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Forensic investigations of the Cima Salti Landslide, northern Italy, using runout simulations

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A B S T R A C T

Over the last decades, a movement has begun to reclassify deposits previously misidentified as having origins other than landsliding. The reverse problem of incorrectly assigning deposits a mass movement origin, however, has been addressed less in the landslide community. The Cima Salti Landslide in the Lake Garda region of Northern Italy is a cautionary tale of assuming source areas and volumes. It was traditionally thought to have dammed Tenno Lake in the Middle Ages, and to have a volume of 20–30 Mm^3. We show through geological field data and simple runout simulations with the codes DAN3D and SHALTOP (which produced comparable results) that the volume of the landslide was likely significantly overestimated in the past, and that it most likely did not dam Tenno Lake, as has been assumed. We propose that a smaller volume landslide (2–5 Mm^3) was deposited on stagnant ice melting in situ in the Lateglacial period, a relatively minor event in the complex history of the Magnone valley. This interpretation emphasizes the importance of careful field investigations and assumption validation, at Cima Salti and in a broader context. It also shows the unique capacity of landslide simulation to guide field observation and discriminate mass emplacement processes.

1. Introduction and setting

Over the last few decades, landslide research has focused on exposing and highlighting material that had previously been classified as having other origins, expanding the global inventory of landslides (cf. Hart et al., 2012; Reznichenko et al., 2012; Reznichenko and Davies, 2015; Schleier et al., 2015). Assumed landslides, however, have also been misidentified and misrepresented (McColl and Davies, 2011; Brunet et al., 2016, 2017), with implications for hazard assessment. In this paper, we present the cautionary tale of the Cima Salti Landslide in Northern Italy, that was hypothesized to be responsible for the formation of Tenno Lake. Our aim is to expand the understanding of the landslide within the context of the evolution of the Magnone valley, and to determine, ultimately, how Tenno Lake was dammed. The paper addresses first the geomorphic and geological context of the landslide as well as methods applied to investigate it, then summarises the results of runout simulations of volume considerations and glacier presence and absence.

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The Cima Salti Landslide is situated north of Lake Garda in the Trentino region of Italy. It has an obvious headscarp with a crown at approximately 1220 m asl on the NE slope of Cima Salti, but the lower limit of the depletion zone and the extent of the deposit are not clear. The Fahrböschung of the landslide is 21.8°. Talus covers most of the slope at present, and this material locally remobilised during a rotational sliding event in 2000. After this recent event, the slope was further altered by stabilization works (Fig. 1).

The Magnone valley has a complex history (Fig. 2). It is dissected by reverse and transpressive faults, including two NNE-striking reverse faults in the crown area of the landslide. The valley is divided by the Ballino line, a major transpressional fault that inverted a previous rift structure, separating two distinct Mesozoic facies (Castellarin and Picotti, 1990). The peak of Cima Salti comprises bedded, high-strength (Uniaxial Compressive Strength, UCS = 100–200 MPa, estimated in the field) Maiolica Fm limestones (Uppermost Jurassic to Lower Cretaceous) crosscut by two discontinuity sets and several faults, with the underlying Selcifero Lombardo Fm radiolarites (Middle to Upper Jurassic) and Tofino Fm cherty limestones (Lower to Middle Jurassic) downslope (Fig. 3).

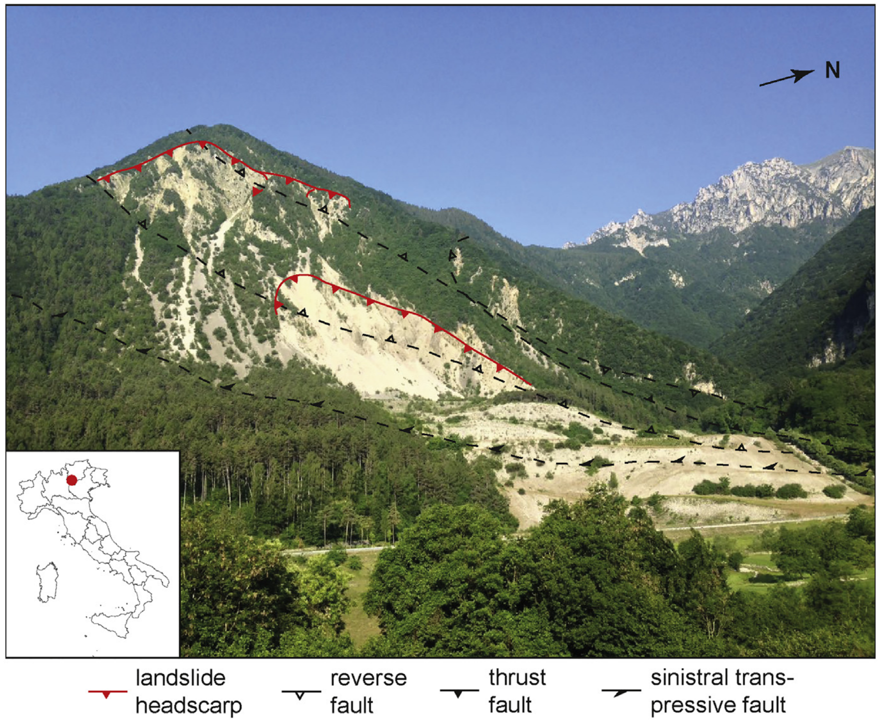

Fig. 1. View of the Cima Salti slope in northern Italy. The upper headscarp is the Cima Salti landslide scarp, the lower the 2000 event. Faults after Picotti (2003). Image taken by authors (June 2017).

During the Pleniglacial, a branch of the main Adamello-Adige-Garda glacier flowed to the south over the Ballino transfluence saddle, located just north of Tenno Lake. In the Lateglacial age, this transfluence was deactivated and the Magnone valley was obstructed by a shallower ice tongue flowing north. During its retreat, this glacier deposited several orders of sinuated moraines, the most continuous of these at the base of Cima Salti and south of Tenno Lake. Erosional remnants of lake sediments have been found at elevations decreasing from approximately 740 to 600 m asl in the area, suggesting multiple ice-contact lakes (Picotti, 2003).

Considering the regional context, several large rock avalanches affected the Trentino region during the Lateglacial and the Holocene, contributing significantly to landscape evolution in the area (Fuganti, 1969; Perna, 1974; Chinaglia, 1993; Bassetti, 1997). For example, in

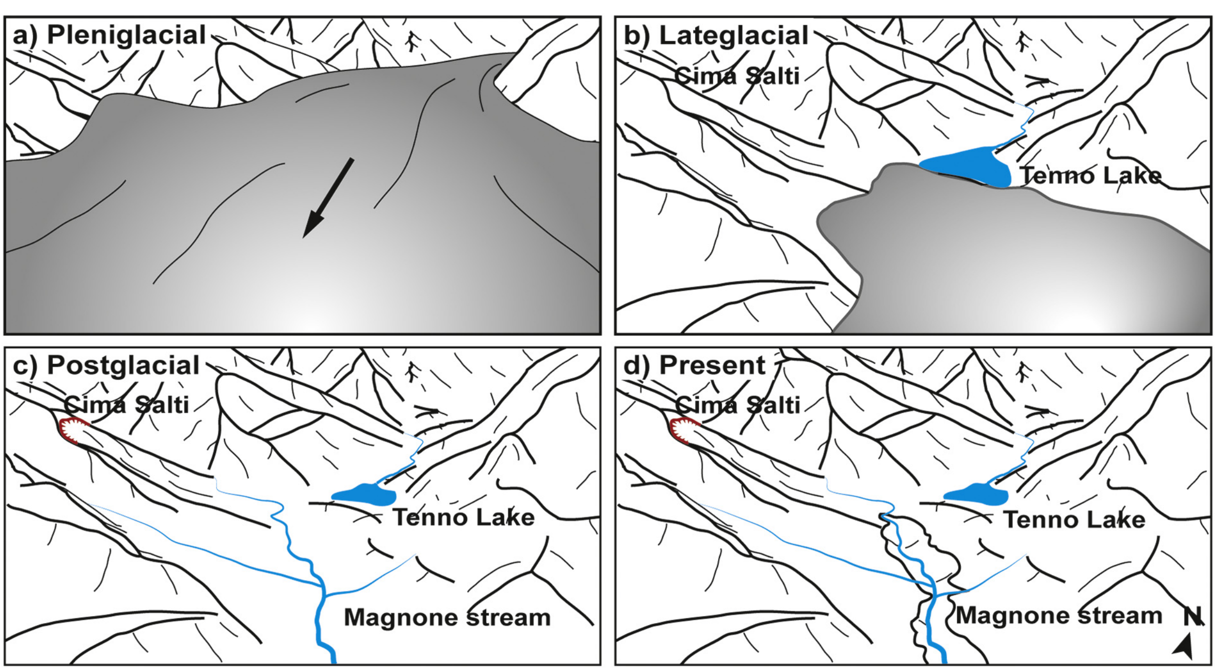

Fig. 2. Evolution of the landscape in the Cima Salti area. a) Pleniglacial ice flowing to the south. b) Lateglacial ice coming from the south. c) Postglacial landscape with headscarp of the landslide in red. d) Present topography with the incision of the Magnone stream.

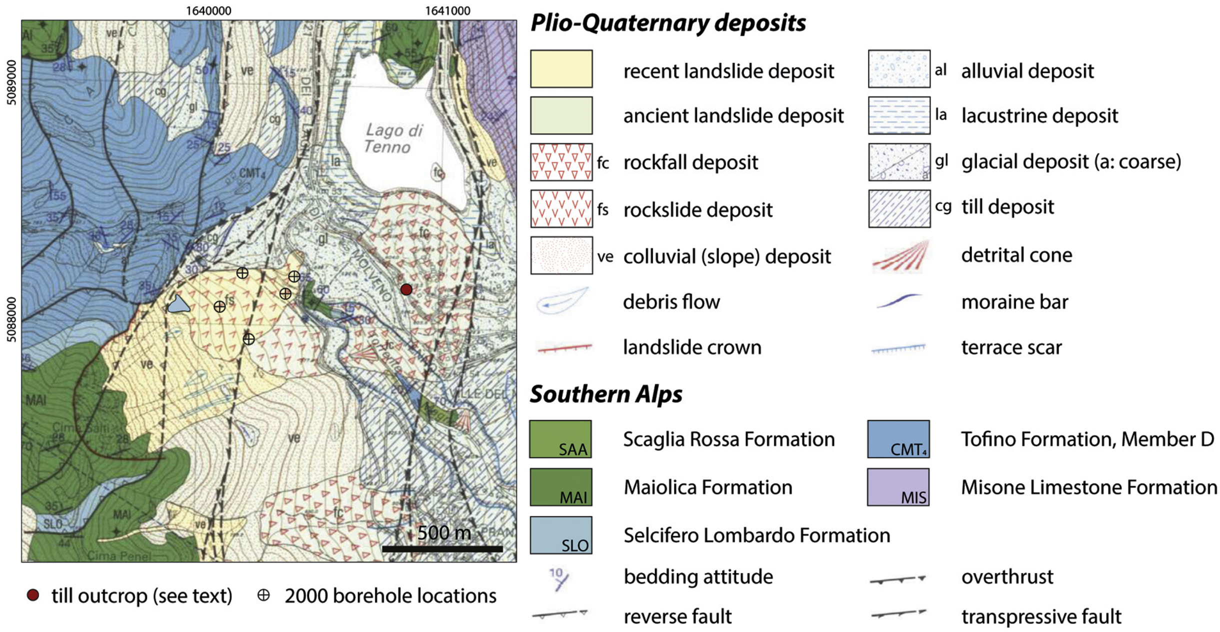

Fig. 3. Geological map of the Cima Salti area, modified after Picotti and Tommasi (2002). Till outcrop refers to the outcrop described in the text. Coordinates are in the ROMA 1940 UTM Sistema Geodetico Nazionale.

the Sarca valley large deposits comprising limestone megaboulders, known as "Marocche", can be found (Trener, 1924; Perna, 1974; Chinaglia, 1993; Bassetti, 1997). Trener (1924) recognised three large landslides and nine small events. Based on the finding of Roman relics, he suggested a post-Roman age for at least one of them. More recently, Perna (1974) dated the "Marocche" deposits using paleo-karst features to post-Last Glacial Maximum. Bassetti (1997) identified six landslides and found Bronze Age materials within the deposits, and suggested an historical age. Based on ^{36}Cl exposure dating of carbonate megaboulders, Ivy-Ochs et al. (2017) dated the main "Marocche" rock avalanches to around 5000 years BP. Two periods of enhanced landslide activity followed: one around 1600 years BP (late Roman Age) and one Medieval, which may have been triggered by the 1117 CE Verona Earthquake (Guidoboni et al., 2005). The Lavini di Marco rock avalanche (Orombelli and Sauro, 1988; Tommasi et al., 2009), whose deposit dammed and deviated the Adige River, was supposedly triggered by this earthquake (Guidoboni et al., 2005; Galadini et al., 2001: 1040–1215 CE). Recently, however, Martin et al. (2014) showed that the Lavini di Marco rockslide deposit dates to 3000 ± 400 years BP. Some ages on the sliding plane record small-scale reactivations; a single age of 800 ± 210 years suggests a reactivation at Lavini di Marco coincident with the Verona earthquake. Galadini et al. (2001) related the Cima Salti Landslide to the same seismic event.

Several previous authors, including Dalla Torre (1913), Venzo (1935), Tommasi (1963), Vaia (1981), and Pirocchi (1992), have assumed that Tenno Lake, located at the NE border of the landslide at 570 m asl with a current maximum depth of 47.7 m and an area of 0.22 km^2 (APPA, Trento Province, 2017), was dammed by the Cima Salti Landslide, and that the topographic high in the centre of the Magnone valley comprises the landslide deposit. Relatively young radiocarbon ages (950–1380 CE) of submerged trees in the lake seem to support their theory of a 1300 CE event (Alessio et al., 1973). Penck and Brückner (1909), Picotti and Tommasi (2002), Picotti (2003), and Ghirotti et al. (2015), however, interpreted most of the surficial material as till, based on field observations. Outcrops are extremely limited in number due to vegetation cover and anthropic reworking of material. Nonetheless, one small outcrop in the centre of the valley (see Fig. 3) indicates lodgment till overlying pre-Quaternary bedrock, with 40% reddish-brown silty matrix surrounding, 60% polymictic clasts (cm to dm scale) and underlying 30 cm of brownish soil. Boreholes drilled on the Cima Salti flank in 2001–2002 show 30–60 m of gravel assumed to be pre-2000 landslide debris overlying up to 30 m thick dark clayey silts assumed to be lacustrine deposits in direct contact with bedrock. The clayey silts were absent toward the lake. Unfortunately, no boreholes were drilled outside the 2000 landslide extent, and hence conclusions about the centre of the valley are limited to isolated outcrops of till. Critical in distinguishing till from landslide deposits is lithology (texture, origin and shape of clasts) and degree of induration, weathering and fragmentation. The till deposits in the area are polymictic and tend to be matrix-supported, whereas the landslide deposits comprise solely Maiolica blocks and are clast-supported. According to Penck and Brückner (1909), Picotti and Tommasi (2002), Picotti (2003), and Ghirotti et al. (2015), the ridge damming the modern Tenno Lake consists of a rock drumlin covered with the ablation till of the Lateglacial moraine and partially with Maiolica blocks, deriving from the Cima Salti event. The submerged trees in the lake, in the opinion of these latter authors, could indicate later fluctuations in the lake levels.

The Cima Salti Landslide, therefore, may not have changed the valley morphology significantly. Ghirotti et al. (2015) proposed that the landslide may have occurred when ice was still in the valley, hypothesizing that the glacier could have transported a portion of the landslide deposits downvalley. Thus, two hypotheses regarding the timing of the landslide exist: i) the landslide occurred in the Middle Ages, long after deglaciation in the area, and ii) the landslide is older, perhaps coinciding with the Lateglacial period, like other rock avalanches in the region.

The landslide volume is also debated. Initially, a larger volume of 20–30 Mm^3 concerning the whole slope was hypothesized, based on geomorphological features on the Cima Salti slope (Ghirotti et al., 2015). During our field survey however, only a few boulders were recognised as belonging to the landslide (Fig. 4). A lithological boundary between limestones of the Maiolica Formation and radiolarites of the Selcifero Lombardo Formation was identified at 950–1000 m asl in the depletion zone of the landslide. No radiolarite blocks were found in the deposit area, suggesting the source area was much smaller than originally proposed, with a volume of 2–5 Mm^3, and included only Maiolica blocks. If the landslide did involve the whole slope, a significant portion of the deposit is now missing. This could result from erosion and transport by the Magnone stream or transport by an actively retreating glacier. Neither hypothesis is satisfactory, because the erosion rate and transport capacity of the stream would have had to be extremely high,

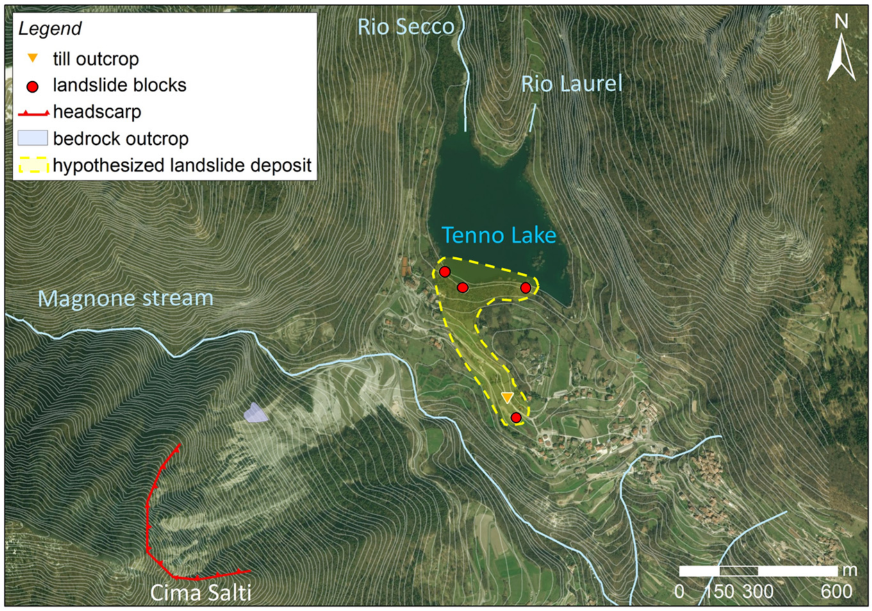

Fig. 4. Orthophoto of the study area; red points represent the rock blocks identified as belonging to Cima Salti landslide deposit. An interpretation of the current landslide deposit boundary is shown in yellow. Light blue curves represent local streams.

and no landslide deposits have been found downstream (Picotti, 2003; Ghirotti et al., 2015).

2. Methodology and model validation

This paper focuses on the use of runout modeling to understand landslide dynamics and valley evolution, and tests the two hypotheses mentioned above (Lateglacial vs. Middle Ages event). Landslide simulation is a good tool to confirm or question emplacement processes inferred from geological observations. As an example, such granular flow simulations of landslide runout were performed in Brunet et al. (2017) to investigate the size of individual past debris avalanches in Martinique, Lesser Antilles. Results supported field observations suggesting that these debris avalanches were much smaller than previously thought.

Granular flow models on real topography are currently used to simulate natural landslides. They are generally based on the thin-layer depth-averaging of the mass and momentum conservation equations, assuming a relatively small thickness of the fluid compared to its other dimensions, and include different friction laws. We decided here to perform simulations using two codes, namely DAN3D and SHALTOP, widely used and validated on laboratory experiments and past landslide studies. The use of two codes may strengthen event reconstruction if the results are comparable in terms of chronologies and extents. The difference between the two codes is mainly related to the description of the topography in the thin-layer approximation (i.e., shallow-water approximation) and to the numerical method used. They are both based on the description of the granular mass as an incompressible equivalent fluid. SHALTOP, however, assumes a homogeneous and continuous material, and DAN3D discretizes the material into smooth fictitious particles, based on smoothed particle hydrodynamics (SPH). Both are very simple approaches, compared to the complexity of natural granular flows (different particle sizes, nature and shape, presence of a fluid phase, erosion processes, fragmentation, etc.) (see e.g. Delannay et al., 2017 for a review on laboratory and natural granular flows). DAN3D (McDougall and Hungr, 2004) is based on a Lagrangian numerical method, whereas SHALTOP is based on the finite volume Eulerian method (Bouchut et al., 2003; Bouchut and Westdickenberg, 2004; Mangeney-Castelnau et al., 2005; Mangeney et al., 2007). In DAN3D the user can choose among several rheologies, whereas in SHALTOP only Coulomb-type frictions are implemented at present. Beyond the numerical method used, the originality of SHALTOP is the precise description of the topography by including in the equations the full terrain curvature tensor (Mangeney et al., 2007; Favreau et al., 2010).

2.1. DAN3D

Different case studies, analyzed with the codes DAN W (2D simulations) and DAN3D (3D simulations), and reported by several authors (Hungr and Evans, 1996; Sosio et al., 2008; Welkner et al., 2010; Sosio et al., 2012; Delaney and Evans, 2014; Schleier et al., 2015), were examined to validate our models. Hungr and Evans (1996) back-analyzed 23 rock avalanches using DAN W, changing the basal rheology from Frictional (Eq. (1)) to Voellmy (Eq. (2)) and Bingham. They concluded that, generally, the Voellmy rheology produces the best-fit results for rock avalanches, as also suggested in Pirulli and Mangeney (2008) using the code RASH3D, similar to SHALTOP (Pirulli et al., 2007).

$$\tau_{zx} = -\sigma_z \tan\varphi_b \tag{1}$$

$$\tau_{zx} = -\left(\sigma_z f + \frac{\rho g \overline{v_x}^2}{\xi}\right), \tag{2}$$

where τ_{zx} is the basal shear stress, σ_z is the bed-normal stress at the base of the sliding mass, φ_b is the bulk basal friction angle, f is the Voellmy friction coefficient, ρ is material density, and ξ is the Voellmy turbulence coefficient.

Assigning a fixed Voellmy rheology, with a 0.1 friction coefficient and a 500 m/s^2 turbulence coefficient, 16 of 23 cases resulted in a prediction that was within 10% of the actual runout. In two events the runout was underestimated, possibly because of fluid entrainment, whereas in five it was overestimated, possibly because no saturated soils occurred in the flow path. In Sosio et al. (2008), the runout of the Thurwieser rock avalanche (Fahrböschung = 21°, Italian Central Alps) was simulated. Results were constrained using the final geometry, characteristics of the deposit and the mean front velocity, estimated from videos taken during the phenomenon. A Frictional rheology was implemented on the failure surface and on rock outcrops, whereas a Voellmy rheology was assumed for glacial ice. The values of the adopted parameters are reported in Table 1. In the same work, typical ranges of

Table 1
Back-calculated values for the rock avalanches analyzed in literature using DAN3D.

Reference	Event	Material	Rheology	F_b (°)	μ	? (m/s^2)	H/L	Volume (Mm^3)
Hungr and Evans (1996)	Various	–	Frictional	8–23	–	–	–	–
		–	Voellmy	–	0.03–0.24	100–1000		
Sosio et al. (2008)	Thurwieser	Source	Frictional	24	–	–	0.48	2.5
		Rock outcrops	Frictional	26	–	–		
		Glacial ice	Voellmy	–	0.05	1000		
		Glacial deposits	Frictional	26	–	–		
Welkner et al. (2010)	Portillo	Source	Frictional	30	–	–	–	50
		Valley floor	Voellmy	–	0.1	500		(2 events)
Sosio et al. (2012)	Various	–	Frictional	2.75–26	–	–	0.11–0.48	1–20
		–	Voellmy	–	0.03–0.1	1000–2000		
Delaney and Evans (2013)	Mount Munday	Snow-covered glacier	Voellmy	–	0.08	1050	0.185	3.2
Schleier et al. (2015)	Innerdalen	Natural slope	Voellmy	–	0.15	500	0.23–0.42	23.5–31.5
		Glacier	Voellmy	–	0.06	1000		

values found in literature are reported, organized based on the analyzed phenomena and involved materials. For rock avalanches, debris avalanches and rockslides, a range of friction angles between 8° and 30° was used when a Frictional rheology was chosen, whereas a friction coefficient of 0.05–0.25 (i.e. friction angles between about 3° to 14°) and a turbulence coefficient varying between 200 and 1000 m/s^2 were adopted using the Voellmy rheology. In Welkner et al. (2010), the results of a back analysis of the prehistoric Portillo rock avalanche in Chile were compared with the current distribution of rockslide deposits. They indicated the presence of two separate sliding events originating from different sources. A Frictional rheology was adopted in the source area, whereas a Voellmy rheology was considered in the distal part (valley floor), as this combination best fit field observations. In Sosio et al. (2012) a review of the best-documented ice-rock avalanches is presented. The authors back analyzed these events (volume ranging between 1 and 14 Mm^3) using SPH and FEM numerical methods, employing Frictional and Voellmy rheologies. Generally, for the Voellmy rheology, the friction coefficient ranges between 0.03 and 0.1 and the turbulence coefficient is between 1000 m/s^2 and 2000 m/s^2. For the Frictional rheology, the bulk friction angle is 2.75° to 26°, with values inversely related to event volumes. In Delaney and Evans (2014), a Voellmy rheology was used to simulate the 1997 Mount Munday rock avalanche (Fahrböschung = 10°, BC, Canada). The authors focused on the geometric characteristics of the debris sheet. In glacial environments deposits are usually more extensive in area relative to volume than rock avalanches in non-glacial environments. In Schleier et al. (2015), DAN3D runout analyses were used to understand the origin of a rock-boulder deposit in Innerdalen, Norway. Voellmy rheology was used both for the natural slope and for the glacier surface (values are shown in Table 1).

2.2. SHALTOP

The SHALTOP code has been used to reproduce experimental granular flows and natural landslides. Simulations were shown to reproduce the deposit characteristics of lab-scale granular flow experiments well (Mangeney-Castelnau et al., 2005; Mangeney et al., 2007; Lucas et al., 2014). In Kuo et al. (2009), the back analyzed basal friction angle (φ = 6°) of the simulation of the very large Tsaoling earthquake-triggered rock avalanche in Taiwan (volume of 126 Mm^3) was found to be considerably lower than the internal peak friction angle of the Cholan Formation, comprising sandstones and intercalated shales (Table 2). Indeed, for large-volume landslides (>1 Mm^3), the empirical friction angle is usually found to be smaller than the typical friction angle of the involved material (Campbell et al., 1995; Pirulli and Mangeney, 2008).

By analyzing and simulating tens of landslides with a wide range of volumes using SHALTOP, Lucas et al. (2014) showed that the empirical effective friction required in the model to reproduce the landslide runout decreases with the volume. They proposed an empirical fit relating the effective Coulomb friction coefficient $\mu = \tan\varphi$ to the volume involved V:

$$\mu = V^{-0.0774} \tag{3}$$

They found values as small as $\mu = 0.11$ (φ~6–7°) for volumes as large as 36 km^3. By comparing seismic data and numerical modeling with SHALTOP, Levy et al. (2015) showed that this empirical volume-dependent friction was able to explain the seismic signal of 200 rockfalls in Monteserrat (for volumes up to 1 Mm^3), whereas a constant friction coefficient was not. Using seismic data makes it possible to calibrate the friction coefficient based on the landslide deposit and on its dynamics.

Favreau et al. (2010) simulated the Thurwieser landslide; the model was calibrated using the seismic signal generated by the landslide. A Frictional rheology was assumed with a friction angle of 6° for the glacier and 26° everywhere else. These values are similar to the ones found for the same event using the DAN3D code by Sosio et al. (2008). Comparison between SHALTOP simulations and seismic signals suggested a friction angle of 35° for small rockfalls (V < 2000 m^3) in La Réunion. The 2005 Mount Steller rock-ice avalanche in Alaska, USA was simulated in Moretti et al. (2012). The initial mass was composed of rock, ice, and snow; the path included bedrock and a glacier. In this case the frictional parameters were also assessed by comparing the simulation results with the seismic signal recorded by 7 broadband seismic stations. The Mount Meager landslide (6 August 2010, BC, Canada), which initiated as a rockslide and rapidly transformed into a debris flow, was simulated by Moretti et al. (2015). They assumed different friction coefficients for the parts of the path where the rockslide travelled and where the event evolved into a debris flow. They assigned a lower friction angle to the glacier. The calibrated values of the friction coefficient on the glacier are in the same range for these different case studies (friction angles 5–7°). Yamada et al. (2016, 2018) simulated four landslides in Japan with volumes of 2–8 Mm^3. Friction coefficients between 0.3 and 0.4 (i.e. friction angles 16.7°–21.8°) were constrained from comparison with seismic data, in good agreement with Lucas et al. (2014) (i. e. Eq. (3)).

Because of the lack of field evidence at Cima Salti (uncertain deposit thickness, landslide velocities, deposit shape and location), the most widely used rheological relationships and a range of model parameters were initially chosen from the back analyses of similar case studies described in literature. For our models, we used the parameters reported in Table 3 for rock and ice materials, based on the rock mass and runout characteristics observed in the field and the values found in literature (Tables 1 and 2). In DAN3D, the unit weights of rock mass and ice were kept constant at 20 kN/m^3 and 9 kN/m^3, respectively. The internal friction angle (varying from 30° to 35° for rock and held constant at 40° for ice, based on values from the literature) did not have a significant effect on the results, and, hence, these are not presented in this paper. The number of smooth particles was set to 4000 (maximum number of particles). In the absence of more detailed information, the rate of erosion was set to zero, i.e. entrainment was neglected. Other parameters and options were set based on the suggestions given in literature and

Table 2
Back-calculated values for the rock avalanches analyzed in the literature using SHALTOP.

Reference	Event	Material	Rheology	φ_b (°)	H/L	Volume (Mm^3)
Kuo et al. (2009)	Tsaoling	Natural slope	Frictional	6	0.3125	126
Favreau et al. (2010)	Thurwieser	Natural slope	Frictional	26	0.48	2.5
		Glacier	Frictional	6		
Hibert et al. (2011)	La Réunion rockfalls	Natural slope	Frictional	35	–	(1–2000 m^3)
Moretti et al. (2012)	Mount Steller	Natural slope	Frictional	11–18	–	40–60
		Glacier	Frictional	7		
Lucas et al. (2014)	Various	–	Frictional	6–35	–	–
Moretti et al. (2015)	Mount Meager	Natural slope (rockslide)	Frictional	18	–	48.5
		Natural slope (debris flows)	Frictional	8		
		Glacier	Frictional	5		
Levy et al. (2015)	Montserrat rockfalls, pyroclastic flows	Natural slope	Frictional	19–31.7		(500–10^6 m^3)
Yamada et al. (2016)	Akatani	Natural slope	Frictional	16.7	–	8.2
Yamada et al. (2018)	Iya	Natural slope	Frictional	17.7		4.67
Yamada et al. (2018)	Nagatono	Natural slope	Frictional	21.8		3.63
Yamada et al. (2018)	Nono	Natural slope	Frictional	19.8		2.72

in the software manual. For SHALTOP, we used the Coulomb frictional model, and the same material parameters as the DAN3D Frictional simulations. A downsampled DEM with a pixel resolution of 40 × 40 m was used for both programs; this resolution was considered adequate given the uncertainties in the paleo-topography and the benefit of reduction in simulation time. The topography of the area was derived from the 1983 contour lines, i.e. before the remobilization of the lower portion of the slope and associated stabilization works in 2000. Two scenarios were created to simulate the landslide in the Middle Ages (after Alessio et al., 1973) and in the Lateglacial period (Fig. 5). In the first case, the valley topography was modified by decreasing the depth of incision of the Magnone stream. For the Lateglacial simulations a reconstruction of the glacier occupying the Magnone valley was attempted. Field evidence of kame terraces and the reconstruction of the glacier in the neighbouring Ledro valley (Picotti, 2003) were used. Two different landslide volumes were hypothesized from the 3D reconstruction of the original topography, based on similar slopes in the surrounding area. Assuming a failure of the whole slope, a volume of about 18 Mm^3 was found, whereas limiting the failed area to the upper portion of the Cima Salti slope, i.e. including only the Maiolica Formation, produced an estimated volume of 2.2 Mm^3.

Based on these input data, several simulations were conducted using the two numerical codes, varying material properties systematically. DAN3D simulations were completed first, and then compared with SHALTOP simulations. The analysis results, considering deposit location and thickness, were then compared with the available field data to constrain the simulations and discriminate between more and less plausible hypotheses. Based on field investigations and literature (Picotti, 2003):

- the geomorphology of the investigated area was not significantly influenced by the landslide, suggesting a small thickness of the landslide deposit;
- no deposits were found downstream along the Magnone river;
- the position of the blocks belonging to the landslide deposit and the lack of deposits in other areas were used to constrain the simulation results (Fig. 4).

Table 3
Values adopted in the DAN3D and SHALTOP simulations.

Scenario	Material	Rheology	Φ_b (°)	μ	ξ (m/s^2)
Without glacier	Rock outcrops	Frictional	5–35	–	–
		Voellmy	–	0.03–0.25	250–2000
With glacier	Rock outcrops	Frictional	5–35	–	–
		Voellmy	–	0.03–0.25	250–2000
	Glacier	Frictional	4–6	–	–
		Voellmy	–	0.05–0.15	1000–2000

Particular attention was paid to analyzing the results in which the landslide deposit could have dammed the river and, thus, created Tenno Lake.

Below, we investigate whether: i) the Cima Salti Landslide involved a large (18 Mm^3) or small (2.2 Mm^3) volume, and ii) the Cima Salti Landslide occurred in an ice-free valley or when glacial ice was still present at the base of the slope.

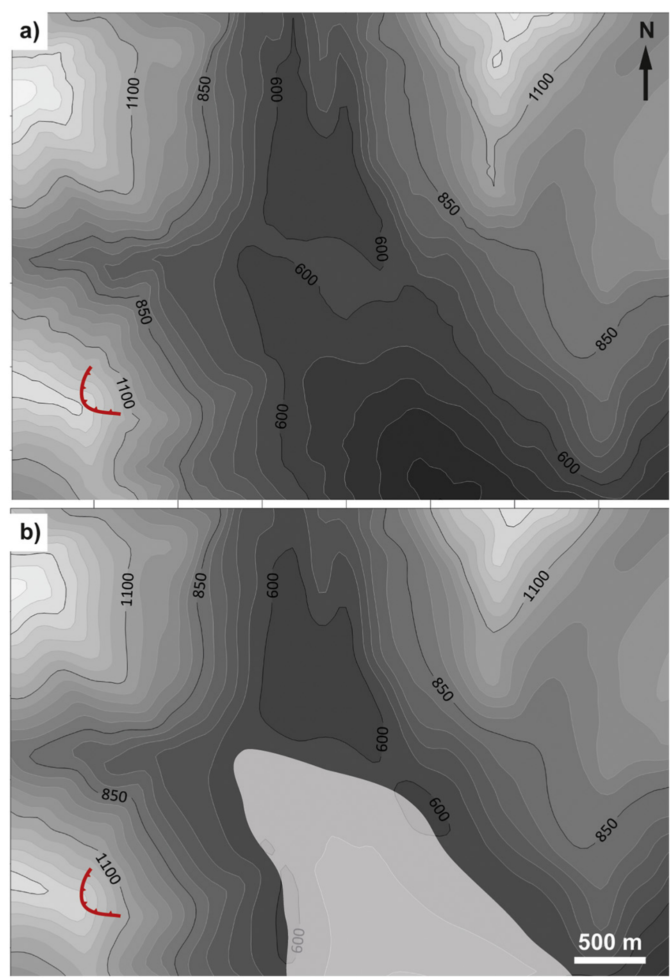

Fig. 5. Input topographies for scenarios without glacial ice (a) and with glacial ice (b). The red curve represents the headscarp of the Cima Salti Landslide, and the grey area in b) is the ice. Compare with Fig. 4 for present-day topography. Contour intervals = 25 m.

3. How large was the Tenno Landslide?

Considering the large (18 Mm^3) landslide volume, none of the simulations performed using the Voellmy rheology lead to a landslide dammed lake. Using a low value of μ (<0.15) or a very high value of ξ (1000 m/s^2), part of the landslide material stopped in the lake depression and part travelled downstream. With higher values of μ (>0.15) most of the deposit was found at the foot of the slope (Fig. 6).

In the large volume Frictional rheology models, simulations with a basal friction angle higher than 15° showed that the landslide material came to rest at the foot of the slope. Note that this friction angle corresponds to the value obtained with the empirical friction law in Eqs. (1) and (3) for a volume of 18 Mm^3 (15.3°), whereas this law gives a friction angle of 17.9° for $V = 2.2$ Mm^3. When the basal friction angle was decreased to 10°, which is small for this volume according to Eq. (3), the landslide material spread into the middle of the valley, with a maximum thickness of approximately 30 m at the base of the Cima Salti slope and about 6.5 m in the SW portion of the current Tenno Lake (Fig. 7). With an average lake depth of about 20 m, this deposit thickness would probably not have been enough to dam the river for a long period of time and create Tenno Lake. Furthermore, the lake would probably have had a different shape. With lower friction angles the landslide material mainly accumulated in the lake depression or moved downstream.

With the smaller volume, changing the parameters of the Voellmy rheology in the defined range of values, two typical scenarios were identified:

- with low values of μ: most of the landslide deposit travelled downstream; in several cases (with higher values of ξ) part of the deposit entered the depression in the middle of the valley;
- with high values of μ (>0.1): the landslide material was deposited at the foot of the Cima Salti slope, not reaching the middle of the valley (Fig. 8).

Using the Frictional rheology, with lower values of the basal friction angle (5 and 10°), the landslide material was deposited partly in the lake depression and partly on the sides of the valley (Fig. 9), without creating the condition for a possible river damming, i.e. the deposit was too spread out and did not completely block the valley bottom. The distributions did not coincide with the location of the deposits mapped in the field.

With a basal friction angle of 15° the landslide deposit is located in the middle of the valley (Fig. 10). The maximum thickness of the deposit reaches 13 m in the region just below the Cima Salti slope and 1.5 m in the SW part of the current Tenno Lake. According to these results, the shape of the deposit and its thickness would probably not have been sufficient to dam the river and create Tenno Lake. In this simulation and the one illustrated in Fig. 7 (larger volume, Frictional rheology with a basal friction angle of 10°), however, material accumulates in the area where a little island is located, in the SE part of the lake. Comparing these two simulations with the landslide blocks mapped in the area some discrepancies were found in the eastern part of the valley, where deposit locations in both simulations do not correspond to field observations. Moreover, in these two simulations, part of the landslide material travelled downstream, where no evidence was found in the field (Picotti, 2003; Ghirotti et al., 2015).

When the basal friction angle was changed to 17–18°, the area occupied by the landslide deposit was very similar to the one derived from field evidence. This value of the friction angle coincides with that of 17.9° given by Eq. (3). The thickness, position and shape of the deposit were probably not compatible with long-term damming of the river. For example, water would be able to flow around the proximal and distal margins of the deposits. No stratigraphic evidence or strand lines have been found to suggest long-standing water or outburst floods.

In all small-volume simulations, the resulting maximum deposit thickness is quite small, typically around 10 m, except for the simulations with higher friction angles (20–35°), whereas in the simulations performed using a larger volume the maximum deposit thickness is always larger than 20 m, reaching values of 65 m with the higher friction angles (Fig. 11). Since significant changes in the valley geomorphology because of the Cima Salti Landslide are not expected, very thick deposits were not considered as plausible.

The landslide reached a velocity peak approximately 20 s after initiation (Fig. 12) in the DAN3D simulations; the main event had a duration

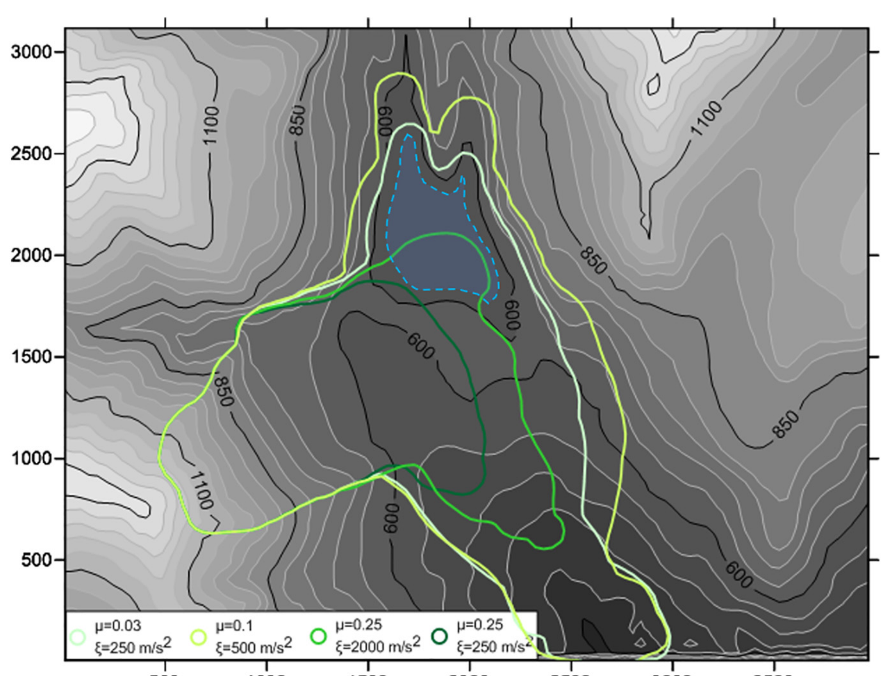

Fig. 6. The effect of friction and turbulence parameters on impact area for DAN3D Voellmy rheology ice-free simulations with larger volume (18 Mm^3). Note that the green outlines are the maximum thickness = 2 m contours. Blue area represents current extent of Tenno Lake for reference. Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

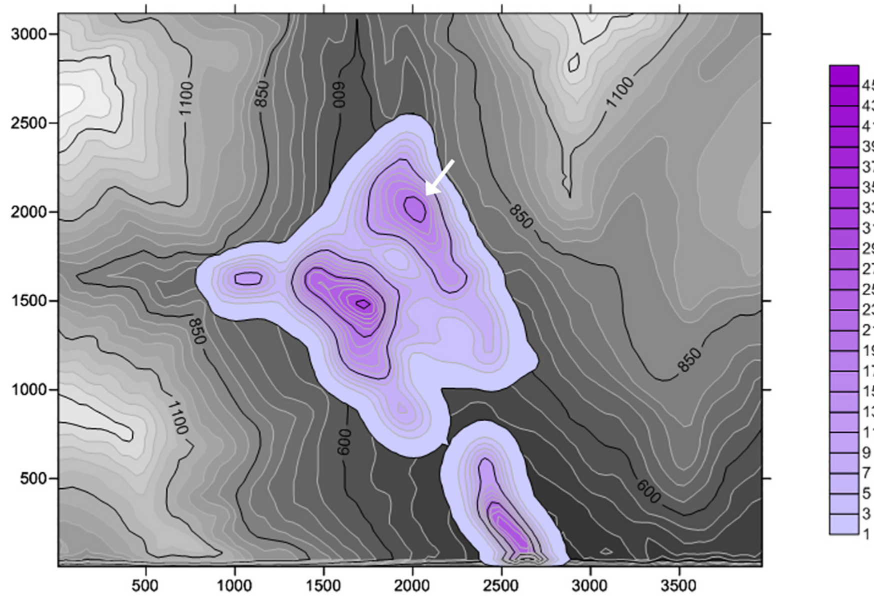

Fig. 7. Final results of the DAN3D simulation, deposit thickness (contours in metres, see colour bar). Simulation with larger volume (18 Mm^3), frictional rheology, basal friction angle 10°. White arrow indicates location of island. Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

of <70 s. SHALTOP and DAN3D models with Frictional rheology showed similar responses (Figs. 12 and 13). In the SHALTOP simulation, the landslide reached the bottom of the valley between 40 s and 60 s after the failure initiation, then, approximately 20 s later, the material started to run up the topographic high in the middle of the valley and finally came to a halt. The main movement phase lasted <80 s, whereas the entire event had a duration of <100 s. The duration of the event is similar in the two codes. Generally, the SHALTOP simulations seemed to be more affected by the topographic roughness and showed slightly more distributed deposits. With higher values (20–35°) the landslide material stopped at the foot or even in the middle part of the slope (Fig. 9).

4. What was the role of ice at Tenno?

The results of the simulations with glacial ice in the Magnone valley bottom are highly dependent on the ice location and morphology. Using an ice friction angle of 4°, the DAN3D Frictional rheology simulations run with low to intermediate basal friction angles show the deposits of even the small unstable volume reaching the opposite valley flank (Fig. 14). Only with sliding mass friction angles above 20° do most of the deposits come to rest at the base of the source area. With basal friction angles ≤ 20° most of the deposits travel across the glacier tongue into the depression of Tenno Lake, with maximum deposit depths of <20 m. With a friction angle of 17° (based on deposit distribution

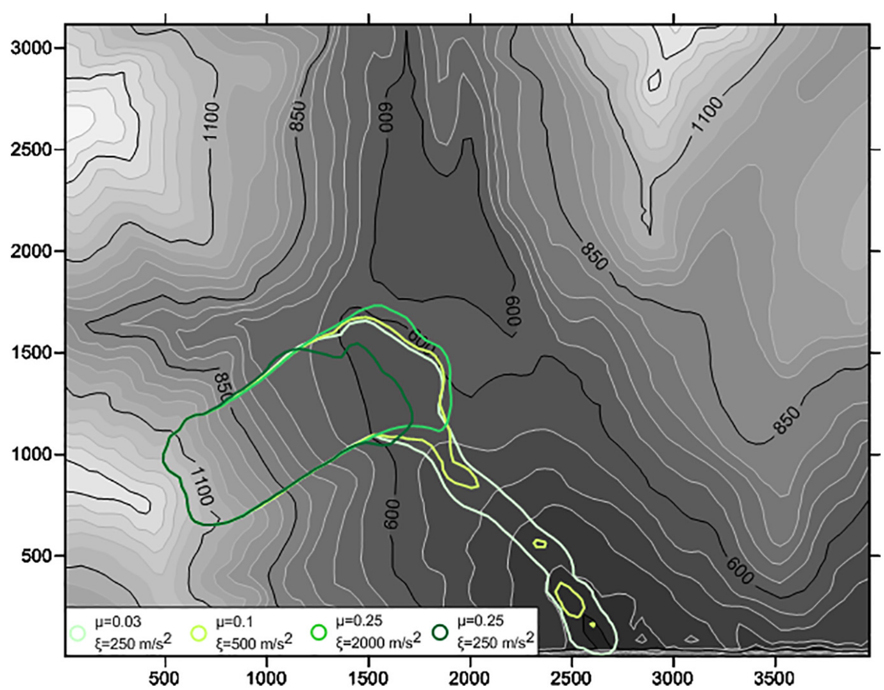

Fig. 8. Impact areas for some of the DAN3D Voellmy rheology, smaller volume (2.2 Mm^3). Note that the green outlines are the maximum thickness = 2 m contours. Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

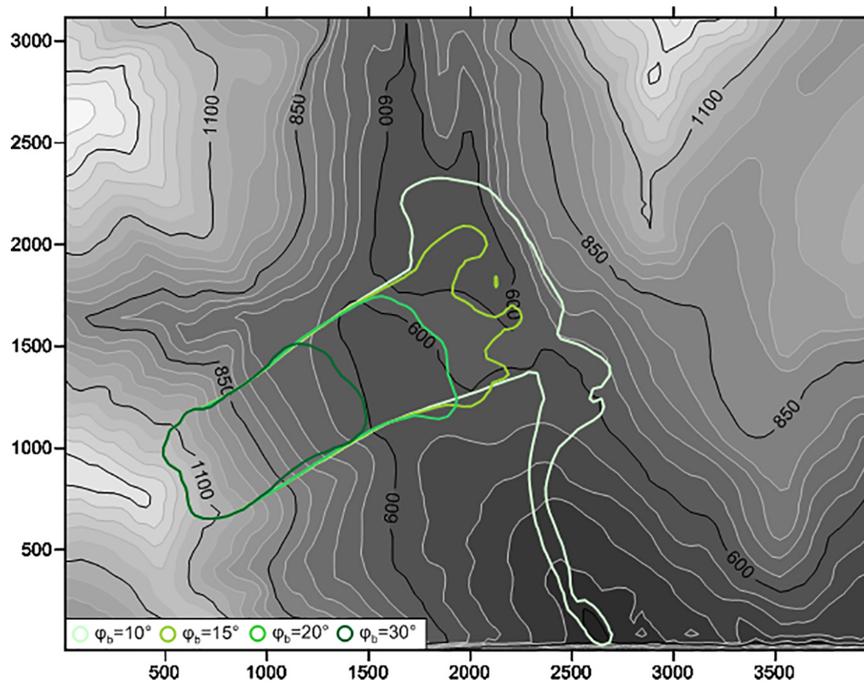

Fig. 9. The effect of friction angle on impact area for the DAN3D Frictional rheology, smaller volume (2.2 Mm^3). Note that the green outlines are the maximum thickness = 2 m contours. Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

observed in the field, the most likely simulations correspond to friction angle values between 15° and 20°, as in the ice-free simulations), the maximum deposit depth is located where the island in Tenno Lake is currently situated (Fig. 15).

The simulations with the large volume show similar distributions of deposits, but deposit thickness reaches 45 m. Again, basal friction angles of >20° resulted in the deposits coming to rest at the base of the Cima Salti slope.

The DAN3D Frictional and SHALTOP results are comparable, particularly when considering deposit thicknesses > 5 m (Fig. 15). Both show deposits east and west of the glacier ice in the valley bottom; however, SHALTOP also shows deposits on the slope south of the landslide headscarp and in the upper reach of the Magnone streambed. Most SHALTOP simulations assumed an ice friction angle of 4°. The results of those with a 6° ice friction angle did not differ significantly from the 4° simulations. For example, with a rock basal friction angle of 17°, maximum deposit thickness decreased slightly (from 22 to 20 m), and runout increased by a few metres relative to the 4° simulations.

The friction coefficient dominated runout response in the DAN3D Voellmy simulations. When $\mu > 0.2$, the deposits came to rest at the base of the slope. With lower friction coefficients ($\mu \leq 0.1$), the deposits travelled across the valley. With a constant friction coefficient (for

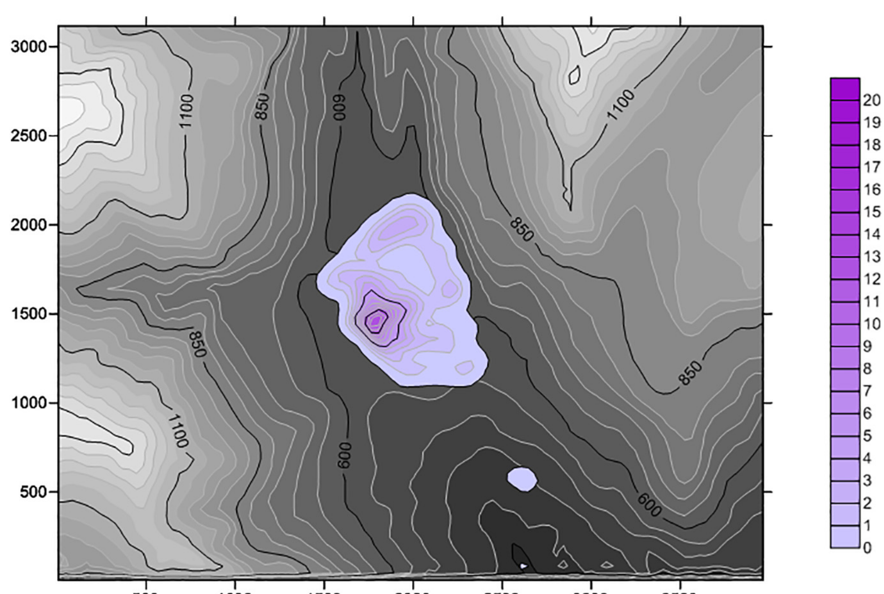

Fig. 10. Deposit thickness results (contours in metres, see colour bar) of the DAN3D simulation with smaller volume (2.2 Mm^3), Frictional rheology, basal friction angle 15°. Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

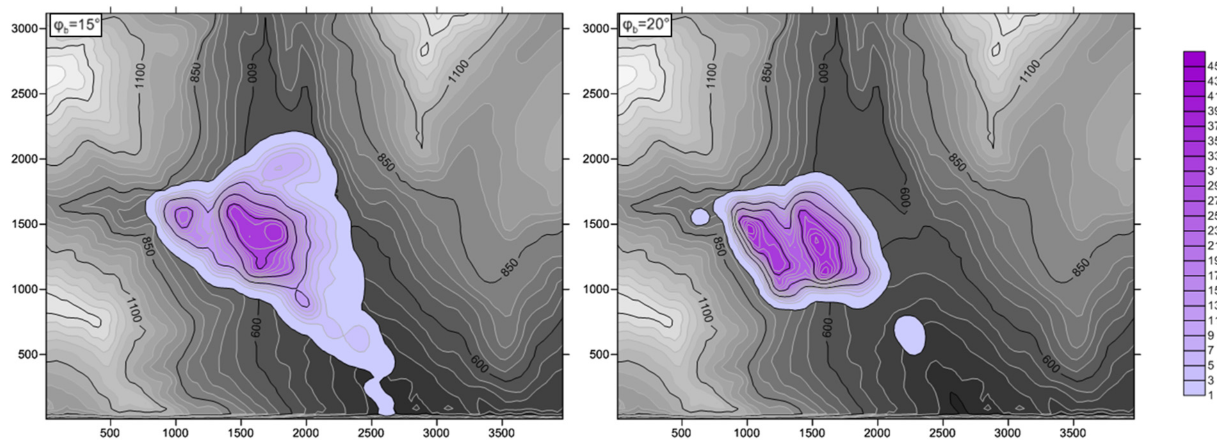

Fig. 11. Final results of the DAN3D simulation, deposit thickness (contours in metres, see colour bar). Simulation with larger volume (18 Mm^3), frictional rheology, basal friction angle 10° (on the left) and 20° (on the right). Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

example, $\mu = 0.03$ in Fig. 16), a high turbulence coefficient corresponded with a longer runout. Low values resulted in proportionally more deposits travelling down the west side of the Magnone valley between the valley flank and ice, whereas high values caused proportionally more of the deposits to cross the ice and valley to the NE. The Voellmy simulations showed distinct deposit thickness distributions when compared to both the DAN3D Frictional and SHALTOP results, and the deposits commonly separated into two main clusters, one in the lake and the other along the base of Cima Salti. These deposit distributions correlate poorly with our field observations.

When the source area was classified as having a Frictional rheology ($\varphi_b = 17°$), and the ice as Voellmy ($\mu = 0.05$, $\xi = 1000$ m/s^2) as in Sosio et al. (2008), the centre-of-mass of the deposits travelled farther than in the Frictional ice simulations, across the glacier tongue. The deposits were also more distributed, coming to rest around the glacier tongue rather than on the ice.

The maximum model velocity of reasonable simulations did not exceed 70 m/s. The maximum model velocity reached in the most realistic simulation ($\varphi_b = 17°$) was 69 m/s, comparable to the ice-free simulations above, whereas the average velocity was significantly lower (<30 m/s) (Fig. 17). The duration of the main event, approximately 70–80 s, was similar to the ice-free simulations. The durations of the main movements (i.e., not reactivations of parts of the sliding mass after most of the deposit has come to rest) of the larger volume (18 Mm^3) models increased to 100–200 s, with residual movements of up to 10 m/s lasting up to 5000 s (83 min).

5. Discussion and conclusions

The results of the DAN3D and SHALTOP simulations provide valuable insight into the Cima Salti Landslide. The DAN3D Frictional rheology produced more reasonable results than the Voellmy simulations, and compared well with the results of the SHALTOP model, validating the use of both codes. For example, in the most likely scenario (i.e., glacial ice with $\varphi = 4°$, Frictional rheology, $\varphi = 17°$), the two codes show a difference of approximately 36% in the deposit area (DAN3D deposit is larger) and roughly 6% difference considering the duration of the event (the DAN3D main event lasts 85 s and SHALTOP 90 s). Based on the lithology and the limited distribution and thickness of landslide blocks found in the field, the small volume simulations seem to be more realistic. If the Cima Salti Landslide involved the entire slope, a large portion of the deposits is now missing.

The ice-free and glacier Frictional models indicate that the most reasonable basal friction value is 17°-20°, based on deposit runout and thickness, and field investigations. This agrees well with Hungr and Evans (1996), Moretti et al. (2012) and the empirical friction law (Eq. (3)) of Lucas et al. (2014) (Fig. 18). This is, however, lower than the friction angle found in Favreau et al. (2010) for the Thurwieser

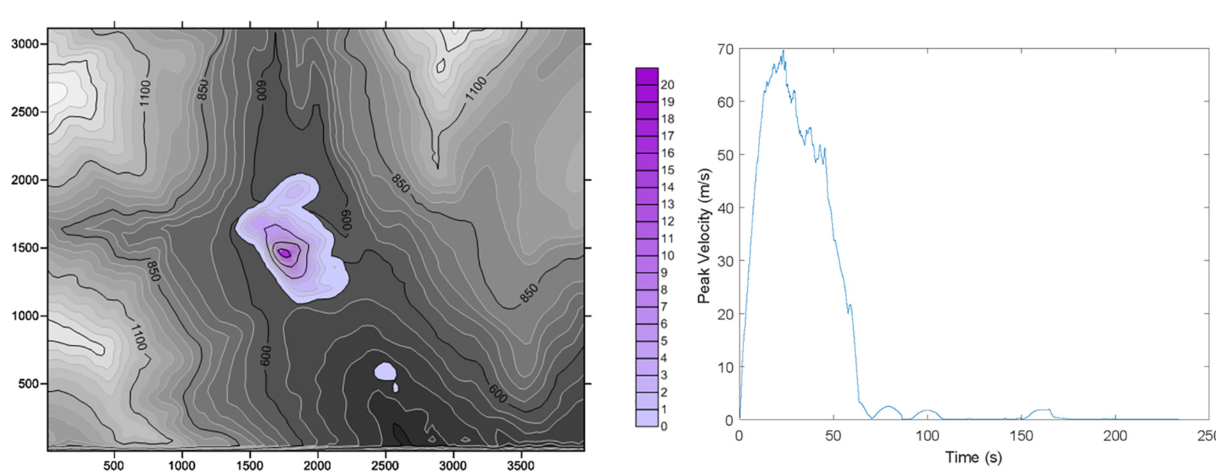

Fig. 12. Final results of the DAN3D simulation, deposit thickness (contours in metres, see colour bar). Relative north and east scales (starting at 0 in the bottom left corner) in left figure are in metres. Simulation with smaller volume (2.2 Mm^3), Frictional rheology, basal friction angle 17°.

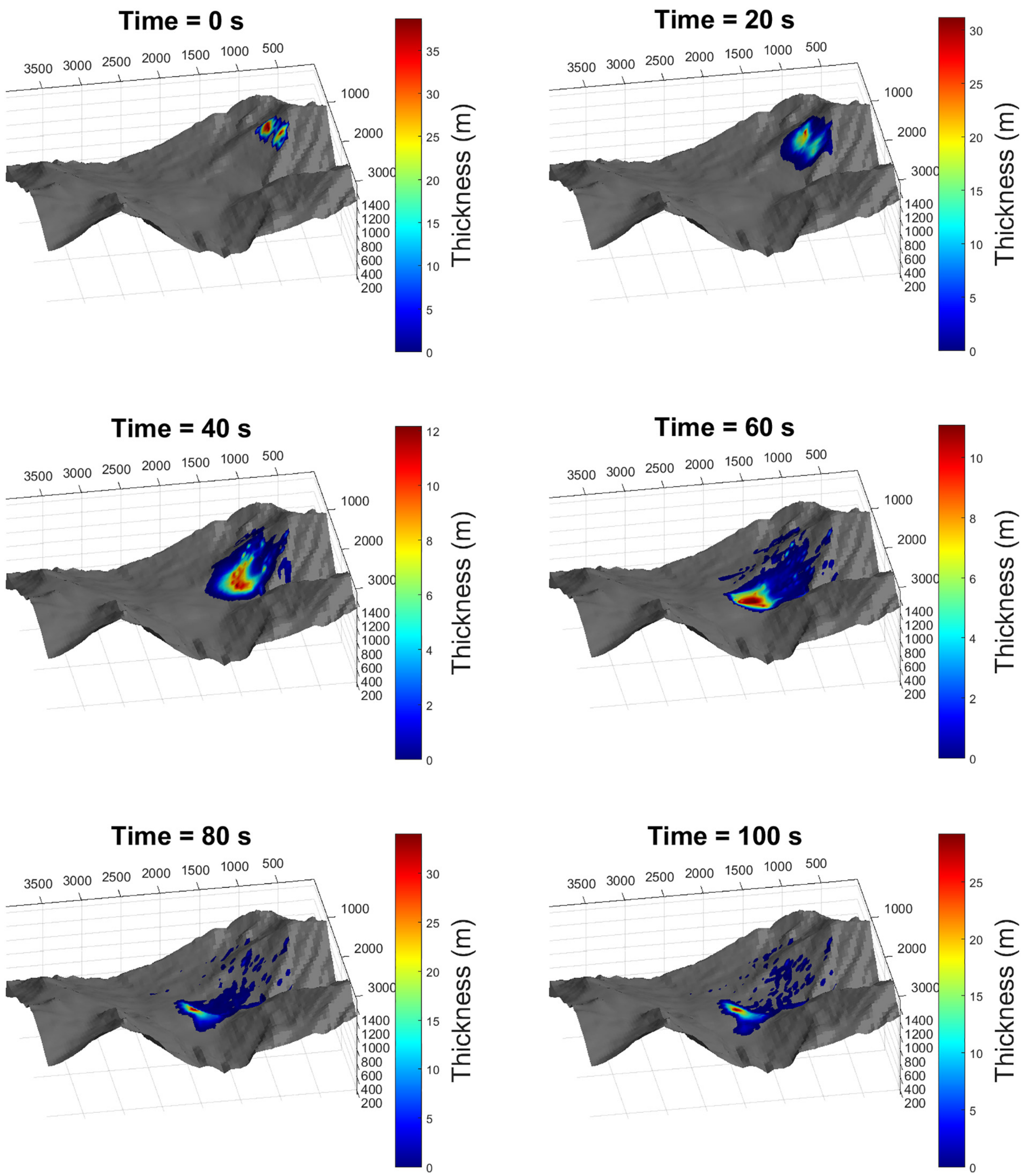

Fig. 13. Results of the SHALTOP simulation at different times. Simulation with smaller volume (2.2 Mm^3), Frictional rheology, basal friction angle 17°.

landslide with a similar volume. The simulated failures attain maximum velocities of 70 m/s, and durations of approximately 70–80 s, indicating the landslide failed as a rapid rock avalanche.

The obtained results were compared with the rheology parameters reported in literature. The Eperon de la Brenva, Martin River Unnamed1 and Becca di Luseney ice-rock avalanches (Sosio et al., 2012) have similar volumes (1.1–4.4 Mm^3) and H/L values (0.39–0.42) to the Cima Salti Landslide. In these cases, the friction angle used for the simulations is lower ($\varphi_b = 9–12°$) than the one obtained for Cima Salti. This could result from the large entrainment of ice and snow, which resulted in a low shear resistance and longer runout distances (see e.g. Mangeney et al., 2010 and Farin et al., 2014 for increase in runout distance in granular flows on erodible beds). Evans et al. (2001) simulated the 1984 Turbid Creek rock avalanche (volume = 0.74 Mm^3, $\varphi = 19°$). They proposed a Voellmy and a Frictional rheology ($\varphi_b = 30°$), even if the simulated velocities appeared to be too high in the Frictional rheology simulations. The Thurwieser rock avalanche was found to be very similar to the Cima Salti Landslide (Fig. 19). It is one of the few events recorded on video, and, thus, its exact duration, velocities, source area, travel paths, and deposition location are known. Furthermore, it was simulated with DAN3D and SHALTOP (Sosio et al., 2008; Favreau et al., 2010). In the DAN3D models, the best simulation was obtained with a Frictional rheology ($\varphi_b = 24–26°$) for the rock outcrops and a Voellmy rheology for the glacier ($\mu = 0.05$, $\xi = 1000$ m/s^2). Using SHALTOP, almost the

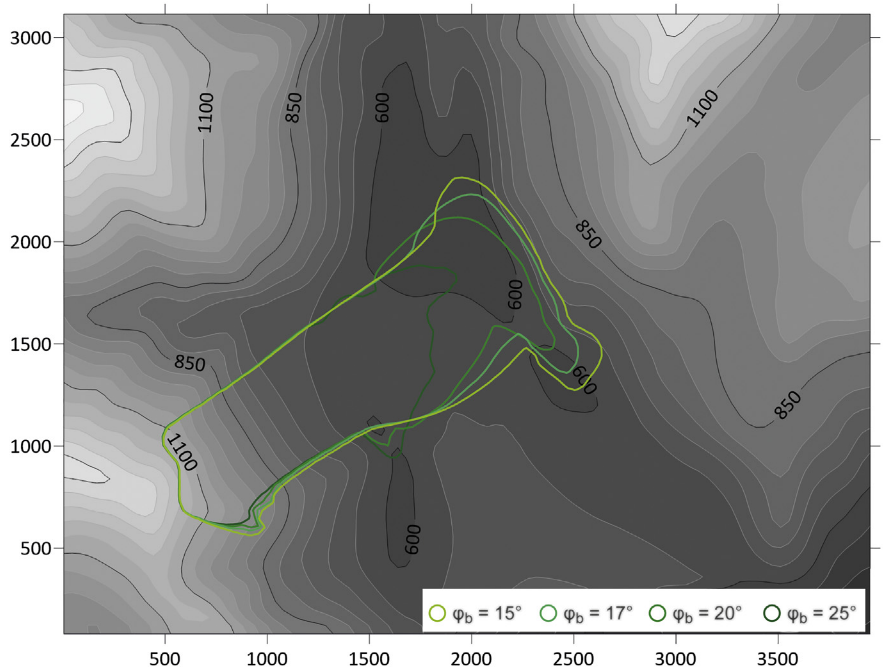

Fig. 14. The effect of basal friction angle on impact area for the DAN3D Frictional rheology glacial ice simulations with small volume (2.2 Mm^3). Note that the green outlines are the maximum thickness = 2 m contours. Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

same parameters where used for the rock outcrops, whereas a friction angle of 6° was used for the glacier. The duration and velocities measured for the Thurwieser rock avalanche (duration of 75–90s, mean velocity of 36–38 m/s, highest values of 60–65 m/s) are comparable to the ones obtained from the simulations of the Cima Salti Landslide.

All simulations indicated a travel path previously not considered for the Cima Salti Landslide. The headscarp crosses the south ridge on Cima Salti, and, thus, a minor secondary component of the slide could have travelled into the adjacent watershed. Certainly, mass movement material is found in this watershed, but its origins are unknown.

Given the extensive distribution of till in the area and the lack of landslide debris, it seems likely that the Cima Salti Landslide deposited material on ice. Had the landslide occurred in the Middle Ages, the deposits would have been more widespread today, as the Magnone stream could not have removed as much material as suggested by the current distribution of landslide debris.

The tree dates cited in previous papers are also questionable. The medieval age of the landslide is based on radiocarbon dating of fossil trunks found underwater dated to 1040–1215 CE (Alessio et al., 1973). This agrees well with the age of forests that occupied former lake shores

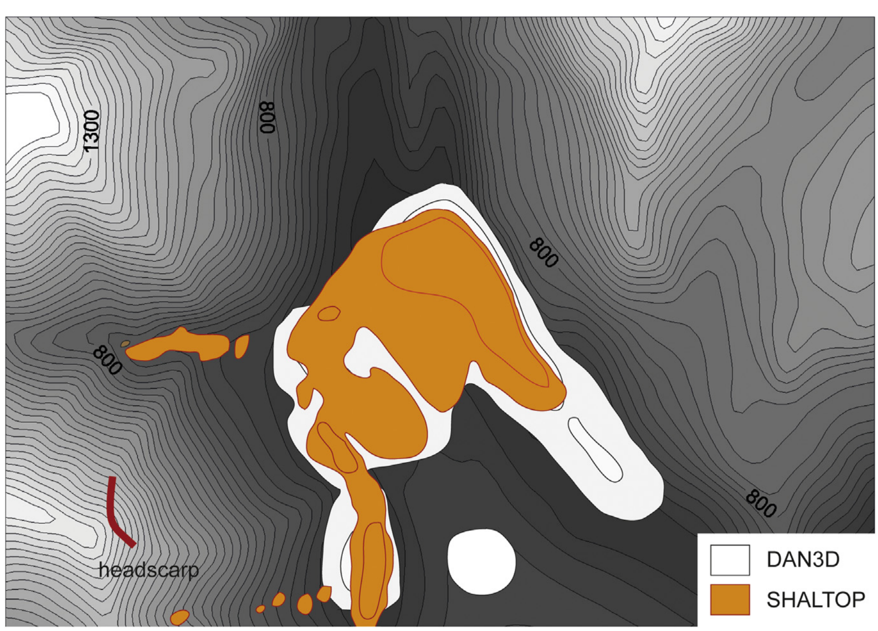

Fig. 15. Comparison of the DAN3D and SHALTOP thickness results at the end of simulation time (velocity ≈ 0 m/s) for a basal friction angle of 17° (rock) and 4° (ice), small volume (2.2 Mm^3). Only the 0 and 5 m thickness contours are shown. Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

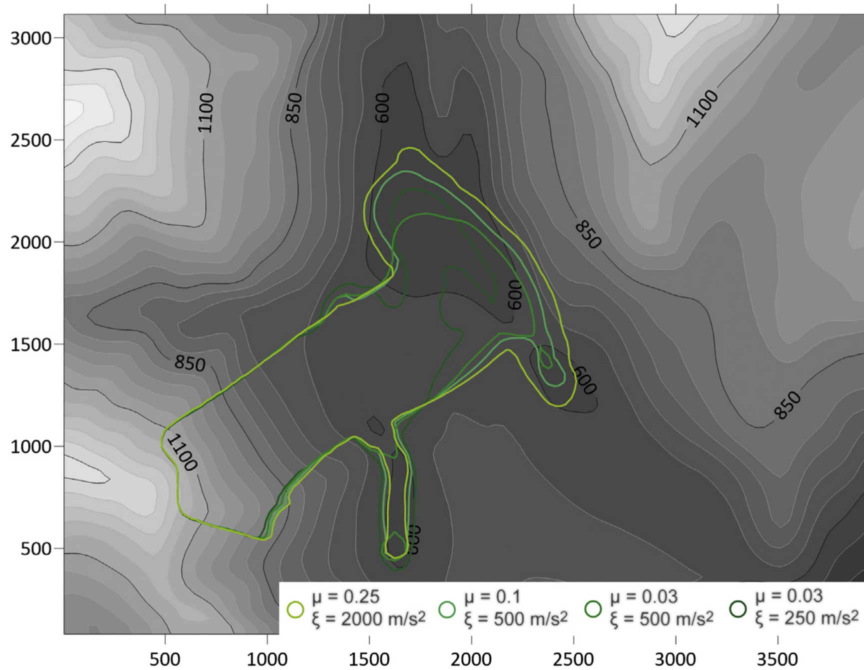

Fig. 16. The effect of friction and turbulence coefficients on impact area for the DAN3D Voellmy rheology glacial ice simulations, small volume (2.2 Mm^3). Note that the green outlines are the maximum thickness = 2 m contours. Relative north and east scales (starting at 0 in the bottom left corner) are in metres.

because of the lowering of lake levels ascribable to regional climatic changes (Biondi et al., 1981). This evidence is confirmed by a well-dated and high-resolution record provided by a deep core from Lake Ledro (southern Alps, Italy). Climate and land-use change (Joannin et al., 2014) and flood frequency (Vannière et al., 2013) during the Holocene were analyzed, together with fluctuations in lake level. Based on these proxy data, some pieces of information can be used with reference to the Tenno Lake paleoenvironmental evolution, because of the similarity of geographical, geological, and geomorphological contexts. A low-stand stage of the lake level, during the so-called Medieval Warm Period, was followed by a rising trend, corresponding to the age of the submerged forest. Therefore, no causal relationship exists between the Cima Salti Landslide and the lake formation based on radiocarbon ages. Furthermore, no historical sources support the medieval hypothesis. The irregular distribution of landslide debris, and the lack thereof downstream of the landslide source area, seems to suggest deposition from stagnant ice (ice melting or downwasting in situ), rather than actively retreating ice, which would have carried landslide material downstream.

Accepting that most of the deposits in the valley bottom are of glacial origin, the most important aspect of the field investigations is the *lack* of landslide evidence. This supports the following conclusions derived from the simulations:

- *The volume of the landslide is relatively small* (*2–5* Mm^3). Thicknesses of the deposit after coming to rest are not >20 m and more commonly <10 m.
- *The deposit travelled across stagnant glacial ice*. This is supported by the discontinuous distribution of landslide debris and the lack of landslide debris downstream of the source area. If the landslide had runout onto actively retreating ice or into the ice-free valley, we would expect to

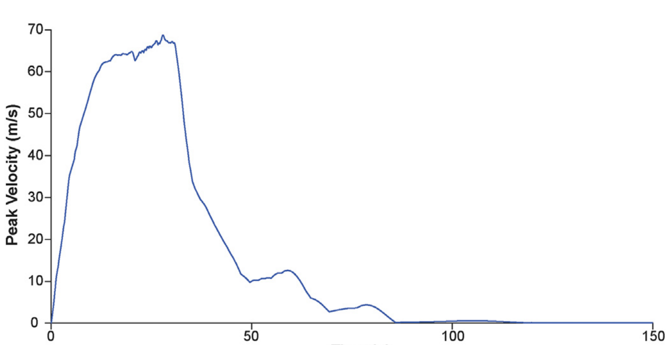

Fig. 17. Peak velocity plot for the DAN3D $\varphi_b = 17°$ simulation with glacial ice. Refer to Fig. 10 for comparison.

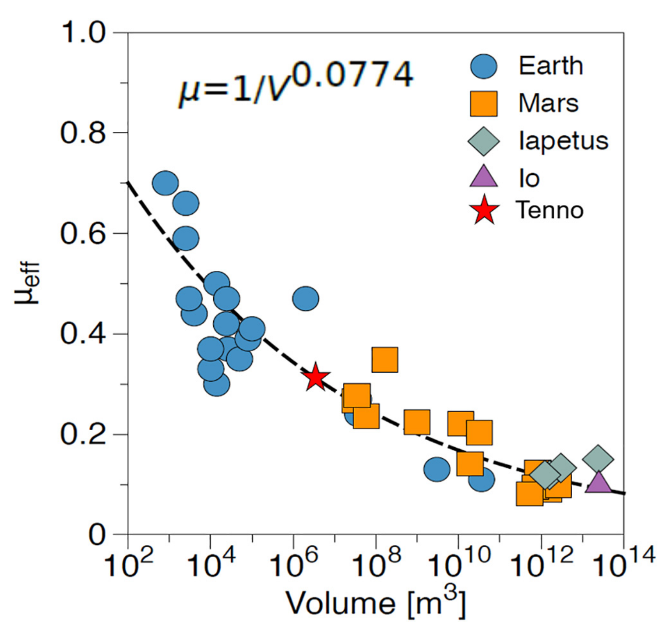

Fig. 18. Plot of empirical friction law, modified after Lucas et al. (2014). Cima Salti Landslide (Tenno) is represented by the red star. Only the small volume (2.2 Mm^3) scenario is plotted, as it is considered most likely.

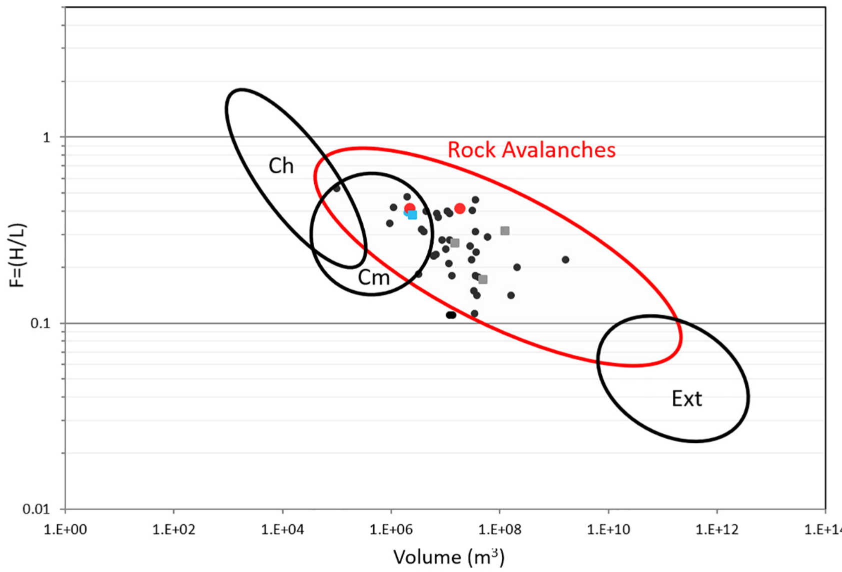

Fig. 19. Diagram relating the H/L ratio and the volume of different types of landslides (Ch = Chalk, Cm = coal mine waste, Ext = extra-terrestrial landslides). Red dots represent the Cima Salti Landslide with the two hypothesized volumes, black dots and grey squares represent, respectively, the rock avalanches analyzed with DAN3D and SHALTOP, described in literature and used as reference in the present work, blue square/dot represents the Thurwieser rock avalanche.
(Modified after Finlay et al., 1999).

find landslide debris downstream. Stagnant ice would have deposited the landslide debris haphazardly in the valley bottom as it melted, corresponding with the debris distribution observed in the field.

- *The landslide did not dam a lake*. All lake sediments found in the valley were deposited in relation to glacial processes.

Our interpretation of the Cima Salti Landslide hence highlights the importance of careful field investigations, distinguishing similar deposits (till vs. landslide). Furthermore, the present work proves how numerical simulations can be used as a tool in understanding valley evolution and natural hazards. Implications for ancient landslides used as analogs in hazard assessments are significant.

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