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CHARACTERISTICS AND DATING OF THE ROCK AVALANCHE AT PRAGSER WILDSEE/LAGO DI BRAIES (DOLOMITES, ITALY).

Marc Ostermann [1], Susan Ivy-Ochs [2], Frowin Ruegenberg [3], Christof Vockenhuber [2]

[1] Geological Survey of Austria, Vienna, Austria.
[2] Ion Beam Physics, ETH, Zurich, Switzerland.
[3] Department of Geology, University of Innsbruck, Innsbruck, Austria.

Corresponding author: M. Ostermann <marc.ostermann@geologie.ac.at>

ABSTRACT: Major gravitational slope deformations are widely disseminated in the Dolomite Mountains (NE Italy), one of the world's most conspicuous landscapes and part of the UNESCO world heritage list. In the Prags valley a rock avalanche still dams a backwater lake - the Pragser Wildsee/Lago di Braies. The volume of rock debris accumulations comprise approximately 30-40 10^6 m³ of mainly dolomitic rock and the area covered by rock debris is about 3.5 km². The run-out distance of about 8.5 km and a maximum vertical drop of 1150 m (H/L-ratio: 0.13) yield a run-out travel angle (Fahrböschungswinkel) of 8°.
Especially in the surrounding of Schmieden/Ferrara a hummocky landscape with numerous hills and ridges is developed. Here some classical Toma hills are encountered, i.e. isolated cone- to pyramidal- or roof-shaped hills composed of rock avalanche debris. Mainly because assumptions about the origin of this hummocky landscape has been related to glacial processes, the formation of Pragser Wildsee was previously thought to be of Lateglacial age.
We applied cosmogenic ^{36}Cl surface exposure dating of four boulders within the debris accumulations and obtained an early Holocene age of 8.3±0.7 ka for the event. Our findings go along with the results of published radiocarbon dates from sediment-drill-cores within the backwater lake, which indicate a recalibrated minimum age for the slope failure of 7410±100 cal years BP (Irmler, 2003).
The accumulations at Pragser Wildsee show strong similarities to the Obernberg rock avalanche in geomorphology as well as in age, making them the first examples of early Holocene rock avalanches forming Toma hill landscapes.

Keywords: Rock avalanche, early Holocene, cosmogenic nuclide dating, Toma hills, Pragser Wildsee/Lago di Braies, Dolomites.

1. INTRODUCTION

In the past, several hypotheses have been formulated regarding the formation of the Pragser Wildsee/Lago di Braies. Although it was clear that the lake was dammed by debris deposits, their origin was controversial. It was especially the hilly valley bottom morphology downriver of the lake itself that caused speculations. According to Damian (1899), Hantke (1983) and Heiss (1992), a huge debris flow fan, spreaded from the Riedl valley (Figs. 1, 2), together with smaller landslides and rock falls gave rise to the damming of the lake. Another hypothesis considered the wide deposits as glacial (Dal Piaz 1930; Pia, 1937) or composed of landslide masses subsequently transported and rearranged by a glacier (Klebelsberg, 1927, 1935, 1956; Castiglioni, 1964; Engelen, 1972). Abele (1974) instead assumed that Pragser Wildsee/Lago di Braies was dammed by a massive rock slope failure event. Recently, the deposits have been described more in detail by Furlanis (2013) and in the comments to the recently published geological CARG map sheet 016 Toblach/Dobbiaco (Gianolla et al., 2018). The reclassification of deposits previously misidentified as having origins other than landsliding has been done commonly in the last decades (e.g. Spreafico et al., 2018).

Here, we describe the results of an extensive fieldwork, including sedimentological, morphological analyses and dating of the rock avalanche in the Prags Valley.

2. METHODS

Field mapping was conducted on a scale of 1:5000 using topographic maps and airborne laserscan images in 10 m resolution provided by the Autonomous Province of Bolzano - South Tyrol. Geometric calculations including volume estimations were made with AutoCAD 2014. The estimations of the deposit thickness is based on the information from a 20 m long drill core conducted by the Geological Survey of South Tyrol (Fig. 3).

For exposure dating with ^{36}Cl in the proximal sector of the rock avalanche, the surfaces of four boulders were sampled (Tab.1). Sample preparation is described in Ivy-Ochs et al. (2009). ^{36}Cl and natural Cl (isotope dilution; Ivy-Ochs et al., 2004) were determined with

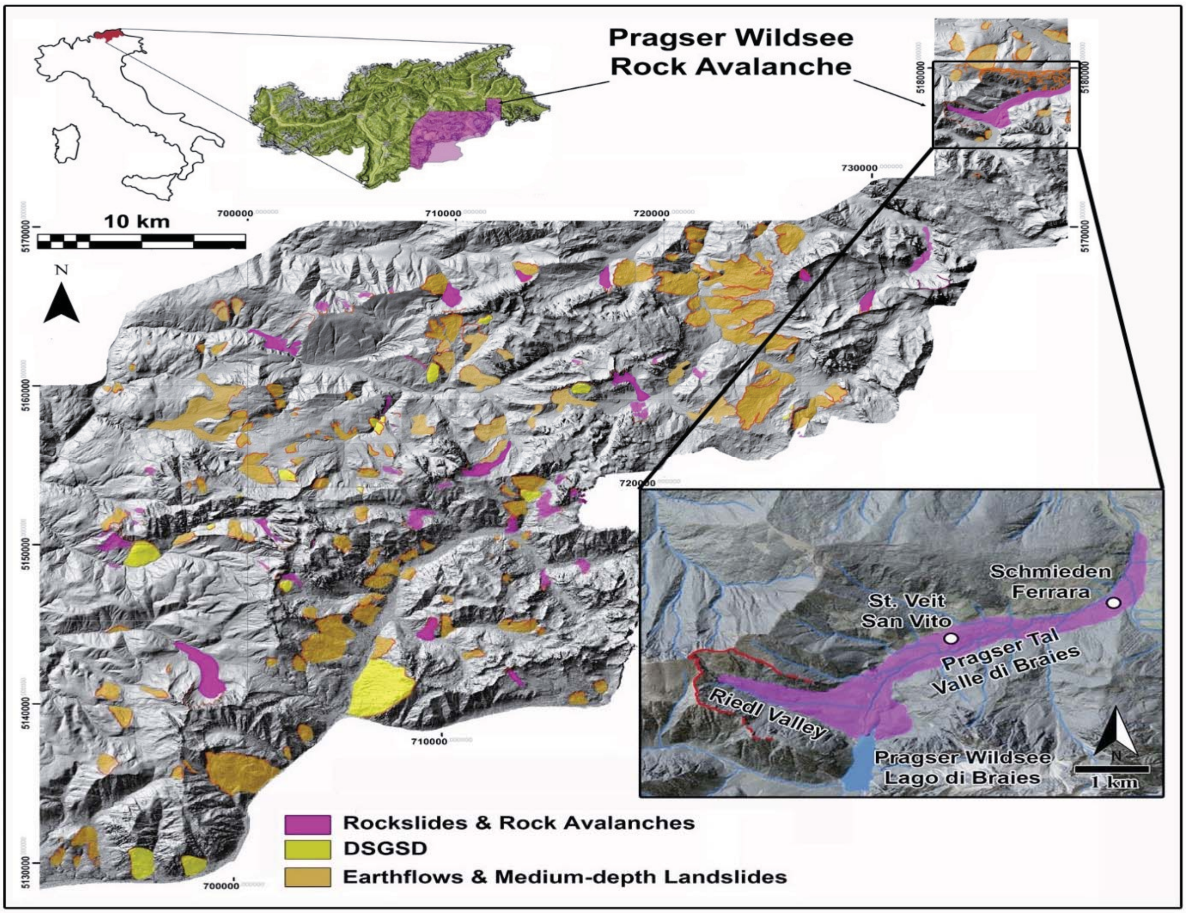

Fig. 1 - Distribution of major mass movements in the western Dolomites, Italy, indicated on a hill-shade image (acc. to Ostermann & Gruber, 2014, based on Brandner et al., 2007a). DSGSD stands for Deep-seated gravitational slope deformation. The insert-map shows the assumed maximum extent of the rock avalanche with removed post-failure accumulations (mainly debris flow fans). The red line represents the scarp.

accelerator mass spectrometry (Synal et al., 1997). Major element and minor concentrations (Tab. 2) were used to determine ^{36}Cl production rates (Alfimov & Ivy-Ochs, 2009 and references therein).

The radiocarbon age published by Irmler (2003) were re-calibrated with OXCAL 4.3 (Bronk Ramsey, 2009).

3. GEOLOGICAL FRAMEWORK

The Prags Valley/Braies Valley is located in the northeastern part of the Dolomites, which are part of the Southern Alps. The Dolomites consist mainly of the marine sediments of the Upper Permian and Triassic periods, which were deposited in tropical to subtropical climate on Permian volcanic rocks and, as in the vicinity of the Puster Valley, on metamorphic crystalline basement rocks (Brandner et al., 2007b) (Fig. 2). Regarding to the Pragser Wildsee rock avalanche there are three lithologies within the Permo-Mesozoic sediment succession (Fig. 2) which are important to describe more in detail, because these are the formations involved in the phenomenon.

The Buchenstein Formation: pelagic basin sediments that interlock with the clinoforms of the prograding Ladinian carbonate platforms (Brandner et al., 2007b). The limestones of the Buchenstein Fm. is well-bedded (cm-dm), partly bituminous and laminated (Keim, 2008).

Thin volcanogenic clastics “Pietra Verde“-layers (cm-dm) are interbedded - decreasing the mechanical properties of the whole succession.

The Schlern Formation consists of pre- and post-volcanic carbonate rocks, which formed mighty reefs or their clinoforms in the Ladinian. The reef slope interlocks with the basin sediments of the Buchenstein Formation. The rocks were formed in a tropical subtropical climate (Muttoni et al., 2003) in marine shallow waters and later dolomitized, whereby the coarse banking is relatively unclearly recognizable (Pia, 1937).

The Fernazza Formation corresponds essentially to the basin-deposits of the proximal, alkaline volcanic activity in the Dolomites. The most common lithotypes are volcanoclastic, turbiditic, massive sandstones, homogeneous or graded, dark green to blackish colour, greenish tuffites of the "Pietra Verde" type, siliceous tuffites, hyaloclastites and laminated calcareous siltites. Laminated, siliceous calcareous lutites, hemipelagites and marls are also found in between. At the top of the

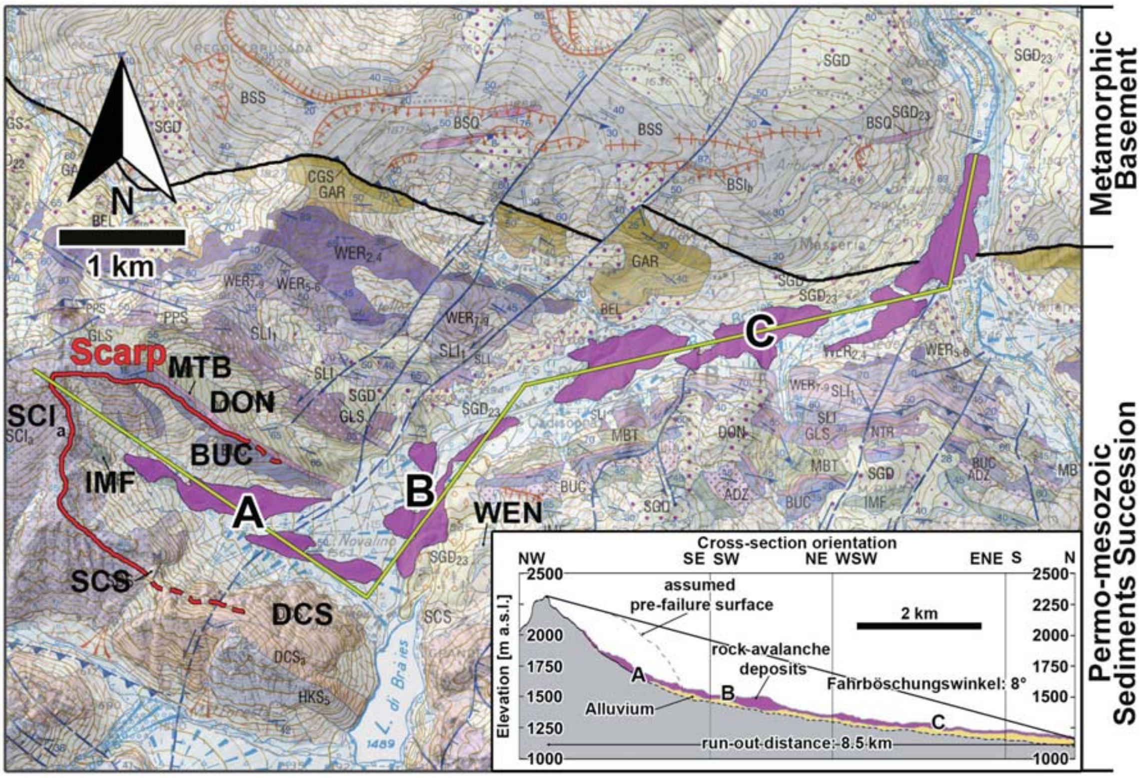

Fig. 2 - Geological map of Prags valley (modified detail of the Carta Geologica d'Italia alla scala 1:50.000, map sheet 016 Toblach/ Dobiaco). In magenta the nowadays outcropped debris accumulations are highlighted. A-C indicate the three different accumulation areas mentioned in the text. SCS: St. Kassian Fm.; SCIa: Schlern Fm. in reef facies; IMF: Fernazza Fm.; DCS: Kassianer Fm.; BUC: Buchenstein Fm.; MTB: Ambata Fm.; DON: Dont Fm.; WEN: Wengen Fm.; The full legend can be found in Gianolla et al., 2018. The black line indicates the thrust fault separating the Permo-mesozoic sediments succession in the South from the metamorphic basement in the North. The green line indicates the orientation of the schematic cross-section (insert figure, 2 x super-elevated).

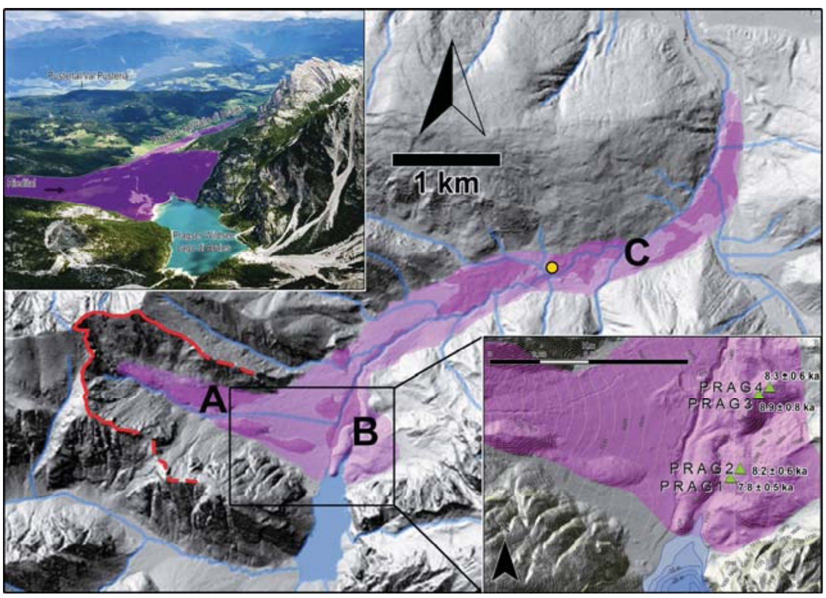

Fig. 3 - Hillshade image of the Prags valley with indicated rock avalanche accumulations in magenta: light magenta for the maximum extent of the accumulations, dark magenta indicates the accumulations as drawn in the Geological map. Red line: main scarp. The yellow circle indicates the location of a 20m long drilling, conducted by the South-Tyrolian Geological Survey. The insert photo, view towards north, shows the Pragser Wildsee in the foreground and the Riedl valley and the Prags valley with indicated debris accumulations in the background. The insert-map shows a detail of the hillshade with 10 m contour lines and the sampling points for surface exposure dating with obtained ^{36}Cl ages.

Fernazza Fm. fine-grained calcarenites and marly limestones are present.

4. CHARACTERISATION OF THE ROCK AVALANCHE SCARP AND THE SLOPE FAILURE ACCUMULATIONS

4.1. Characteristics of the scarp area

The scarp area of the rock avalanche is located in the upper part of the Riedl valley at elevations between about 2000 and 2350 m a.s.l. (Fig. 3). Schlern Fm. is the prevalent formation in the crown area which is also reflected in the lithological composition of the debris accumulations. Along the southern and south-western flank of the Riedl valley, here a well-banked Schlern Fm. is exposed. The banks dip with $\geq 60°$ towards S-SW (more or less parallel to the northern slope) represented a predisposing factor for a dip slope slide (e.g. Abele, 1974; Hoek & Bray, 1981). The Schlern Fm. also shows pronounced jointing and partly karst-widened cracks, which were already mentioned by Pia (1937). There are several tectonic lineaments, in different orientations, nearby the scarp area (Fig. 2) and many rock slope failures show these tectonic constrains (e.g. Stead & Wolter, 2015), but we could not find convincing evidence for tectonic lineaments that delimited the failed rock mass here. According to the map of Van Husen (1987) the LGM-ice surface in the Prags valley was between 2300 and 2400 meters a.s.l., which hints that the scarp area at least was partly covered with ice during this period.

4.2. Characteristics of the rock avalanche accumulation area

The accumulation area of the rock avalanche at Pragser Wildsee can be divided into three distinguishable areas (A-C) (Fig. 2 & 3).

A) Area A refers to the proximal deposits in the Riedl valley. Here the deposits are mainly (>95%) composed of Schlern Fm. blocks, which are strongly weathered and can reach several tens of cubic meters in volume lying on top of finer material (carapace facies). The accumulations are partly overlaid by deposits of secondary landslides coming from the north (shallow landslides, slope debris). In the southern part of the Riedl valley, debris flows accumulation overlay the rock avalanche deposit, mainly consisting of reworked and relocated landslide material.

B) Accumulation at Area B (Fig. 2 & 3) is located on the west side of Herrstein and forms a proximal surge barrier with a maximum total thickness of about 150 m, which was created under high-energy conditions on the opposite slope. The sediments here consist of a massive, matrix-supported diamict with a loose and

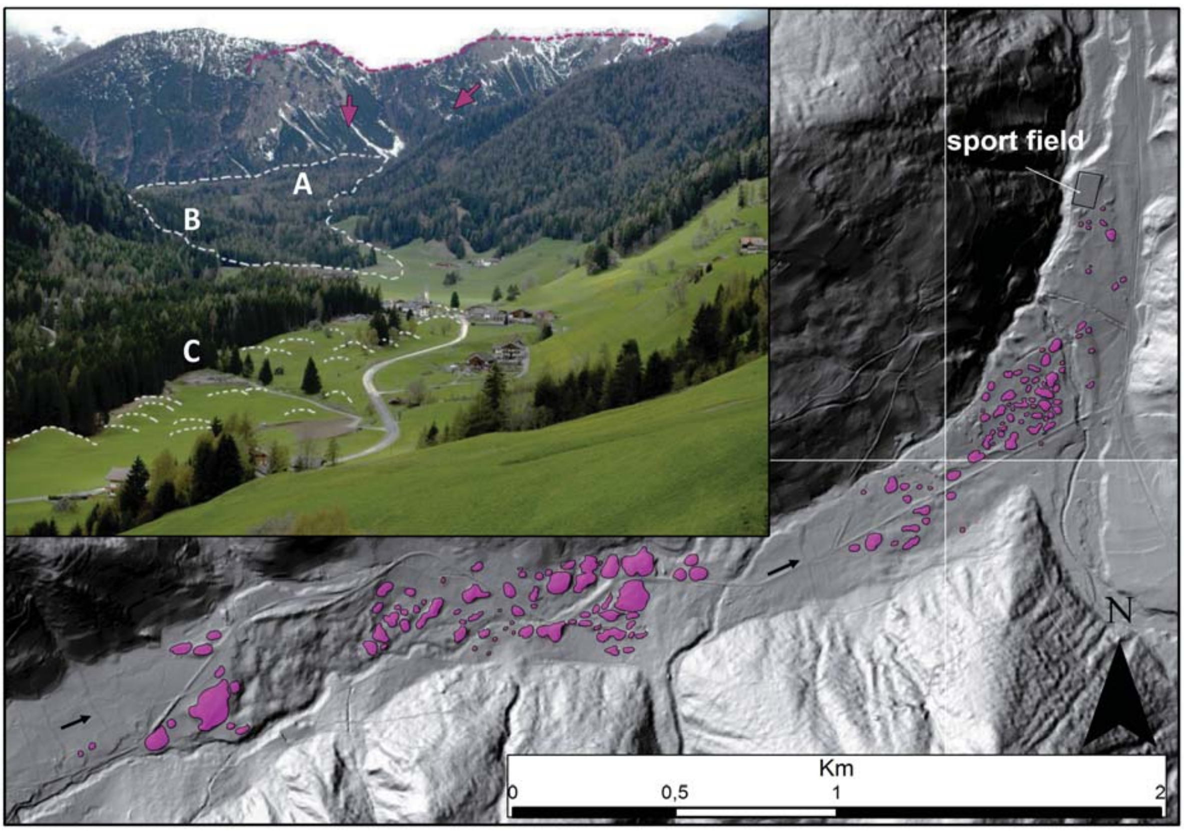

Fig. 4 - Hillshade image of the outer Prags valley with highlighted Toma hills and debris ridges (magenta). The arrows indicate the travel path of the rock avalanche. On the insert photo, view towards southwest, the scarp is indicated with a dashed line in magenta and the accumulations with a dashed with line. In the foreground the Toma hills and ridges are accentuated.

Sample	Lat. (°N)	Long. (°E)	Elevation (m a.s.l.)	Thick (cm)	Shielding corr.	^{36}Cl/Cl measured 10^{-12}	Cl (ppm)	^{36}Cl 10^5 atoms/g rock	Exposure age (years)
PRAG1	46.7011	12.0894	1553	2	0.988	0.0093	61.4 ± 0.9	0.572 ± 0.025	7820 ± 450
PRAG2	46.7015	12.0900	1530	2.5	0.988	0.0103	63.0 ± 1.1	0.652 ± 0.037	8180 ± 550
PRAG3	46.7047	12.0927	1520	2	0.995	0.0047	134.4 ± 1.9	0.630 ± 0.029	8890 ± 765
PRAG4	46.7047	12.0933	1527	3	0.987	0.0070	85.3 ± 2.6	0.591 ± 0.037	8280 ± 640

Tab. 1 - Sample information, AMS data and calculated exposure ages. Exposure ages were calculated using Stone et al.(1996, 1998) production rates (see also Alfimov & Ivy-Ochs, 2009) and Lal /Stone scaling (Stone, 2000). No erosion correction was made.

	PRAG1	PRAG2	PRAG3	PRAG4
SiO_2	0.48	0.29	0.20	0.17
TiO_2	0.007	0.003	0.001	0.004
Al_2O_3	0.20	0.12	0.10	0.12
Fe_2O_3	0.01	0.06	0.06	0.05
MnO	0.011	0.014	0.013	0.011
MgO	7.26	2.98	20.97	10.75
CaO	45.45	51.69	30.67	41.90
Na_2O	0.04	0.03	0.04	0.03
K_2O	0.09	0.05	0.02	0.01
P_2O_5	0.02	0.02	0.02	0.02
L.O.I.	*43.68*	*43.75*	*46.98*	*44.62*
Total	97.25	99.01	99.06	97.68
Gd	0.2	0.1	0.3	0.2
Sm	0.2	0.2	0.2	0.2
Th	0.2	0.1	0.1	0.1
U	0.4	0.6	0.8	0.4

Tab. 2 - Chemical composition of analysed rock samples, major oxides in wt %, trace elements in ppm.

partially open framework structure. Blocks and megablocks of massive dolomites are found, the matrix is gravelly and slightly sandy. All components are from angular to sub-rounded. It represents the main accumulation zone of the rock avalanche and it is primarily responsible for the damming of the lake. The morphology can be described as very unsettled. On the surface, there are dark weathered blocks of Schlern Fm., up to several 10 cubic metres in size, in non-exposed areas the blocks are angular. Landslide material is also found on the NW shore of the lake below the debris cone from the Riedltal valley, which was confirmed by sediment-echographic investigations (Irmler, 2003).

C) Area C represents the distal part of the rock avalanche deposits in the Prags valley and it is primarily characterized by the presence of undulating relief known as Toma hills. Their genesis is directly connected to the rock slope failure event. The Prags valley therefore is a very beautiful example of a so-called Toma landscape (Penck & Brückner, 1901; Abele, 1974). In many places the landslide material is overlain by debris flow and alluvial material from the side valleys, but can be traced back up to the sports field north of the village of Schmieden/Ferrara (Fig. 4). Within the accumulation area C the thickness of the deposit was estimated to be only 5 m. Beside some blocks of Schlern Fm. in meter scale, there are mostly poorly sorted, angular components in cm-dm size. The average size is therefore finer than the material at accumulation area B. Contrary to older assumptions (e.g. Klebelsberg, 1935; Pia, 1937; Castiglioni, 1964; Abele, 1974) the rock avalanche material in the Prags valley was not transported by a glacier out of the valley. There is no evidence of glacial transport, nor of glacial overlay.

4.3. Geometrical characteristics of the Pragser Wildsee rock avalanche

Rock avalanche deposits exposed at the surface cover an area of ~1.7 km^2. Taking into account those parts of the avalanche that are buried by alluvial fans, talus slopes and colluvium, an area of ~3.5 km^2 was estimated. The distance from the upper limit of the detachment scarp (2330 m a.s.l.) to the most distal Toma hill (1180 m a.s.l.) is 8.5 km, yielding a Fahrböschung angle of 8°.

According to our calculation based on a digital elevation model, the total volume of rock avalanche deposits is 36 million m³, so a volume between 30 and 40 million m³ can be given.

5. DATING THE PRAGSER WILDSEE ROCK AVALANCHE

For exposure dating with ^{36}Cl, in the proximal sector of the rock avalanche (accumulation area B), the surfaces of four boulders of Schlern Dolomite were sampled (locations in insert map in Fig. 3). Unfortunately, the distal sector of the avalanche deposit (accumulation area C) with transversal ridges and Toma hills is devoid of suitable boulders (those lying well above the enclosing sediment). We obtained the following exposure ages: 7.82 ±0.45 ka (PRAG1), 8.18 ±0.55 ka (PRAG2), 8.89 ±0.76 ka (PRAG3), and 8.28 ±0.64 ka (PRAG4). Sample site and dating information is given in Tab. 1 and the chemical composition of the samples in Tab. 2. The average age of 8.3 ±0.7 ka indicates an early Holocene age for the rock avalanche event.

Rock avalanche	Volume m^3	Area km^2	Fahrböschung	H/L-ratio	Runout km	Total vertical distance m	Age ka
Pragser Wildsee	~30-40 10^6	~3.5	8°	0.13	8.5	1150	8.3 ±0.7
Obernberg	~45 10^6	~3	10°	0.18	7.2	1330	8.6 ±0.6

Tab. 3 - Major parameters of the rock avalanches at Pragser Wildsee and Obernberg.

At the base of a 12.1 m long drill core a tree needle was found during the investigations of the lake deposits by Irmler (2003). Its age was determined by ^{14}C dating. The age was determined to 6504 ±47 uncal. years BP which corresponds to a calibrated ^{14}C age of 7410 ±100 cal. years BP. This age can be regarded as the minimum age of the lake and therefore as a minimum age of the landslide.

6. DISCUSSION

The Pragser Wildsee/Lago di Braies rock avalanche shows conspicuous similarities to the Obernberg rock avalanche (Ostermann et al., 2012) situated about 60 km in the NW of the Prags valley within the Brenner Mesozoic (Eastern Alps, Austria). Both rock avalanches show runout paths with a runup/impact on the opposite slope and a further propagation within a narrow valley that changes its orientation several times. The conceptual model of the kinematics is discussed in Ostermann et al. (2012) and in Tab. 3 we summarize the basic parameters of both rock avalanches.

The age of 8.3 ±0.7 ka of the Pragser Wildsee rock avalanche and the 8.6 ±0.6 ka Obernberg rock avalanche may suggest a relation with the "8.2 ka cooling event" (cf. Rohling & Pälike, 2005), but for more detailed discussion about this potential relationship, refer to Ostermann et al. (2012). Nevertheless, we underline the importance of strong tectonic events as triggers for Holocene rock avalanches (e.g. Ambrosi & Crosta, 2006; Prager et al., 2008) and there are recent (e.g. 2008 Wenchuan earthquake, Guo et al., 2015) and historic (e.g. 1348 Villach earthquake, Brandt, 1981) examples for earthquake triggered landslides.

7. CONCLUSIONS

1 According to the results of surface exposure dating of boulders we think that the Pragser Wildsee rock avalanche occurred 8300 ±700 years ago; this age is supported by a ^{14}C minimum age of 7410 ±100 a cal BP of organic remnants from a drill core out of the backwater sediments within the Pragser Wildsee (Irmler, 2003).

2 The Pragser Wildsee rock avalanche is one of the few dated mass-wasting event in the Alps that potentially was associated with the 8.2 ka climatic cooling. The precise nature of the 8.2 ka event in the Southern Alps, however, is insufficiently documented to sustain speculations on a triggering cause of the rock avalanche under a particular climatic condition.

3 The distal 3.5 km of rock-avalanche deposits show an array of transverse ridges and Toma hills. These were previously interpreted as moraines and kames. The internal fabric and nature of the sediment of the ridges are, however, incompatible with glacial moraines, but consistent with an origin from a rock avalanche.

4 Several factors can be named as predisposing for the rock avalanche at Pragser Wildsee: the tectonic/structural framework of a dip-slope layered rigid calcareous sediment succession, dissected by faults and joints, the destabilization in the upper part of the Riedl valley due to pronounced facies interlocking and the karstification, especially in the Schlern Fm.

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