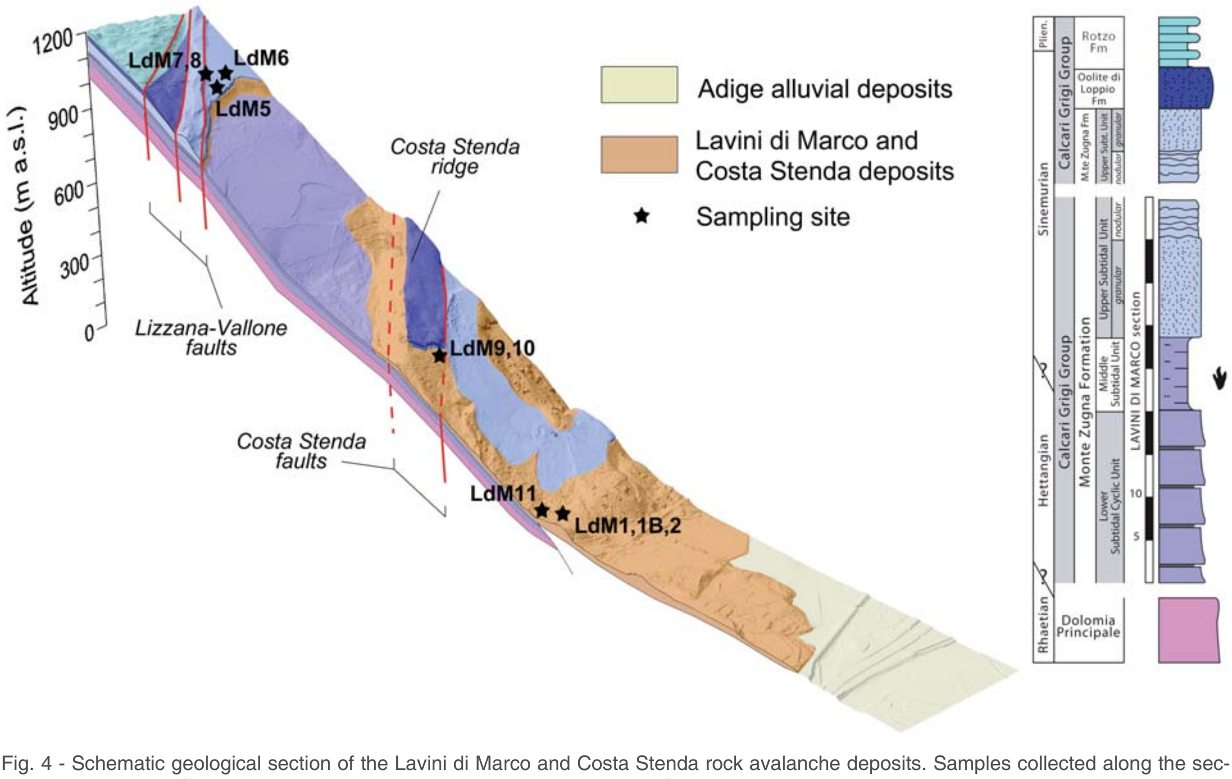

Fig. 4 - Schematic geological section of the Lavini di Marco and Costa Stenda rock avalanche deposits. Samples collected along the section are also shown (from Martin et al., 2014; Elsevier used with permission).

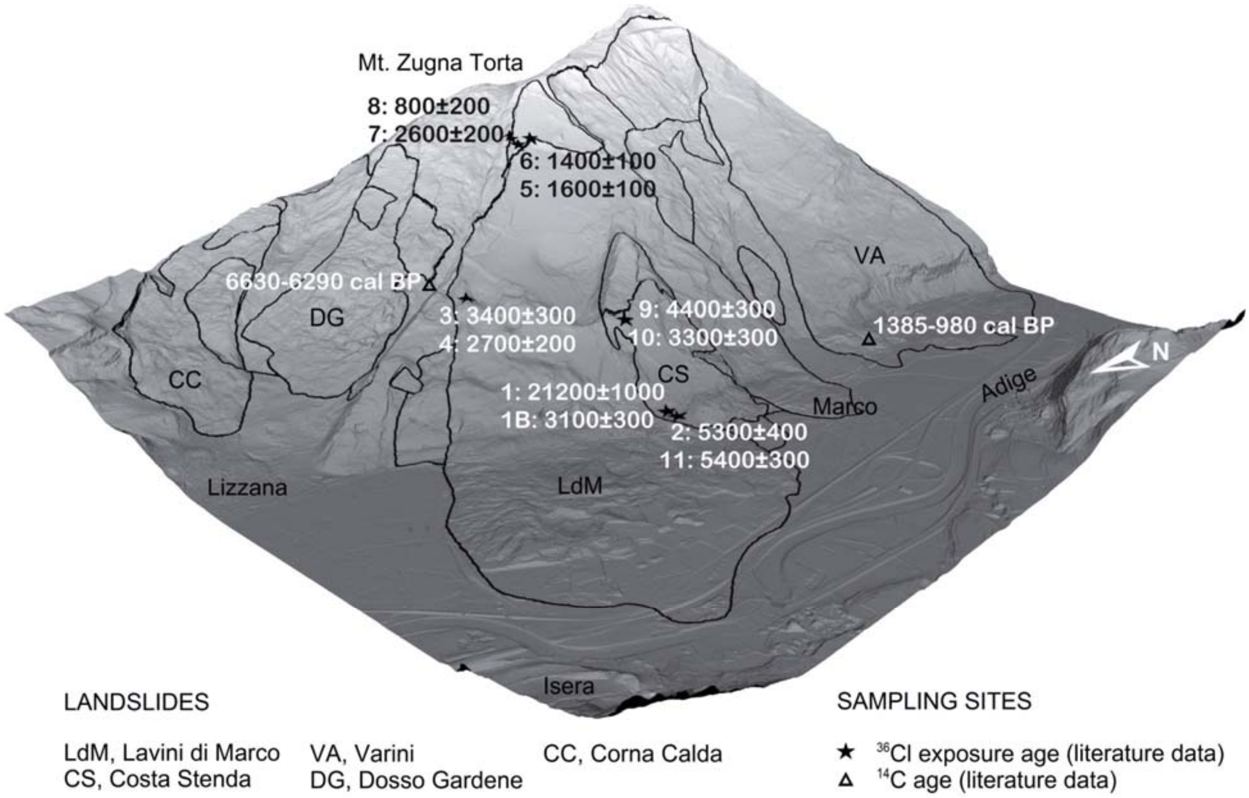

Fig. 5 - Distribution of ^{36}Cl exposure ages (stars) for the Lavini di Marco and Costa Stenda rock avalanche deposits (sample number: age ± uncertainty) (from Martin et al., 2014; Elsevier used with permission). Radiocarbon sites and calibrated ^{14}C ages (triangles) from Orombelli & Sauro (1988) (cf. Fig. 2).

sis, and ^{36}Cl surface exposure dating allowed to interpret the Lavini di Marco deposits (Martin et al., 2014). The main release scarp extends from the town of Marco up to Mt. Zugna Torta, structurally controlled by the Lizzana-Vallone fault (Fig. 4). Clear bedding planes (about 20° to NW) acted as sliding planes (Fig. 4). Upon release, the Lavini di Marco debris spread out on the Adige River flood plain and accumulated deposits with a marked concentric outer ridge made of Monte Zugna limestone, pushing the Adige River to the western side of the valley (Fig. 2).

The ages obtained by dating the Lavini di Marco and Costa Stenda boulders cluster around 3,000 years before present (Fig. 5). The two failures occurred almost simultaneously, giving a final age of 3.0 ±0.4 ka (Martin et al., 2014). Cosmogenic ^{36}Cl data show later failures at the head scarp during the Middle Ages (0.8 ±0.2 ka; samples 7 and 8 in Fig. 5). Published radiocarbon ages give a middle Holocene age for the Dosso Gardene landslide (Orombelli & Sauro, 1988; DG in Fig. 5). Moreover, radiocarbon ages for the Varini landslide event are broadly coincident with the younger ages of Lavini di Marco (Orombelli & Sauro, 1988; VA in Fig. 5). These events seem to overlap in time with a catastrophic flood event of the Adige River in Verona in 883 AD.

In the lower part of the Lavini di Marco sliding surface, strata are buckle folded due to gravity (Martin et al., 2014), pushing to a monitoring of the Monte Zugna Torta slope since the 1990s (Tommasi et al., 2009). Before monitoring started, deformations were believed to be no longer active. This conviction having been strengthened by the high safety factors provided by limit equilibrium analyses (Tommasi et al., 2009). SAR satellite interferometry performed in the period 1990-2002 and probe inclinometer measures showed a very slow sliding of the slabs located uphill of the buckle folds. To strengthen this observation, buckling was back-analyzed using Distinct Element Method (DEM) and Discontinuous Deformation Analysis (DDA), and determining rock mass structure, strength and stiffness by extensive in-situ (core logging, geophysical surveys) and laboratory investigations (geotechnical tests). The studies confirmed that buckling deformations are definitely possible, in the presence of water pressure and minor flexures, suggesting that buckling deformation may evolve into failures and should therefore be considered in evaluating the long term slope stability.

3.2 Termeno

The Termeno case study shows an example of monitoring a steep scarp with big boulders rockfall. The site affected by the landslide (Freisinger Hof) is located between Cortaccia and Termeno along the right slope of the Adige Valley (Fig. 1). Here, the mountain slope rises from the valley bottom (214 m a.s.l.) up to the Mendola ridge (1800-2100 m a.s.l.). The bedrock is composed of

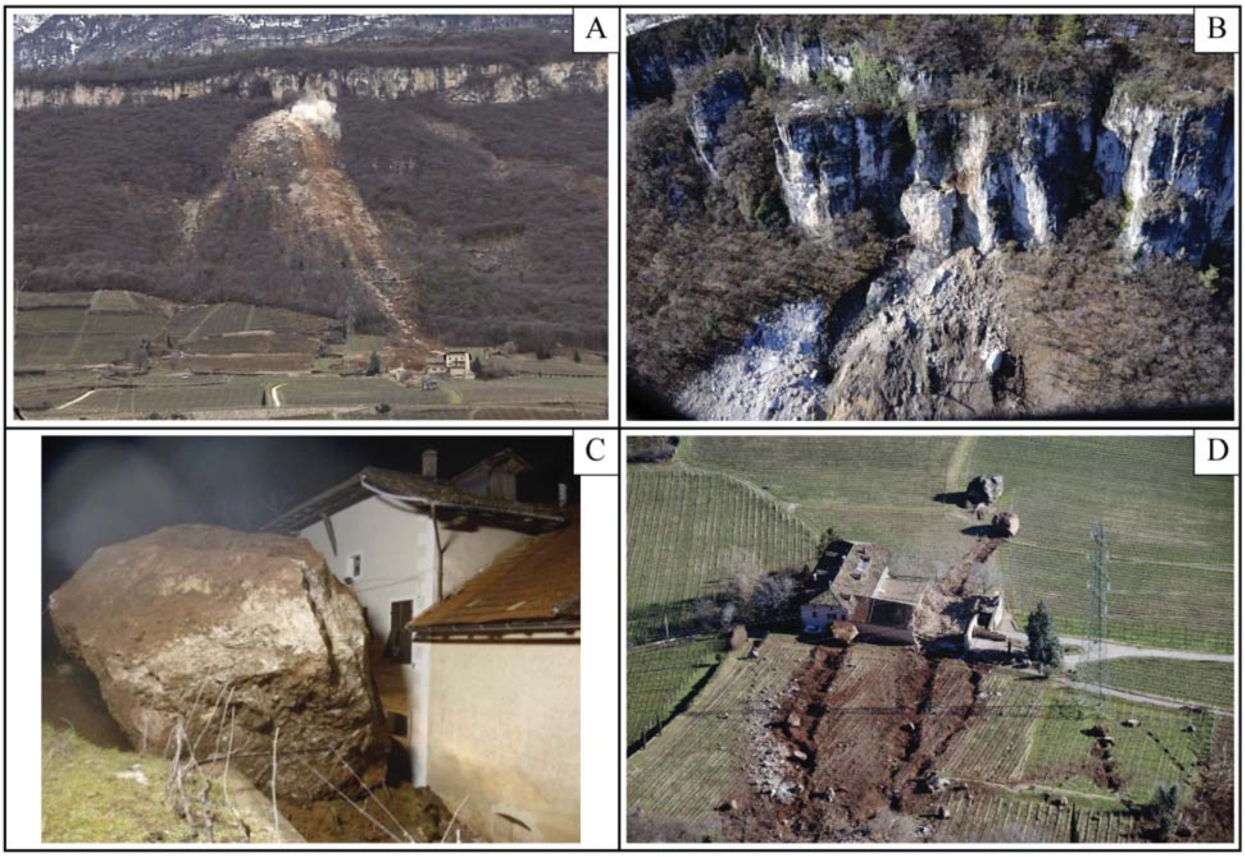

Fig. 6 - A) The rockfall in Termeno (Freisinger Hof), occurred on 21st January 2014. B) The niche composed of Contrin limestone, with remnants of hanging rocks before blasting. C) Final position of a huge boulder, very close to the house. D) Freisinger Hof and the deep grooves made by rockfall boulders.

carbonate rocks and clastic sediments belonging to Permo-Triassic sequences (Avanzini et al., 2012). Uphill of Cortaccia-Termeno there is a 100 m-high vertical steep wall (Fig. 6). Here, the dolomitized limestone of the Contrin Formation shows almost horizontal bedding, which is cut across by pervasive orthogonal fractures. At their base, the presence of silty and clayey metapelites of the Giovo Formation is responsible for the formation of large carbonate towers and pinnacles over the clay layer. This configuration, reported also for other nearby sectors along the Adige Valley right side (Avanzini et al., 2012), is responsible for systematically falling down cubic rock bodies and, in some cases, for toppling rock towers (several meters in diameter, volume up to 400 m^3). For this reason, this area is one of the best examples to reconstruct and understand these types of processes.

One of these events, which occurred on 21st January 2014 (at hour 23:56), is well documented by the Geological Survey of South Tyrol (Fig. 6). The area, evacuated during the night, was later examined by helicopter and photographically documented, to plan all the security measures. Then, yard and power poles were protected by artificial walls, and the remaining portion of the rock tower was blasted. At the same time, a detailed orthophoto map and a digital elevation model of the rockfall area were performed. Special attention was paid to map trajectories of the blocks ejected during blasting (Fig. 7). These observations were used for a detailed back analysis, testing, and calibrating different rockfall simulations (Fig. 8). Notably, there was a good agreement between observations and numerical results, not only on the trajectories, but also on the jump distances and heights, on the impact locations, and on the final position of the blocks. Thus, we can rely on the accuracy of this reconstruction of the 21st January 2014 event. As a final step, the entire slope was mapped in detail, considering all the necessary parameters to carry out simulations and to adequately plan protection structures.

A detailed historical analysis has been carried out in the archives of the Benedictine Order of Freising in Bavaria, which owns the farm. The buildings in the area date back to 1661 AD and provided detailed records of the agricultural activities performed since their construction. In these archives there is no mention of any rockfall that reached the buildings or the vineyards, but at least one huge block rolled down to this place along a trajectory analogous to those of the 21st January 2014 event (Fig. 7B). It is probable that the impact of this event on the buildings or the vineyards would have registered in the financial records of the farm. Henceforth,

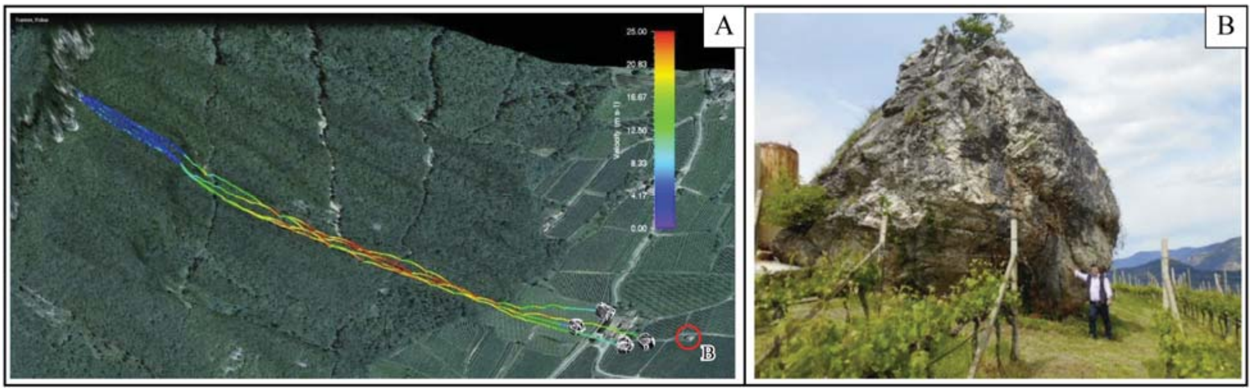

Fig. 7 - A) Boulder trajectories of the Termeno rockfall. B) A huge boulder located near Freisinger Hof since before 1661 AD (location in A, red circle).

we can empirically estimate that the returning period for this event could be about 400 years.

4. ROCK AVALANCHES OF THE SARCA VALLEY

4.1 Marocche di Dro

The Marocche di Dro include some of the most impressive rock avalanche deposits in the Alps (Figs. 9, 10). Earlier authors discussed as many as twelve different landslides, including five grouped as Marocche di Dro (e.g., Trener, 1924). Based on fieldwork, remote imagery analysis and ^{36}Cl surface exposure dating, Ivy-Ochs et al. (2017b) delimited the two main deposits, namely the Marocca Principale and the overlying Kas (Figs. 9, 11). The largest Marocca Principale event, when about 1000 Mm^3 of predominantly Rotzo limestones collapsed, occurred 5.3±0.9 ka ago. The release area extends along the vertical wall from Mt. Casale to Mt. Granzoline, likely also including Mt. Brento (Fig. 9). The Marocca Principale blocked the Sarca River forming a dam; tens of meters of fluvial and lacustrine sediments accumulated upstream, forming the Sarche plain sediments (Fig. 11). On the southern side, the Marocca Principale deposits were covered by the younger Kas event. However, the interpretation of core drilling and geophysical data suggest that further blocky deposits are lying buried beneath the plain (Ivy-Ochs et al., 2017b). The Sarca plain remained swampy over centuries, explaining the lack of towns in the valley as testified by historical records.

Kas deposits show a barren, stark landscape made up of house-sized Rotzo boulders, stacked in an open framework deposit (Fig. 10). ^{36}Cl data show that rock failure (about 300 Mm^3) from the Mt. Brento eastern face occurred 1.1±0.2 ka ago (single ages in Fig. 9). It should be noted that, within the Kas deposits, 5-10 m-high longitudinal flow ridges extend radially, outward from the release area below Mt. Brento (Fig. 11B). During the Kas event the southern portion of the Marocca Principale deposits was buried. The finding of roof tile fragments (probably Roman in age; Trener, 1924) between the two rock avalanche deposits suggests the presence of some “Kasae” (rustica villae) in the valley. Nevertheless, reference to this event cannot be found in any historical document. For both Marocca Principale and Kas, an initial translational failure likely quickly evolved to massive collapse and complex failure, followed by a run-out across the valley and a run-up on the eastern slope.

Several factors contribute to the prevalence of rock slope failures along this reach of the Sarca Valley. First, the extreme relief of more than one kilometer along the Mt. Casale-Mt. Brento wall. This is attributable to Miocene downcutting, amplified by undercutting by the Adige glacier during the Quaternary (Ivy-Ochs et al., 2017b

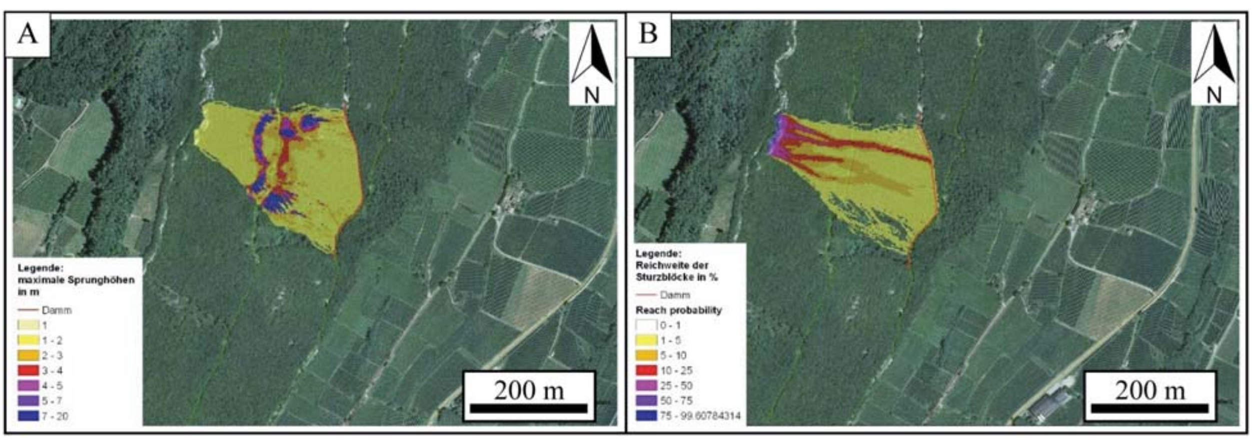

Fig. 8 - Simulation of failures with the planned dam. Left - jump height. Right: reach probability.

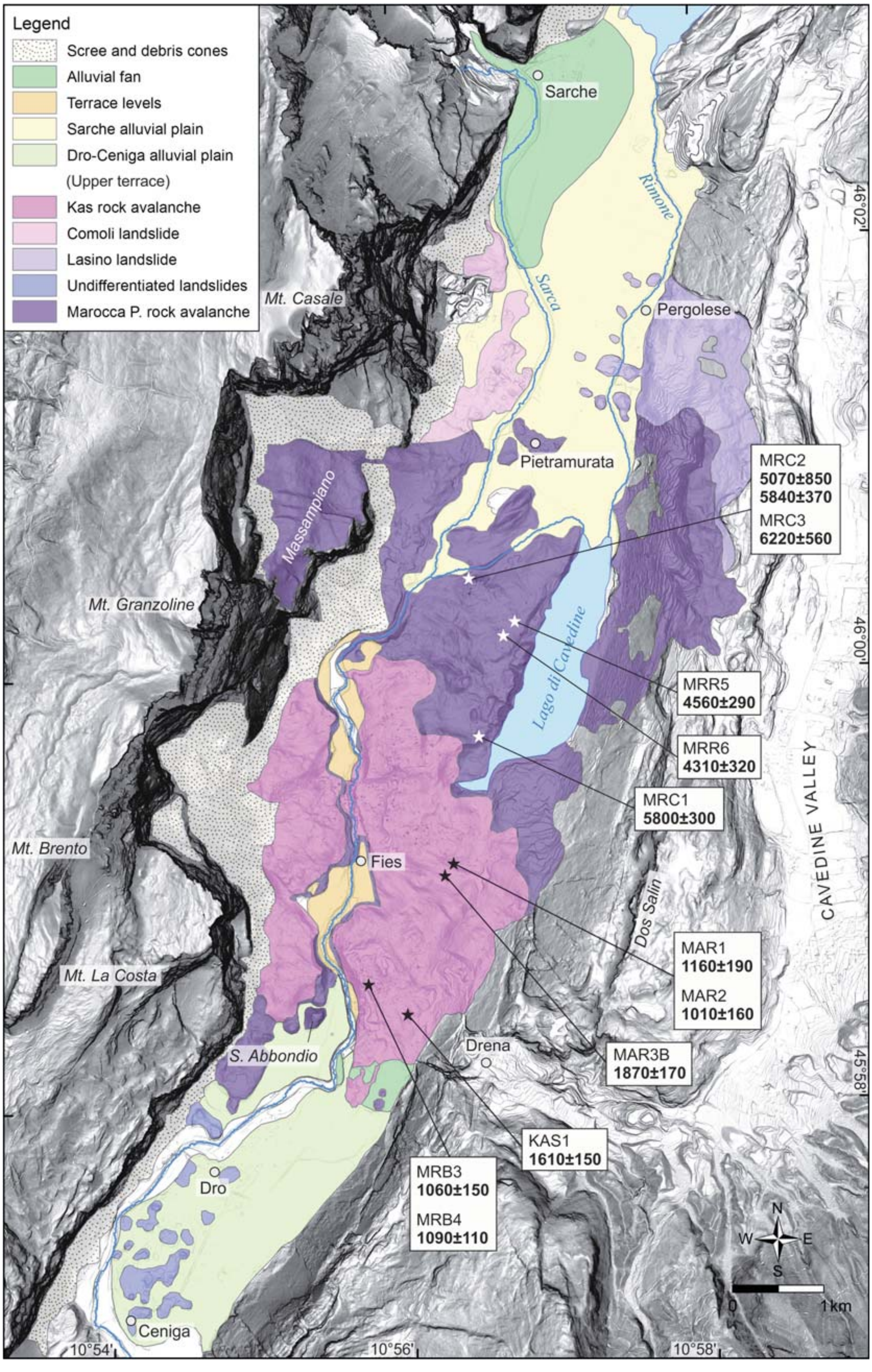
Legend
Scree and debris cones
Alluvial fan
Terrace levels
Sarche alluvial plain
Dro-Ceniga alluvial plain
(Upper terrace)
Kas rock avalanche
Comoli landslide
Lasino landslide
Undifferentiated landslides
Marocca P. rock avalanche
Sarche
Rimone
Sarca
Mt. Casale
Pergolese
Pietramurata
Massampiano
Mt. Granzoline
Lago di Cavedine
MRC2
5070±850
5840±370
MRC3
6220±560
MRR5
4560±290
MRR6
4310±320
MRC1
5800±300
CAVEDINE VALLEY
Mt. Brento
Fies
Dos Salin
MAR1
1160±190
MAR2
1010±160
Mt. La Costa
MAR3B
1870±170
S. Abbondio
Drena
KAS1
1610±150
MRB3
1060±150
MRB4
1090±110
Dro
Ceniga
N
W
E
S
0
1 km
46°02'
46°00'
45°58'
10°54'
10°56'
10°58'

Fig. 10 - The Kas blocky deposit, looking southward. Boulders in foreground are several meters in diameter.

and references therein). Second, tectonics play a decisive role in the repeated failures. In fact, fractures and faults reduce rock mass strength. The lower Sarca Valley is dominated by the NNE-SSW oriented, ESE-to-SE verging Giudicarie fold-and-thrust belt. Moreover, NW-SE oriented nearly vertical strike-slip faults, belonging to the Schio-Vicenza system, cut across the Giudicarie faults dislocating originally adjacent structural blocks (cf. Fig. 1). Post-compressional reactivation of N-S oriented Mesozoic normal faults and fractures facilitated backwall detachment.

4.2 Molveno

The Molveno rock avalanche, with a volume of about 600 Mm^3, is probably the largest single-event rock avalanche in the Brenta Dolomites and one of the largest in the Alps. As shown on Figure 12, rock avalanche deposits dammed the valley to the north forming (or raising the level of) the lake of Molveno (823 m a.s.l.) (Chinaglia & Fornero, 1995; Sauro & Zampieri, 2001). In 1951 (and again recently in spring 2017), the lake was drained and standing tree trunks of a drowned forest buried by delta deposits were discovered.

Detailed geomorphological mapping, cosmogenic ^{36}Cl exposure dating and numerical run-out modelling were used to reconstruct the Molveno rock avalanche (von Wartburg et al., 2020). Due to the complicated morphology of the landslide deposits (e.g., the elevated Pian delle Gaorne plain in Fig. 12), with evidence of internal collapses (secondary scarps within the deposit; Fig. 13), the reconstruction of the source location and dynamics of the landslide remain a challenging issue. Reflecting as well this complicated setting, some authors suggested that the deposits were produced by several events coming from different source areas on both sides of the valley, Mt. Gazza to the east and Mt. Soran to the west (Lepsius, 1878; Fuganti, 1969; Chinaglia, 1992): Conversely, other authors described the deposits as one large event coming from a prominent niche on Mt. Soran (Damian, 1890; Schwinner, 1912).

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Fig. 9 - Geomorphological map of the rock avalanche deposits at Marocche di Dro, Sarca Valley. Cosmogenic ^{36}Cl sampling sites and ages are also shown (from Ivy Ochs et al., 2017b; Elsevier used with permission).

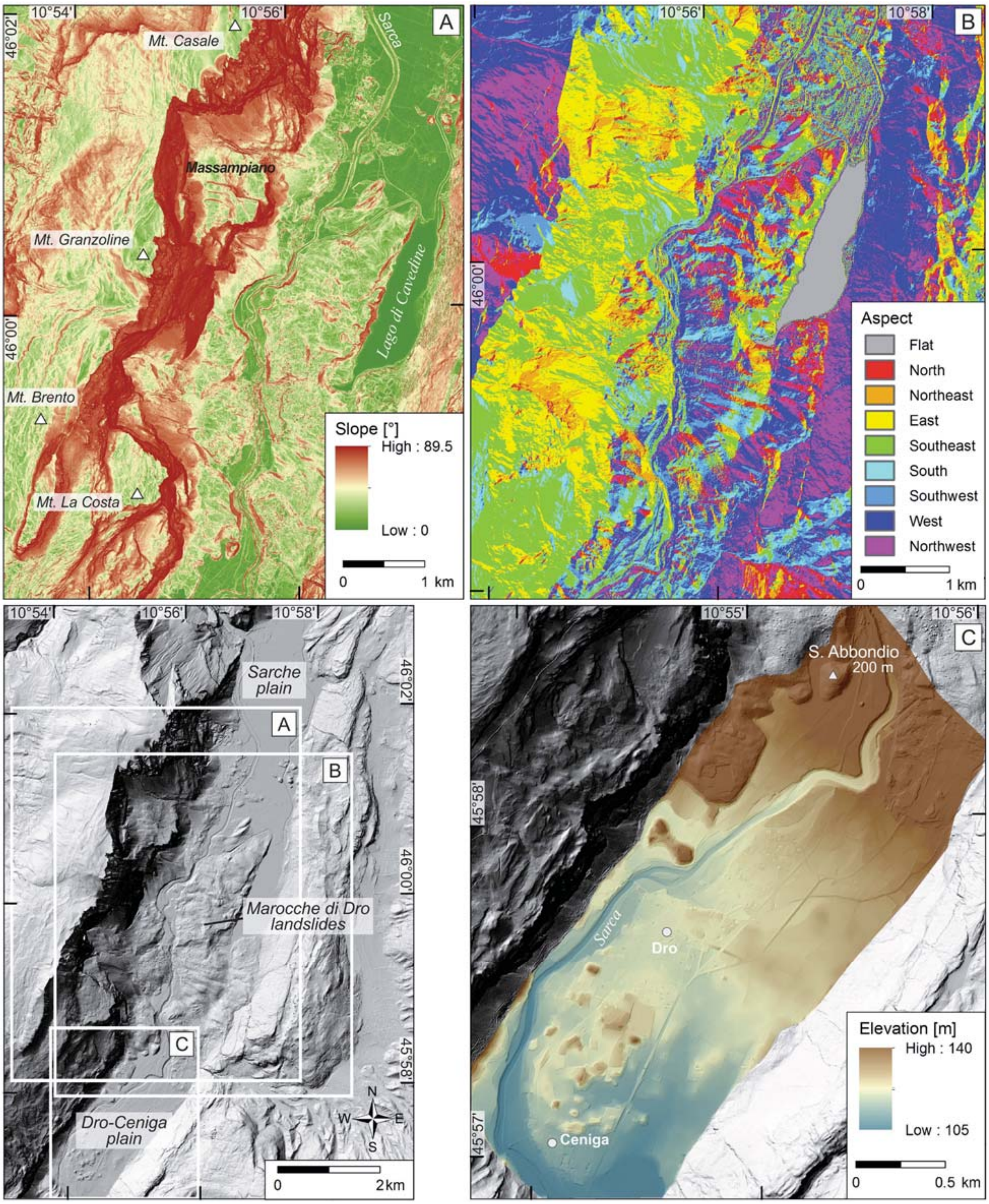

Fig. 11 - Geomorphology of the Marocche di Dro deposits. A) Slope map. B) Aspect map. C) Detailed sketch of the Dro and Ceniga plains, where visible toma likely belong to the Marocca Principale deposits (from Ivy Ochs et al., 2017b; Elsevier used with permission).

von Wartburg et al. (2020) obtained a mean age of 4.8±0.5 ka, based on cosmogenic ^{36}Cl surface exposure dating of boulders across the deposits (Fig. 12). This indicates emplacement as a single huge landslide at Molveno. For this reason, the secondary collapses visible within the deposit (cf. Fig. 13) likely occurred (closely) after this main event. Among all the studied boulders of Molveno, only the two dated ones from Nembia gave ages that are about 2000 years younger (2.1±0.3 and 2.4±0.2 ka; Fig. 12). It is most likely because them were covered by water until 2000 years ago (von Wartburg et al., 2020).

To simulate the Molveno landslide and to test the reliability about only one event from Mt. Soran, a numerical run-out model was performed, assuming a pre-failure topography (Dan3D-Flex code; Hungr, 1995; McDougall & Hungr, 2004; Aaron & Hungr, 2016). The basic software (Dan3D) is designed to simulate extremely rapid, flow-like, mass movements (McDougall & Hungr, 2004), while its add-in (Flex) allows to model initially partially coherent landslides with planar sliding followed by rapid fragmentation (Aaron & Hungr, 2016). The modelling results are shown in Figure 14. They well reproduce the extent of the mapped landslide, despite the predicted thickness locally show significant deviations from observations, such as at Pian delle Gaorne (von Wartburg et al., 2020).

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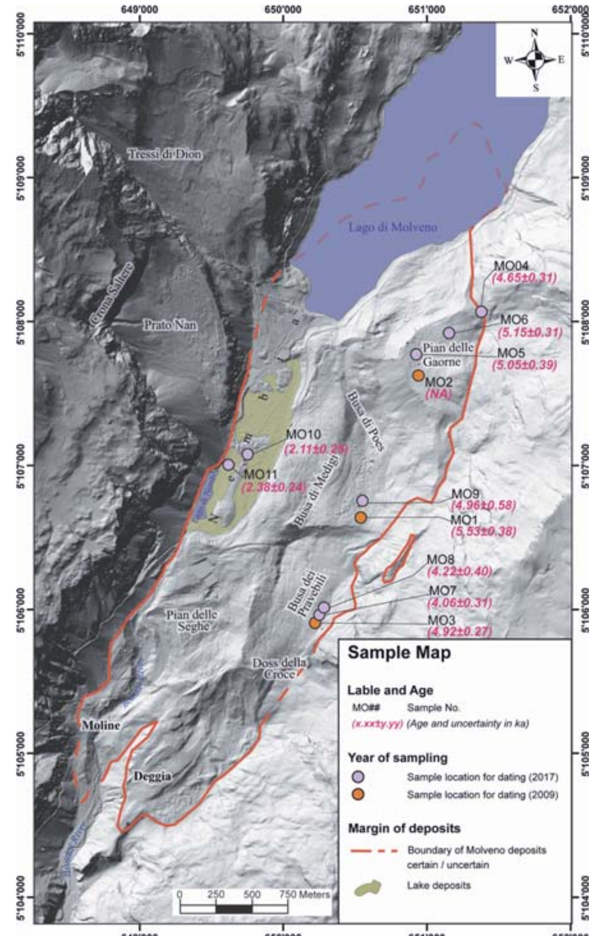
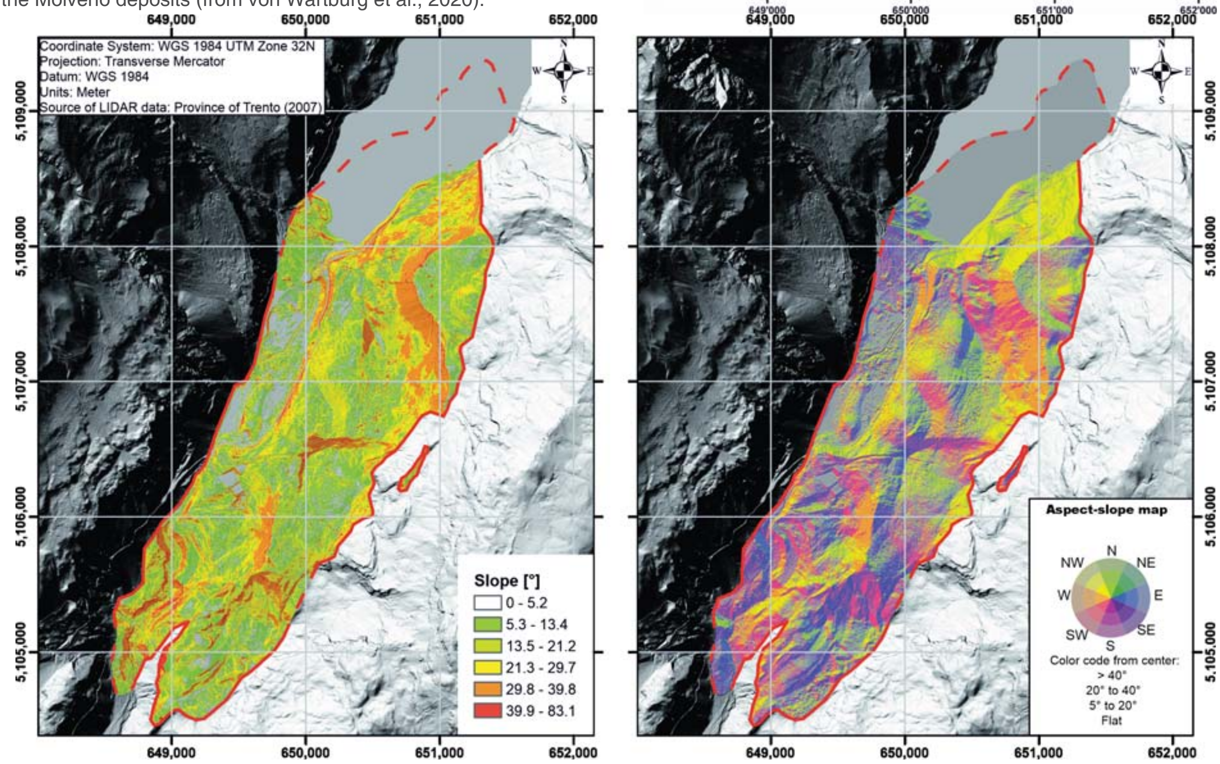


Fig. 12 - Terrain map of the Molveno rock avalanche deposits, with geographical names and ^{36}Cl sampling sites and ages (from von Wartburg et al., 2020).

Fig. 13 - Slope (on the left) and aspect maps (on the right) for the Molveno deposits (from von Wartburg et al., 2020).



5. DISCUSSION

During the last decades, several authors have examined spatial and temporal patterns of catastrophic rock slope failures with the aim of understanding predisposing factors and triggering mechanisms, both in the Dolomites (Fuganti, 1969; Abele, 1974; Perna, 1996; Borgatti et al., 2006; Borgatti & Soldati, 2010; Martin et al., 2014; Ivy-Ochs et al., 2017a; 2017b; von Wartburg et al., 2020) and generally in the Alps (Soldati et al., 2006; Prager et al., 2008; Zerathe et al., 2014; Ivy-Ochs et al., 2017a; Singeisen et al., 2020). Three periods of enhanced slope activity have been discussed: 10-9 ka, 5-3 ka, and 2-1 ka, the latter especially for the Southern Alps. A summary of all the large (>1 Mm^3) dated landslides in the Alps is shown in Figure 15.

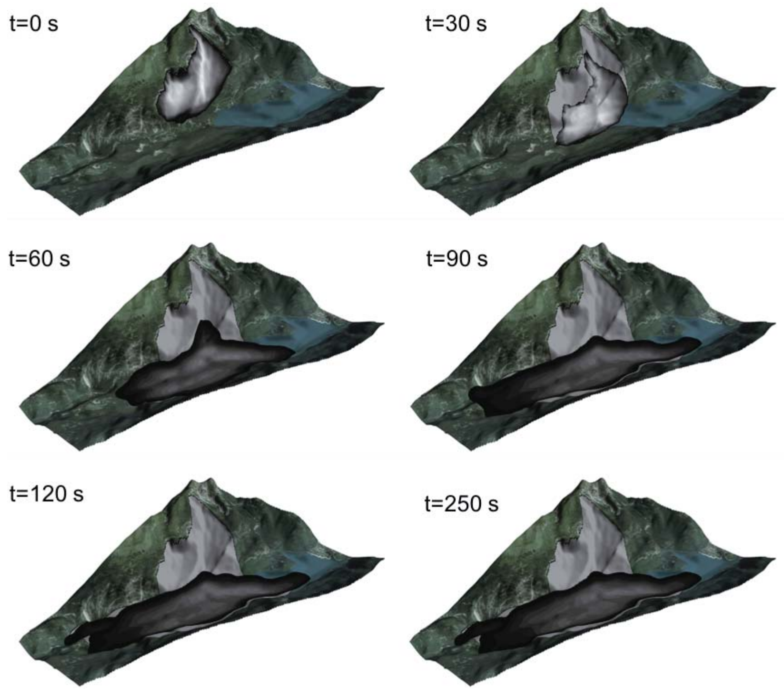


Fig. 14 - Time series of the run-out model for the Molveno rock-avalanche. The extent of the observed deposit is well reproduced (from von Wartburg et al., 2020).

5.1 Bedrock structure and tectonics

The rock avalanches and landslides described herein have clear similarities regarding lithology and structural setting, as they belong to the same tectonic domain: the western Trentino crustal block (Viganò et al., 2015). The Lavini di Marco, Marocche di Dro and Molveno rock avalanches are developed in Jurassic limestones, specifically Rotzo, Loppio and Tofino Formations, which are characterized by the presence of cm-dm thick clay intercalations that can facilitate sliding. Numerous rock slope failures are concentrated in this distinctive area which is constrained between two large, deeply rooted rigid domains: the Athesian Volcanic high (Bargossi et al., 1998) to the northeast and the Adamello intrusions to the west (Fig. 1). Between these two domains, late Alpine deformation, due to counterclockwise motion of Adria, predominantly along the Schio-Vicenza fault with shortening of the western Trentino block, was strongly constrained within the Giudicarie belt. Most of the deformation was concentrated along the Southern Giudicarie master fault bordering the Adamello but also along minor faults of this system. Accordingly, the landslide deposits studied here are concentrated along faults that belong to the NNE-trending Southern Giudicarie and to the NW-trending Schio-Vicenza fault systems, or lay at the junction of those two systems (Castellarin et al., 2005). Along the Giudicarie, asymmetric folds at the kilometer scale also occur. These generate a geological setting dominated by west-dipping monoclinic surfaces and east-facing tectonic scarps. The associated synclines host respectively Lake Garda, Sarca Valley and the Molveno lake. Within this framework, rock masses detached along the dip slope bedding planes associated with clay-rich interbeds on the west-facing slopes, as for example at Lavini di Marco. On the east-facing slopes of the Sarca Valley, toppling and massive collapse are the dominant processes (Perna, 1974; 1996), such as the Marocca Principale rock avalanche. The numerous faults and fractures associated with these major tectonic systems exert strong control on vertical detachment surfaces (i.e. back walls and side walls), as discussed above for the NNW-trending Lizzana-Vallone fault at Lavini di Marco and the NW-oriented steep side wall in the Molveno release area (cf. Figs. 4, 12). Finally, in these mountainous areas, rock damage and associated fatigue and reduction in strength due to past tectonics (Brideau et al., 2009) and recent active deformation pose the question of the present and future hazards of these inhabited Alpine valleys.

5.2 Landslide timing and driving forces

Very few events in the Alps have been dated to the Lateglacial (18-12 ka). Therefore, the concept that the huge landslides in Trentino, or the Alps overall, occurred during the early Lateglacial directly following ice retreat, implicating debuttressing as a driving force, can now be discounted based on the numerous ages presented in Figure 15. Even for two of the oldest dated landslides in the Alps (Flims, Koefels), it is important to note that glaciers had not occupied those valleys for many thousand years prior to the catastrophic events (Ivy-Ochs, 2015). Two of the largest events in the Alps, Flims (10-12 km^3) and Koefels (3 km^3), have been dated to the period 10 to 9 ka ago (Ivy-Ochs et al., 2017b and references therein). Early Holocene rock slope failure events may be related to marked warming at 10.5-10.0 ka that forced retreat of glaciers to positions perhaps even smaller than today's and was likely accompanied by rapid permafrost degradation at higher elevations. However, a seismic trigger has been recently suggested for some coeval early Holocene landslides in the Kander region (Grämiger et al., 2016). Recent

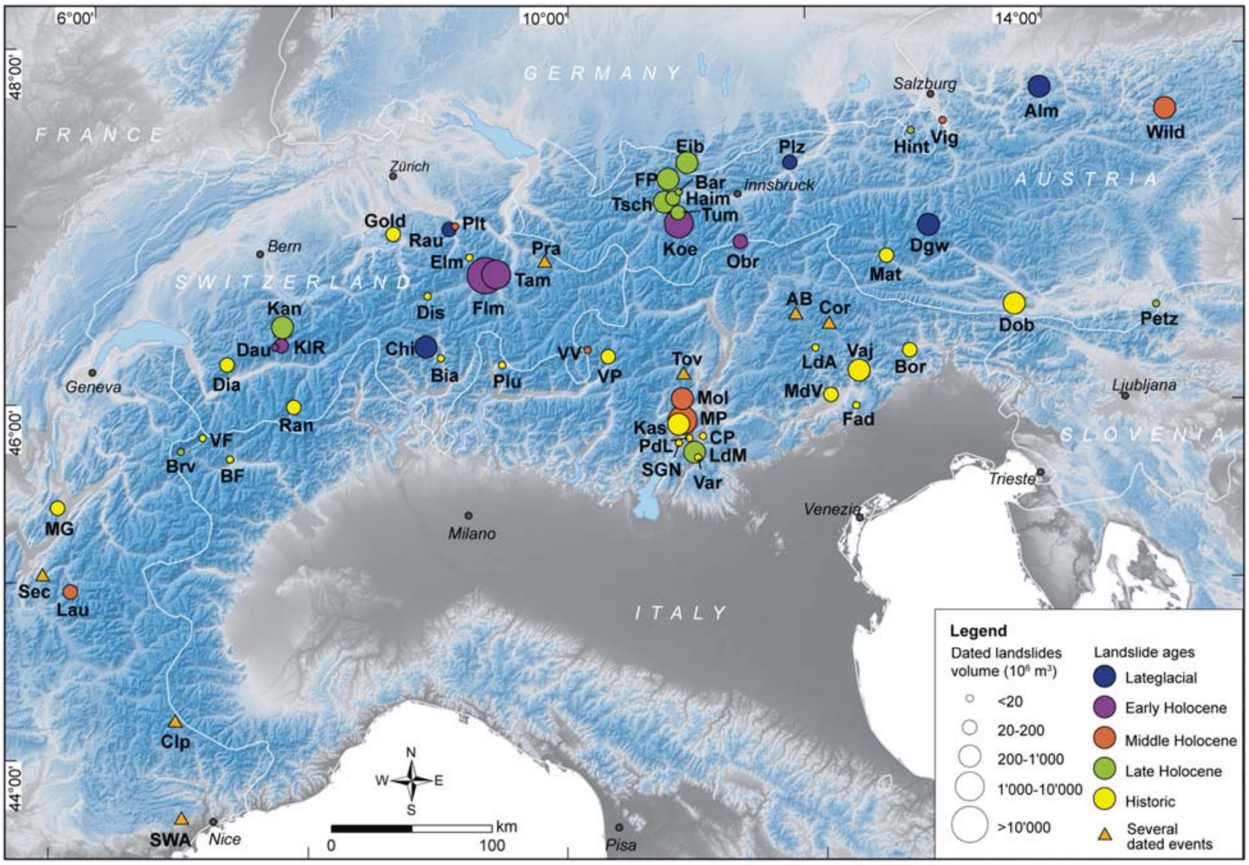


Fig. 15 - Compilation of isotopically dated and historical large (>1 Mm^3) landslides in the Alps (modified and updated from Ivy-Ochs et al., 2017b; Elsevier used with permission). Updates include the late Holocene Kandersteg (Kan), the middle Holocene Molveno (Mol), the late Holocene Masiere di Vedana (MdV) (Rossato et al., 2020a) and the Tovel (Tov) events. Alm Almtal; Plz Pletzachkogel; Chi Chironico; Dgw Durchgangwald; Rau Rautispitz; Dau Daubensee; KlR Klein Rinderhorn; Koe Koefels; Tam Tamins; Flm Flims; Obr Obernberg; VV Val Viola; Vig Vigaun; Wild Wildalpen; Plt Platten; MP Marocca Principale; Lau Lauvitel; FP Fernpass; Eib Eibse; Bar Barwies; Tum Tumpen; Hint Hintersee; Kan Kandersteg; Brv Brenva; LdM Lavini di Marco; Tsch Tschirgant; Mol Molveno; Haim Haiming; Petz Petzer Oberloibach; Mat Matrei; MdV Masiere di Vedana; Fad Fadalto; Var Varini; Kas; CP Castelpietra; PDL Prà da Lago; MG Mont Granier; Dob Dobratsch; SGN San Giovanni Nago; Bia Biasca; BF Becca France; Dis Disentis; Plu Plurs; Bor Borta; Dia Diableret; VF Val Ferret; LdA Lago di Alleghe; Gold Goldau; Elm; Vaj Vajont; VP Val Pola; Ran Randa; Clp La Clapiere; Pra Prättigau; AB Alta Badia; Cor Cortina; SWA southwestern Alps; Sec Sechiellene; Tov Tovel.

^{36}Cl dating of the Kandersteg deposits (location shown in Fig. 15) has revealed that this huge event (1.1 km^3) occurred 3.2 ±0.2 ka ago (Singeisen et al., 2020) and not 9.6 ka ago as previously proposed. This significantly weakens the concept of an early Holocene cluster of major events. No failure events in the lower Sarca or Adige valleys have yet been dated to the Lateglacial or early Holocene. Nevertheless, in both valleys, the presence of landslide deposits buried beneath alluvial fill cannot be ruled out, especially when one considers to the huge volume of rock missing along the Mt. Brento-Mt. Casale mountain front (Ivy-Ochs et al., 2017b).

Numerous authors identify a period of increased landslide activity between 5 and 3 ka in the Alps and specifically in the Dolomites (Panizza et al., 1996; Dapples et al., 2003; Prager et al., 2008; Borgatti & Soldati, 2010; Zerathe et al., 2014). In the lower Sarca and Adige valleys and nearby regions, several mass wasting events have been dated to this period (Perna, 1996; Baroni et al., 2014). At Lavini di Marco the most extensive deposit was dated to 3.0 ±0.4 ka with ^{36}Cl (Martin et al., 2014). Both Molveno, 4.8 ±0.5 ka (von Wartburg et al., 2020), and Marocca Principale, 5.3 ±0.9 ka, fall as well within the discussed time interval. Zerathe et al. (2014) point out that different proxies in the Alps suggest a “4.2 ka” wet climatic event with associated enhanced rock slope failure activity. Similarly, periods of climate degradation characterized by more frequent flooding episodes and extreme meteorological events have been recorded in the same timeframe (Wirth et al., 2013; Benito et al., 2015; Rossato et al., 2015). Under such conditions, stress field changes in the rock due to the added mass of water as well as weakening of clay-rich interbeds may have led to catastrophic failure. This agrees with the opinions of Soldati et al. (2004) and Borgatti & Soldati (2010) for rock avalanches of the eastern Dolomites. Nevertheless, several researchers underline the importance of strong tectonic events as triggers for the middle Holocene rock avalanches (Ambrosi & Crosta, 2006; Prager et al., 2008). Indeed, the notable overlap in the ages of the Molveno and Marocca Principale events which lie no more than 10 km apart (Fig. 1), may implicate a common seismic trigger (von Wartburg et al., 2020).

Recent landslide activity in the western Dolomites, especially over the last several thousand years, is suggested to be related to seismic activity (Borgatti & Soldati, 2010; Ivy-Ochs et al., 2017a; 2017b). Numerous catastrophic landslides are reported for post-Roman times, albeit somewhat schematically (Heim, 1932; Eisbacher & Clague, 1984; Abele, 1997 and references therein). Sauro & Zampieri (2001) suggest a third temporal cluster in the Southern Alps around 1000 AD, which was strongly related to neotectonics. In the presented data set, this would include, the Kas landslide (Ivy-Ochs et al., 2017b), the youngest dated events at Lavini di Marco (Martin et al., 2014), the Varini rockslide (Orombelli & Sauro, 1988) and the Castelpietra landslide (Ivy-Ochs et al., 2017a). Lake Garda, the lower Sarca and Adige Valleys are characterized by low-to-moderate magnitude seismicity (moment magnitude <6.0; Basili et al., 2008), which is interpreted as mainly due to activity of the Southern Giudicarie fault system (Viganò et al., 2013; 2015). Other sources of seismicity are the faults of the Schio-Vicenza system (Viganò et al., 2015), and the thrusts between Brescia and Verona that also bear evidence of middle Pleistocene to Holocene activity. Compilations of historical seismicity (Guidoboni et al., 2018; Rovida et al., 2019) allowed to evaluate the earthquakes, especially if intended as seismic sequences, as a possible driving/triggering factor for landslides and rock avalanches in the study region. Based on the available compilations of historical seismicity, two strong earthquakes struck southern Trentino and the central Po plain around 1000 AD. They are the “Middle Adige Valley” event dated to 1046 AD (estimated epicentral intensity IX MCS, Mercalli-Cancani-Sieberg scale) and the “Verona” earthquake in 1117 AD (estimated epicentral intensity IX MCS; Guidoboni et al., 2018). Although there are significant uncertainties associated with the epicentral coordinates of the 1046 AD “Middle Adige Valley” earthquake, its location (Guidoboni & Comastri, 2005) is considerably closer to both the Kas and Castelpietra deposits (location shown on Fig. 1) than the 1117 AD earthquake location (about 72 and 80 km, respectively). Castelpietra, dated to 1.0 ±0.3 ka ago, and Kas sites lie about 6 and 11 km, respectively, epicentral distance from the “Middle Adige Valley” earthquake location (Ivy-Ochs et al., 2017a).

6. CONCLUSIONS

In this overview, selected landslides of the western Dolomites have been discussed and their age compared with other cases in the Alps. Local active tectonic setting plays a decisive role in the repeated failure along slopes, which is localized along faults of the NNE-trending Southern Giudicarie and the NW-trending Schio-Vicenza fault systems. West-dipping monoclinic surfaces provide the dip slope and shale interbeds in the limestones facilitate sliding, as for example at Lavini di Marco. Faults and fractures localize backwall detachment; strike-slip faults focus lateral constraints for detaching blocks. East-facing tectonic scarps promote toppling and massive collapse, as for example at Marocche di Dro (Marocca Principale and Kas rock avalanches). During both events at Marocche, and at Molveno, complex failure was followed by run-out across the valley and tens of meters of run-up on the opposite slope. Smaller rockfalls may occur due to similar tectonic settings, as in the case of Termeno. Here, the volume of the debris was smaller, and the mass propagated as single blocks, rolling, and jumping.

The ages of the discussed rock avalanches and landslides of the Sarca and Adige Valleys mainly fall in the period 5-3 ka ago. This period broadly coincides with that of increased frequency for failure events, at the transition from the middle to the late Holocene, when a shift to a wetter, colder climate occurred. Nevertheless, a seismic driving factor is suggested for the landslides of this area. Although the Verona earthquake (1117 AD) may have had a greater impact regionally, we suggest the “Middle Adige Valley” (1046 AD) seismic sequence, whose epicentral distance is much closer to the Sarca Valley, as relevant driving force for the Kas rock avalanche (1.1 ±0.2 ka).

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