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Geomorphology and age of the Marocche di Dro rock avalanches (Trentino, Italy)

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ABSTRACT

The Marocche di Dro deposits in the lower Sarca Valley are some of the most distinctive rock avalanche deposits of the Alps. We use geomorphology and cosmogenic ^{36}Cl exposure dating of boulders to divide the Marocche di Dro deposits into two rock avalanche bodies; the Marocca Principale to the north and the Kas to the south. The deposits were previously undated and had been mapped as up to five different events. The largest event Marocca Principale, which comprises an estimated 1000 10^6 m^3 of predominantly Rotzo Formation limestones, occurred 5300 ± 860 yr ago. The release area is located mainly in the alcove between Mt. Casale and Mt. Granzoline, but likely extends all the way to Mt. Brento. The Kas event took place 1080 ± 160 yr ago with detachment below Mt. Brento. The Kas debris, with an estimated volume of 300 10^6 m^3, buried the southern third of the Marocca Principale deposit. Kas presents a barren, stark landscape dominated by house-sized Tovel Member Rotzo Formation boulders bearing distinctive chert lenses. Both the extreme relief of the rock wall (more than 1300 m) and the tectonic setting predispose the range front to massive failure. For the two events, initially translational movement likely quickly evolved into complex failure and massive collapse. Run-out across the valley of several kilometers and run-up on the opposite slope of hundreds of meters followed.

A summary of all dated and large historical landslides in the Alps underlines the periods of enhanced slope activity discussed in the literature: 10-9 kyr, 5-3 kyr, and 2-1 kyr, the latter especially for the Southern Alps. No deposits of the first temporal cluster are found at Marocche di Dro. The age of Marocca Principale at 5300 ± 860 yr suggests occurrence during the second period. Failure may have been related to the shift to wetter, colder climate at the transition from the middle to the late Holocene. Nevertheless, a seismic trigger cannot be ruled out. For the Kas rock avalanche at 1080 ± 160 yr ago we implicate the "Middle Adige Valley" (1046 CE) earthquake as trigger. Its epicentral distance is much closer to the Sarca Valley in comparison to that of the Verona earthquake (1117 CE).

1. Introduction

In no more than a few minutes landslides transform mountain landscapes profoundly and irreversibly. In addition to the huge scars left on the valley walls, valley floor morphology and drainage patterns are strikingly altered as well (Hewitt et al., 2008; Fort et al., 2009; Korup et al., 2010). Rock slope failures are a first order process in relief destruction in steep mountain ranges (Densmore and Hovius, 2000; Korup and Clague, 2009; Egholm et al., 2013). High and continually increasing population density in narrow mountain valleys in the Alps combined with ongoing climate change makes understanding critical factors for landslide occurrence crucial and relevant (Huggel et al., 2012; Stoffel et al., 2014; Wood et al., 2015).

The location of catastrophic, deep-seated, bedrock slope failures is strongly related to the location and orientation of faults, shear zones, and joints with respect to bedding, as well as to triggering

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mechanisms (Ambrosi and Crosta, 2006; Gugliemi and Cappa, 2010; Hermanns and Longva, 2012; Crosta et al., 2013; Jaboyedoff et al., 2013; Stead and Wolter, 2015). The latter includes increased pore water pressures due to extended periods of extreme precipitation and seismic triggering. Both recent (2008 Wenchuan earthquake, Guo et al., 2015) and historic (1348 Villach earthquake, Brandt, 1981) examples highlight the fundamental importance of landslides triggered by intense ground shaking. Nevertheless, it is a challenge to constrain the magnitude and location for past earthquakes based on the extent of damage in impacted areas (e.g. Guidoboni et al., 2005) or on the record contained in lake sediments (Strasser et al., 2013).

Before the introduction of isotopic dating, it was generally accepted that the most voluminous landslides in the Alps occurred right after deglaciation (Heim, 1932; Abele, 1974). It seemed logical that withdrawal of glaciers and associated debuttressing would lead to massive collapse. Additional evidence such as sediments interpreted as glacigenic on top of landslide deposits and the presence of toma hills (previously interpreted as kames) led support to the hypothesis (Abele, 1974 and references therein). However, McColl et al. (2010) and Ballantyne et al. (2014) point out that in order to attribute events to glacial debuttressing, the landslide would have had to occur within a millennium of glacier downwasting. As more and more Alpine landslides were dated, it became apparent that most occurred during the Holocene, thus 6000 years or more after withdrawal of glaciers from the affected valleys (von Poschinger and Haas, 1997; Cossart et al., 2008; Prager et al., 2009). In any case, the role of glacial valley overdeepening (Fort et al., 2009; Delunel et al., 2010; Ambrosi and Crosta, 2011), as well as the effects of repeated glaciation on bedrock stress patterns (Ziegler et al., 2013; Leith et al., 2014), remain key considerations (Stead and Eberhardt, 2013).

The lower Sarca Valley and the upper Lago di Garda region are characterized by numerous post-glacial gravitational events (Fig. 1) (Taramelli, 1881; Fuganti, 1969; Perna, 1974), likely closely related to neoalpine tectonics (Viganò et al., 2008, 2013, 2015; Baroni et al., 2014). The landslide deposits of the Trentino region are called “Marocche,” a local term for extensive, chaotic deposits of huge, angular blocks thought to have been in part transported by glaciers (Martin et al., 2014 and references therein). The Marocche di Dro of the middle reach of the lower Sarca Valley in Trentino are some of the most famous and most beautiful of Alpine rock avalanche deposits (Fig. 2). The release areas of the Marocche are sourced in the steep towering walls of the Mt. Brento- Mt. Casale mountain group along the western side of the valley. The Marocche di Dro have been studied since the 19th century (Omboni, 1878; Taramelli, 1881; Trener, 1924; Perna, 1974, 1996; Bassetti, 1997; Bassetti and Borsato, 2007; Bassetti et al., 2013), receiving particular attention during construction of tunnels for hydroelectric power in the 1920's (Trener, 1924). During excavation, roof tile fragments, suggested to be of Roman age, were found between two rock avalanche deposits. This provided already an indication of the age of the deposits. Additional age constraints for the Marocche come from associated archeological rests and radiocarbon dating of related sites (Trener, 1924; Bassetti et al., 2013) (see also below). In recent years, Perna (1974, 1996) assigned relative ages to the Marocche based on the extent of karst dissolution features on boulder and bedrock detachment surfaces. Nevertheless, a clear subdivision of the deposits and their respective ages has remained elusive.

Along this reach of the Sarca River as many as 12 different landslides, including five from Marocche di Dro, have been discussed (Trener, 1924; Perna, 1974; Bassetti, 1997; Bassetti et al., 2013). Based on fieldwork, remote imagery analysis, and ^{36}Cl surface exposure dating, we subdivide the Marocche di Dro into two landslides; the Marocca Principale and the younger overlying Kas deposits (Fig. 2). Post-glacial events, river development patterns, and archeological information are incorporated into reconstruction of the evolution of the lower Sarca Valley. We examine the possible causes of the rock avalanches and their relationship with structural geological features, neotectonics, as well as historical seismicity data.

2. Setting

2.1. Geographic setting

The studied landslides lie in the lower Sarca Valley, which extends for about 25 km from Lago di Toblino (245 m a.s.l.) to the northern shores of Lago di Garda (65 m a.s.l.). The main peaks on the western side of the valley are from south to north Mt. Brento (1544 m a.s.l.), Mt. Granzoline (1549 m a.s.l.), and Mt. Casale (1634 m a.s.l.) (Fig. 2). Lago di Cavedine (240 m a.s.l.) is located on the eastern side at the foot of Dos Salin ridge (802 m a.s.l.). Farther to the south the Sarca River passes through a marked bedrock narrows between Moletta and Arco before flowing out onto the Arco fan and the alluvial plain north of Lago di Garda (Bassetti et al., 2013; Baroni et al., 2014). The Lago di Garda bedrock structure, and its northern prolongation into the lower Sarca Valley, suggests a very deep, steep-walled valley formed during the late Miocene related to desiccation of the Mediterranean (Bini et al., 1978).

2.2. Bedrock stratigraphy

The release area of the studied landslides is dominated by rocks of the Calcari Grigi Group (Lower Jurassic), which were deposited on the Trento carbonate platform during the Early Jurassic (Castellarin et al., 2005a, 2005b) (Figs. 3 and 4). The rock units exposed along the Mt. Brento- Mt. Casale rock wall are described herein in stratigraphic order from bottom to top (Castellarin et al., 2005b; Avanzini et al., 2010). The Monte Zugna (FMZ) consists of peritidal dolomitic limestones with fenestrae and stromatolites, as well as micritic limestones (mudstone and wackestones) rich in fossils, such as bivalves and algae (age: Rhaetian?- Sinemurian). Overlying the FMZ lies the Calcare Oolitico di Loppio (LOP), which is characterized by cream-colored grainstones with ooids and botroids and common intra- and bioclasts (age: Sinemurian). This unit is followed by the Rotzo Fm (RTZ) comprising subtidal micritic limestones, intercalated with dark to greenish marly levels. Biocalcarenites can be present at the top of the formation (Sinemurian to Pliensbachian). The Tovel Member of the Rotzo Fm (RTZ1) consists of alternating gray micritic sediments mostly mudstone and wackestone, and gray to yellow packstone/wackestone with bioclasts and algae. In the upper part chert nodules are present (Sinemurian to Pliensbachian). The next unit is the Oolite di Massone (OOM) an oolitic micritic limestone with gray sparry calcite cement with cross and parallel lamination. Oolites and oncoids are relatively large; they are dominant over bioclasts (upper Pliensbachian). The OOM is followed by the San Vigilio Oolite (OSV), which typically consists of radial oolitic grainstone with crinoids and encrinites (Toarcian-Aalenian). The uppermost unit at Mt. Casale in the study area is the Rosso Ammonitico Veronese (ARV). These comprise pink to red nodular micritic limestones (Bajocian-Tithonian).

2.3. Structural setting

The lower Sarca Valley and Lago di Garda region are dominated by the NNE-SSW oriented Giudicarie fold-and-thrust belt, with its intricate structural pattern (Fig. 1) resulting from a polyphase deformation history since the Mesozoic (Avanzini, 1992; Picotti