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POST-LGM CATASTROPHIC LANDSLIDES IN THE DOLOMITES: WHEN, WHERE AND WHY

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ABSTRACT: This paper aims to present the state-of-the-art about large and catastrophic landslides that have occurred in the Dolomites since the Last Glacial Maximum (LGM). Such events have been proved to happen multiple times in the same area, in correspondence of prolonged rainfall events, ice/snow melting and seismic shakings. Predisposing factors, such as rock fracturation and vertical bedding strata, may accumulate rock fatigue and induce the formation/weathering of shear planes, weakening the rock mass and allowing low-magnitude events to trigger the movement.

KEYWORDS: Cosmogenic ^{36}Cl, geological risk and hazard, geomorphic hazard, Dolomites

1. INTRODUCTION

Landslides are phenomena that can deeply affect both natural and anthropogenic landscapes, and they can represent a serious risk (e.g. Petley, 2012). Understanding their predisposing factors and potential triggers is of utmost importance to reduce their potential impacts, especially in the Alps where narrow valleys are increasingly inhabited (e.g. Huggel et al., 2012). In the last three decades, it has been estimated that the costliest natural event occurred in Italy was the notorious Val Pola rock avalanche, occurred on 28th July 1987. It has been estimated that the total amount of damages reached US$ 400 million (Crosta et al., 2004).

In the Alps, the largest landslides were presumed to have occurred during the latest phases of the Last Glacial Maximum (LGM), or within a few millennia after deglaciation as a response to glacial unloading of valley slopes. Recently, some of them, such as “Lavini di Marco”, (Martin et al., 2014), “Marocche di Dro” (Ivy-Ochs et al., 2017a), “Castelpietra” (Ivy-Ochs et al., 2017b) and “Mt. Peron” (Rossato et al., submitted), have been isotopically dated, proving to be Holocene in age, thus suggesting that such large events may occur without major changes in the equilibrium of the slopes.

In the Dolomites several landslides occurred, such as the Fadalto, Antelao and Vajont events, causing damages and casualties, even when the moving masses were small. The Vajont event hit the headlines all over Europe for its disruptiveness, being the most catastrophic events in the study area, but other large landslides occurred in the past. Here we summarize the largest and most catastrophic landslides in the Dolomites, focusing on their type, timing and impact on human life/activities, discussing their possible predisposing and triggering factors. We will not discuss Deep-seated Gravitational Slope Deformations and creep deformations, since they are characterized by relatively low deformation rates.

2. CATASTROPHIC DOLOMITES LANDSLIDES

All landslides occurred in the dolomitic area that are relevant in terms of volume and/or impact on human activities are here presented (Tab. 1) and shortly described based on the papers listed.

2.1. Alta Badia (Borgatti & Soldati, 2010)

Numerous events took place near Corvara, since 10 ka cal BP to present. Earth/mud/debris flows constitute most of the events, along with rotational rock slides. Water availability, due to permafrost melting and/or rainfall events, is believed to be the potential trigger for these events and climatic conditions are believed to be the main cause of widespread landsliding.

2.2. Alleghe (Ermini & Casagli, 2003)

The Alleghe event was a large (10 Mm^3) translational rock fall, possibly evolved into a rock avalanche. The debris mass reached a runup elevation of about 150 m above the valley bottom, on the opposite flank. A second, smaller (3 Mm^3) event took place some months after. Both events have been linked to the high amount of rain and snow occurred during that winter.

2.3. Antelao (Montandon, 1933)

On 21st April 1814, a large debris mass fall from the Mt. Antelao, split into two tongues and inundated the localities of Taolen and Marceana, causing 260 casualties. A temporary lake formed in the Boite Valley. This event was the most damaging of a sequence of landslides falling at the same place (e.g events are recorded also on 1348, 1729 and 1737 AD).

2.4. Col Mandro (Montandon, 1933)

In December 1933, a debris mass, detached from the Col Mandro, dammed the Vanoi Valley, forming a temporary lake. This event was the biggest of a sequence of mass movements in the area. It is believed

Name	Age (AD or BP)	Dating method	Volume (Mm^3)	Reference	Casualties
Alta Badia	10 ka BP to present	^{14}C, historical	-----	Borgatti & Soldati, 2010	?
Alleghe	11th January 1771 AD	Historical	10	Ermini & Casagli, 2003	49
Antelao	21st April 1814 AD	Historical	>1	Montadon, 1933	260
Col Mandro	1825 AD	Historical	?	Montadon, 1933	Tens
Cortina d'Ampezzo	14 ka BP - present	^{14}C, historical	-----	Borgatti & Soldati, 2010	?
Fadalto	Lateglacial - Present	?	135	Pellegrini et al., 2006	?
La Valle	1701 AD	Historical	?	Montadon, 1933	48
Marziai	17 - 15 ka BP	Radiocarbon	50	Pellegrini et al., 2006	?
Monte Salta	1674 AD	Historical	2.5	Marcato et al., 2007	0
Pecol	1841 AD	Historical	?	Montadon, 1933	24
Mt. Peron	Roman Era (<2nd century AD)	^{36}Cl, historical	170	Rossato et al., submitted	?
Siror	1348 AD	Historical	?	Montadon, 1933	Tens
Vajont	9th October 1963 AD	Historical	270	Borgatti et al., 2004	1910
Val Cia	1882 AD	Historical	?	Montadon, 1933	Tens
Valle San Lucano	1908 AD	Historical	0.25	Aldighieri et al., 2016	28

Table 1 - Summary table of the largest and most damaging (in terms of human lives) landslides in the Dolomites.

that such events were due to deforestation and poor management of irrigation.

2.5. Cortina D'Ampezzo (Borgatti & Soldati, 2010)

Since 14 ka cal BP, in this area several events (earth flows and translational rock slides) have occurred. As for the Alta Badia case, climate is invoked as the possible driving factor, due to their clustering in specific time intervals. It is noteworthy that a single earthflow was triggered by the 15th September shock of the 1976 Friuli earthquake sequence.

2.6. Fadalto (Pellegrini et al., 2006)

This event is a large (135 Mm^3) and complex landslide involving various types of movements (rock slide, rock avalanche, debris slump, etc). It blocked the whole Valley, forming the S. Croce Lake. The initial trigger is believed to be the relaxation of the slopes owing to glacier retreat, but the main scarp has been repeatedly reactivated since then.

2.7. La Valle (Montandon, 1933)

In April 1701, a "rock avalanche" (this term may not correspond to its modern scientific meaning) detached from the Mt. Moschesin, causing 48 casualties. Other minor events occurred later at the same place.

2.8. Marziai (Pellegrini et al., 2006)

The rocky mass detached from Mt. Miesna, where rock layers are lightly dipping towards the slope and pervasive foliation is present. The landslide was suggested to have occurred in the first phase of deglaciation (i.e. 17-15 ka cal BP) by means of palynological data obtained from the remains of the temporary lake formed by the landslide itself. As for the Fadalto landslide, the reaction of the slopes to glacier retreat is evoked as possible trigger.

2.9. Monte Salta (Marcato et al., 2007)

This rock avalanche, which occurred in 1674 AD, is strictly connected to the presence of major faulting, folding and fracturing of the rock mass, that dips steeply towards the slope. Such an unstable setting makes the slopes prone to failure and the authors suggested that seismicity may be, or may have been, the trigger.

2.10. Pecol (Montandon, 1933)

This event occurred in 1841 AD, evolved by steps during an entire week, causing various casualties and destroying an entire part of the village of Pecol.

2.11. Mt. Peron (Rossato et al., submitted)

This enormous rock avalanche (170 Mm^3) fell from the top of Mt Peron and spread in the area where the villages of Peron, Ponte Mas, Vignole and Roe are currently located. The event was believed to be Lateglacial in age, but recent cosmogenic dates and historical data proved that it occurred during the Roman Era, prior to the 2nd century AD.

2.12. Siror (Montandon, 1933)

This event was one of the many mass movements related to the occurrence of an earthquake on 25th January 1348. It detached from Mt. Belvedere and destroyed the village of Pubiaco, causing tens of casualties.

2.13. Vajont (Borgatti et al., 2004)

The infamous, and extremely large, Vajont event was due to the reactivation of an old landslide, after nearly three years of progressive creeping. On 9th October 1963, 270 Mm^3 of debris and rock mass fell into an artificial reservoir, forming a flood wave that wiped out the village of Longarone, causing nearly 2000 casualties.

2.14. Val Cia (Montandon, 1933)

The rocky mass detached from the left flank of the Cia Valley in the 1882 AD, blocked the valley, and formed a temporary lake that breached soon after. The resulting flood, 4 Mm^3 large, affected the whole valley and propagated down to the Vanoi Valley.

2.15. Valle San Lucano (Aldighieri et al., 2016)

On 3rd December 1908 a landslide detached from the fourth Pala di San Lucano and buried Pra and Lagunàz villages, causing 28 casualties. Unstable rock masses are still visible in the main scarp area.

3. PREDISPOSING AND TRIGGERING FACTORS

The history of the Dolomites documented several landslides that caused damages and casualties, even when the moving masses were small (e.g. Valle San Lucano). The Vajont event hit the headlines all over Europe for its disruptiveness, being the most catastrophic events occurred in the study area (Borgatti et al., 2004). However, other similar events occurred in the past, but are less known due to their "limited" amount of losses (e.g. Antelao) or old age (e.g. Mt. Peron). In some occasions, such landslides caused a radical change in the landscape, as the Alleghe landslide: the debris mass blocked the Cordevole River and induced the formation of the Alleghe Lake. Such natural barrier has been artificially stabilized, and the lake is still present (Draganits et al., 2014).

Catastrophic slope failures are often related to the presence of discontinuities in the rock mass, as faults, shear zones and joints (Jaboyedoff et al., 2013; Stead and Wolter, 2015). Favorable bedding of strata (e.g. Mt. Peron) and the presence of relict landslides (e.g. Vajont) can concur to reduce the internal strength of the rock mass, contributing to the progressive accumulation of rock fatigue. The lower the energy required to break the equilibrium, the weaker the magnitude of the trigger event and the more probable the occurrence of forerunner events (Loew et al., 2017). Triggering events may be geological, hydrological, structural or even anthropogenic (Cruden and Varnes, 1996; Wieczorek, 1996). Prolonged and intense rainfalls are recognized to initiate movements, along with progressive failure, seismic shaking/volcanic activity, human activity or accelerating creep (Keefer, 1993; Di Crescenzo and Santo, 2005; Adushkin, 2006; Loew et al., 2017). Catastrophic events may happen with (e.g. Loew et al., 2017), or without a clear trigger or precursory events (e.g. Dunning et al., 2006).

The Dolomites are disposed to earthquake activity, as the instrumental record testifies (up to ~Mw=6.5; Viganò et al., 2015), and seismicity has been classified as a possible trigger for numerous Holocene large landslides in the Alps (Ivy-Ochs et al., 2017a). Only one of the considered events has been surely related to an earthquake, but there is a long record of seismicity-related minor rockfalls and shallow landslides (Borgatti & Soldati, 2010). Conversely, some authors highlighted a good correspondence between large dolomitic landslides (Borgatti & Soldati, 2010, Rossato et al., submitted) and rainfall climatic events/phases occurred at various scales (e.g. Tinner and Kaltenrieder, 2005; Benito et al., 2015; Rossato et al., 2015).

4. CONCLUSIONS

As the predisposing factors (rock fracturation, vertical bedding strata, fracture planes cutting the stratigraphic sequence) and triggers (seismicity and/or rainfall events) are often still present after the landslide occur, there is a high likelihood of generating rock failures at the same place that may reach high magnitude. The dolomitic landslide record suggests that no exceptional event is required for large mass movements to happen, the continuing accumulation of predisposing factors lowering the energy needed to trigger them. Low-magnitude shakings, especially in combination with an increase of pore-pressure due to prolonged and intense rainfalls, may be enough to overcome the stability threshold.

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