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Field Survey of the 2017 Rigopiano Avalanche

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Sammendrag / ***Abstract***

In the evening of January 18, 2017, a large snow avalanche descended from the east flank of Monte Siella in the municipality of Farindola in the Abruzzo region of Italy. It completely destroyed the Hotel Rigopiano and killed 29 of the 40 persons waiting there for evacuation, making it one of the most disastrous avalanches in Europe since World War II. The avalanche also destroyed or heavily damaged more than 5 ha of partly mature and partly young beech forest. The survey reported here focused on the forest damage in order to provide data for numerical simulations of the event that take into account the retarding effect of the forest. The observations are supplemented by information collected from diverse sources on the Internet. In addition, a digital elevation model with a resolution of $10 \times 10\ \mathrm{m}^2$ has been retrieved and prepared for numerical simulations with dynamical models like RAMMS::AVALANCHE and MoT-Voellmy. Raster files that specify the initial conditions (spatial distribution of release height, erodible snow-cover depth) and boundary conditions (shear strength of the erodible snow cover, forest density times mean trunk diameter) are also provided. These files are required for numerical simulations with MoT-Voellmy.

1 General background information on the avalanche event

In the middle of January 2017, the Gran Sasso area of the Apennine in central Italy received some two meters of snow in the course of four days. On January 18, a series of earthquakes—six main shocks with Richter-scale magnitudes between 4.7 and 5.7 at depths of about 10 km—occurred some 50 km north-west of Farindola between 09:25 and 13:30, produced considerable damage near the epicenter and killed five persons (`https://en.wikipedia.org/wiki/January_2017_Central_Italy_earthquakes`). Around 16:48, a large avalanche released at about 1900 m a.s.l. near the summit of Monte Siella, in the municipality of Farindola (province Pescara, region Abruzzo) in central Italy (Figs. 1 and 2). Descending the channel and mowing down and entraining a large area of beech forest, it reached the plateau of Rigopiano and completely destroyed the four-story hotel there.

Of the 40 people waiting for evacuation at the hotel, according to press reports two were outside to the north of the main hotel building when the avalanche struck. They were not injured and could alarm the authorities. The rescue work was severely impeded by the preoccupation with the preceding earthquakes, bad weather, large quantities of snow

Figure 1 Overview map of central Italy. Farindola is approximately 20 km west of Pescara and 100 km north-east of Rome at the border of the Gran Sasso National Park. Map created on the site `https://maps.google.com`

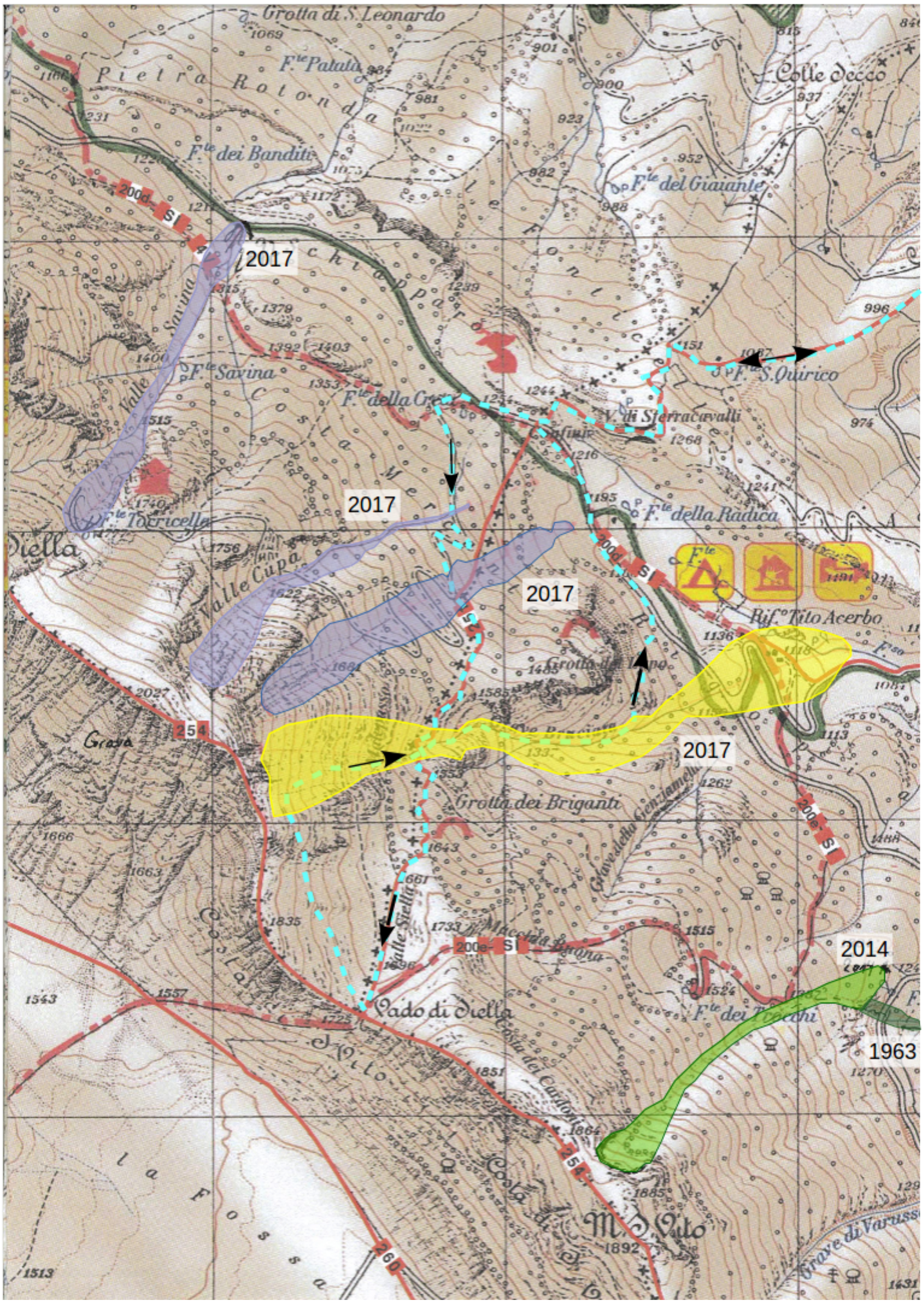


Figure 2 Overview map of Rigopiano, grid size 1 km, equidistance 25 m. Avalanche perimeters are approximate. The Rigopiano avalanche is drawn in yellow, other avalanches from the same avalanche cycle in blue, earlier avalanches in green. The 1963 avalanche from Monte San Vito continued for approximately 1 km to the east. Survey track in turquoise

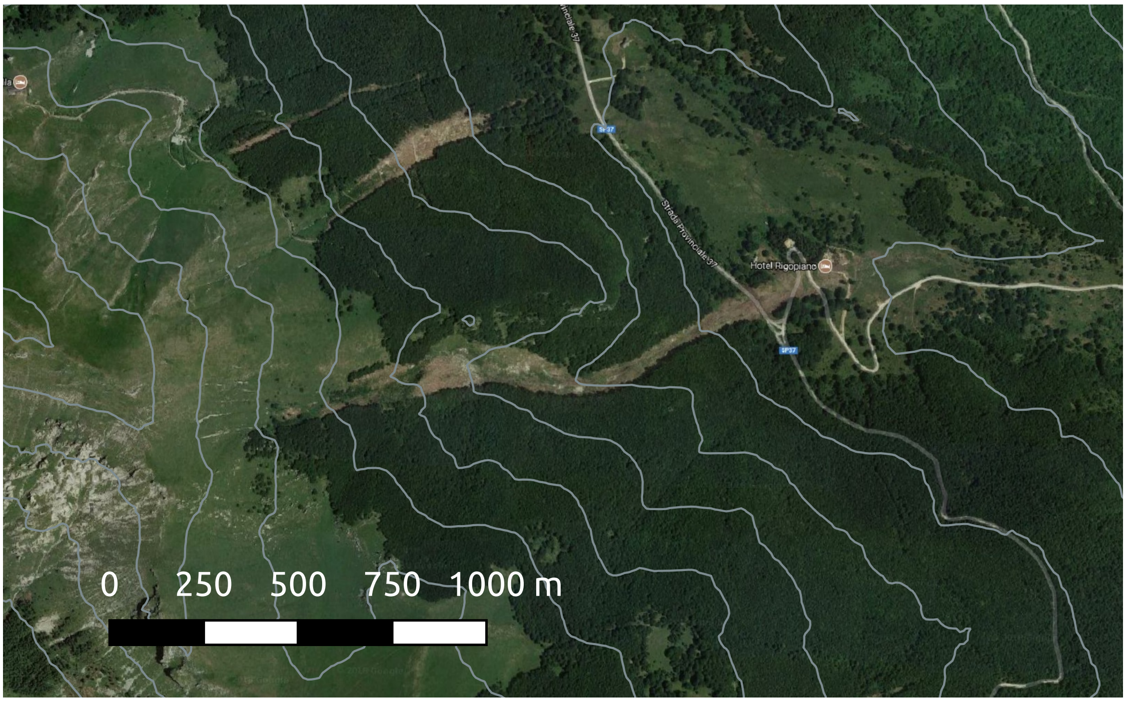


Figure 3 Satellite image after the avalanche event, showing the scars in the forest left by three avalanches (Grava dei Bruciati/Rigopiano in the middle, Grava di Costa Mercante and Grava di Valle Cupa further to the north). Retrieved from Google Maps on 2018-07-27. Equidistance of isolines 100 m

on the long and tortuous roads to the resort, and a number of additional avalanches that had reached the roads. Working in shifts around the clock for an entire week, up to 140 rescuers were able to liberate nine children and adults alive from the colossal heap of rubble, tree debris and snow, some of them as late as four days after the event. With 29 victims, this was one of the deadliest snow avalanches in Europe in the past 100 years. It attracted enormous public attention not only in Italy, but in all of Europe and even around the world.

While most of the victims were tourists, about ten victims were hotel personnel living in Farindola. The avalanche disaster caused an emotional shock that has changed life in this community of about 1600 inhabitants. One has to expect that the court trial to be held will bring further tension to the situation when sensitive questions will be raised: Why was permission given to build a luxury resort hotel at this location? Should this avalanche have been foreseen? Why was there apparently no evacuation plan for such situations? Some of these questions are of legal nature and concern handling of land-use planning and disaster preparedness in Italy, but the event also raises scientific and practical questions of relevance to other countries.

This report will not consider the mentioned legal aspects and only briefly touch on the lessons to be learned for avalanche mitigation work outside Italy in Sec. 5. The main

Figure 4 The village of Farindola (500–600 m a.s.l.) with the chain of the Gran Sasso massif. In the left-hand half of the background, one sees the slopes of Monte Siella (2027 m a.s.l.) with three active avalanche paths: Grava dei Bruciati (leading to Rigopiano, which is hidden behind the forested hills in the middleground),Grava di Costa Mercante, and Grave di Valle Cupa (from left to right). The photo (from the website `http://altrocanto.it`) predates the 2017 Rigopiano avalanche

goal is to understand the dynamics of this avalanche and its interaction with the forest. To this end, information from different sources—maps, aerial photos, reports in the media and oral information from locals summarized in Sec. 2—is combined with observations from the author's field survey on 2017-06-03 (Sec. 3). In the companion report (Issler, 2019), henceforth named [II], this data is used in semi-quantitative analyses of the dynamics of this avalanche as well as updated vulnerability relations based on the framework proposed by Issler and others (2016). The presentation in this report is in a form that hopefully will be useful as input to numerical simulations or for constraining unmeasured parameters through comparison with the simulation results (Sec. 4). The last section presents some preliminary thoughts about the lessons to be learned from this disaster.

This report was written in 2017 and early 2018, but not made available because of concerns connected to the ongoing court case. At the Intl. Snow Science Workshop 2018 in Innsbruck, October 7–12 2018, several papers on this event were presented that review the meteorological situation and the emergency management (Chiambretti and Sofia, 2018), present the forensic techniques applied during the investigation of the disaster (Chiambretti and others, 2018), and study the dynamics of the avalanche including numericval simulations with RAMMS (Frigo and others, 2018). Several of these authors participated already in the first surveys after the disaster and/or were in charge of providing the expert report for the court case. They thus have access to a wealth of data and documents that are not available to the author. However, because of the ongoing court case, no detailed, comprehensive scientific analyses have been published so far. Under these circumstances, it now appears justifiable and opportune to issue the present report. Work on simulating the avalanche with MoT-Voellmy is planned for 2019.

Figure 5 View of the potential release area and upper track of the Grava dei Bruciati path as seen from Farindola (south to the left, north to the right). Two wide, gentle depressions with some scree can be seen in the southern part of the potential release area whereas three or more less pronounced depressions are present in the northern part. Note that the ridge line sharply rises to the north. Extensive forest damage from the 2017 event is clearly visible. In the central part of the uppermost track, relatively large beech trees survived the avalanche. The young, only partly damaged stand below is a strong indication that avalanches release frequently, but are stopped most of the time just above the pronounced shoulder protruding into the path from the south.

2 Information collected from external sources

The Rigopiano disaster caused enormous attention in the media. For this reason, much valuable information has become accessible on the Internet, e.g., videos taken during drone flights, aerial photographs since the mid-1940s, and accounts of earlier avalanche events. In some cases, however, it is difficult to assess whether the information is correct or not. In this section, information that is believed to be accurate and that is relevant to the goal of understanding the event and back-calculating it with dynamical models is collected and interpreted.

Figure 6 The Gran Sasso massif seen from the south-east some days after the disaster (probably on 2017-01-26). Monte Siella is the leftmost peak, its flank facing the viewer is the Grava dei Bruciati. The cuts due to avalanches in the two neighboring paths to the north are also visible.

Section 2.1 is mainly based on the map 140 II-NO (Castelli), series 25v of the Istituto Geografico Militare from 1955 at scale 1:25,000. In addition, some photos taken during the field survey and drone videos published on the Internet were used. For Sec. 2.2, a number of Internet sites were used as indicated. Information from local people was crucial for Sec. 2.3 and supplemented by documents and old aerial photos found on the Internet. Section 2.4 was compiled on the basis of Sec. 2.3 and the mentioned map.

2.1 Characteristics of the avalanche path

The Grava dei Bruciati path extends from a maximum altitude of 1900 m a.s.l. down to about 1090 m a.s.l. for the most extreme events. In such cases, the projected length can be up to 2200 m. The release area extends to roughly 1650 m a.s.l. It has a projected length of up to 350 m and a similar maximum width. This gives a maximum projected release area of roughly 10 ha. The uppermost part of the release area above 1800 m a.s.l. is steepest, with an inclination of 35–40°, while the lower parts are inclined at 30–35°. As a whole, the release area is slightly concave, with a planform curvature (i.e., measured along contour lines) of less than 0.001 m^{-1}. As Fig. 6 shows, it is partitioned by some gentle ridges, which cannot, however, prevent fractures from propagating across them in many situations.

From about 1700 m a.s.l., the path becomes progressively channeled. At 1550 m a.s.l., a pronounced, 15–20 m high rock outcrop on the right-hand side in flow direction forces the avalanche to either flow over or to turn left (radius of curvature approximately 150 m, depending on direction of approach) and pass through a narrow gate. Below this altitude, the gully is fairly narrow at its center, with the sides typically sloping at angles between 25° and 35°. At 1430 m a.s.l., the gully starts a right turn with a radius of curvature at the centerline of about 100 m below a cliff. After about 100 m, at an altitude of 1350 m a.s.l., a wide left turn (radius 500–700 m) leads to the outlet of the Grava dei Bruciati onto the plateau of Rigopiano at 1200 m a.s.l. Between 1400 and 1300 m a.s.l., the average slope is about 18°. The β point (where the slope falls below 10°) is located in the vicinity of the intersection of the provincial roads to the north, to Farindola and to the south across the Siella ridge at approximately 1150 m a.s.l. The terrain then slopes gently in easterly direction.

Before the 2017-01-18 event, the Grava dei Bruciati was covered by dense beech forest from 1550–1600 m a.s.l. to 1220 m a.s.l. There was a "peninsula" of forest at about 1650 m a.s.l. that protruded into the potential path of large avalanches. During the field survey (Sec. 3.2), it was found that the forest consisted of very young trees around the centerline of the avalanche track down to the foot of the mentioned rock outcrop (1450 m a.s.l.) whereas there was nearly mature forest farther away from the centerline. The total projected length of the forest-covered part of the path is about 1.0 km.

2.2 Snow and weather conditions

Around January 6, 2017 a persistent synoptic situation developed where a high-pressure system over north-eastern Europe channeled large quantities of arctic air towards a low-pressure system over the Tyrrhenian Sea (Figs. 7 and 8). Crossing the Adriatic Sea in south-westerly direction, these air masses retrieved unusual amounts of humidity that were dumped on the NE flank of the Apennine due to the stau-effect. This resulted in snowfalls of up to 1 m/24 h and accumulated snow depths up to 2.5 m even at moderate altitudes (Fig. 9). The snowfalls were most intense in the period 16–18 January.

The website `http://www.severe-weather.eu/news/exceptionally-intense-snowfall-and-four-strong-earthquakes-in-abruzzo-central-italy-today-january-18-2017/` (last accessed on 2017-09-01) shows photos of Abruzzan towns below 500 m a.s.l. with exceptional quantities of snow and summarizes the synoptic situation as follows:

> In response to huge pressure difference between high pressure over Balkan peninsula / central Europe and deep low pressure system over Mediterrenean [*sic*], a severe to hurricane force Bora wind gusts will

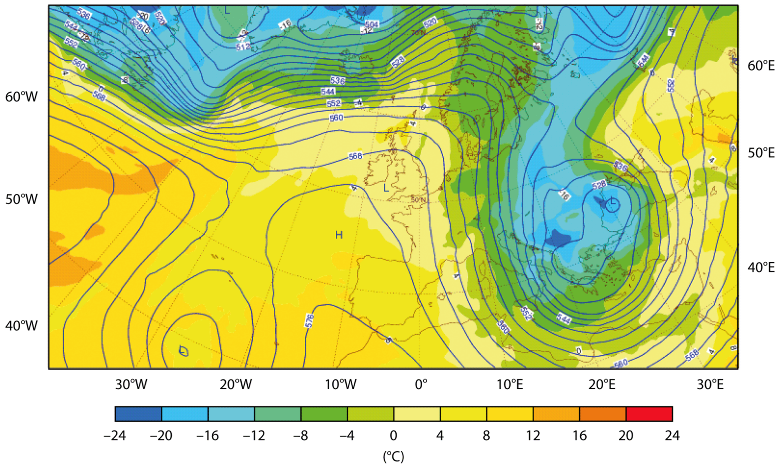


Figure 7 Synoptic situation on 2017-01-08. From the website of the European Centre for Medium-Range Weather Forecasts, `https://www.ecmwf.int/en/newsletter/151/news/cold-spell-eastern-europe-january-2017`, retrieved on 2017-09-01.

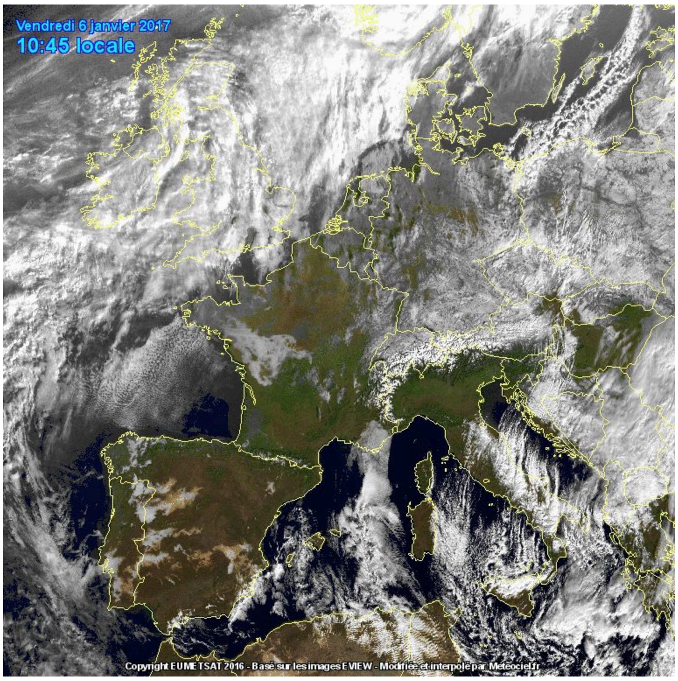


Figure 8 Satellite image over Italy and southern/central Europe on 2017-01-06 showing the persistent streaks of clouds traveling from NE to SW across the Adriatic Sea. Source: EUMETSAT / Meteociel, retrieved from `https://watchers.news/2017/01/06/arctic-air-snow-bora-europe-january-2017/` accessed on 2017-09-01.

> continue through this afternoon/evening and also tomorrow. Expected wind gusts are 140 to 170 km/h over larger area while locally even in excess of 200+ km/h.
>
> On the other side of the Adriatic sea, strong Bora combined with humid ESE-rlies provides strongly sheared environment for excessive precipitation and especially sea-effect snowfall and orographic "stau effect" snowfall into Marche and Abruzzo region in central Italy. There, another 75–100 cm seems likely through the next 36 hours after already 100–150 cm of fresh snow being reported.

The temperatures in eastern Europe dropped to record lows (e.g., −30°C in Bucharest, Romania) during the cold spell. According to the simulated meteogram for the Monte Siella area (Fig. 10), the maximum temperature in the release area of the Rigopiano avalanche presumably was well below freezing during the entire month of January, except perhaps on January 14. Moderate northerly to easterly winds prevailed during the precipitation period starting on January 15 and extending beyond the avalanche event to January 20. Pescara, situated on the coast, received about 60 mm of precipitation during the first period January 4–11 and then another 230 mm during the five days January 16–20. The precipitation must have been significantly higher at Monte Siella. From January 4 to 11, the first major snowfall of the season may have brought 1–1.5 m of snow to the release area. Precipitation likely exceeded 200 mm in the three-day period January 16–18 until the release. Given the wind direction, there was probably moderate snow transport into the release area. A snow depth increase (measured vertically) of 1.5–2.5 m would appear plausible. The precipitation falling after the avalanche event was large enough (roughly one additional meter of snow) to pose a threat to the rescuers.

The first snowfall occurred at unusually low temperatures so that the snow did not rapidly settle and gain strength. Fair weather and sharply rising temperature from January 12 to 15 may well have helped to stabilize the top layer, but probably not so much the bottom layers. If the brief warm spell of January 13 led to some melting in the top layer, it will have refrozen during the night, possibly forming a surface to which the following new snow could not bond very well when the temperature fell again below −5°C. Thus the fracture may have occurred at the interface between the early-January snow and the new snow, suggesting an average fracture depth (measured perpendicular to the snow surface) of 1–2 m at a density of 100–150 $\mathrm{kg\,m^{-3}}$. Alternatively, the fracture might have occurred in a weak zone near the bottom of the early-January snow, with a fracture depth in the range 1.5–2.5 m. In snow profiles taken near Rigopiano after the accident, no pronounced weak layers were identified (J.-T. Fischer, pers. comm.).

2.3 Avalanche activity around Rigopiano

Based on information from D. Borgheggiani (Farindola) and various news items on the Internet, a rather coherent picture of avalanche activity in this region of the Apennine

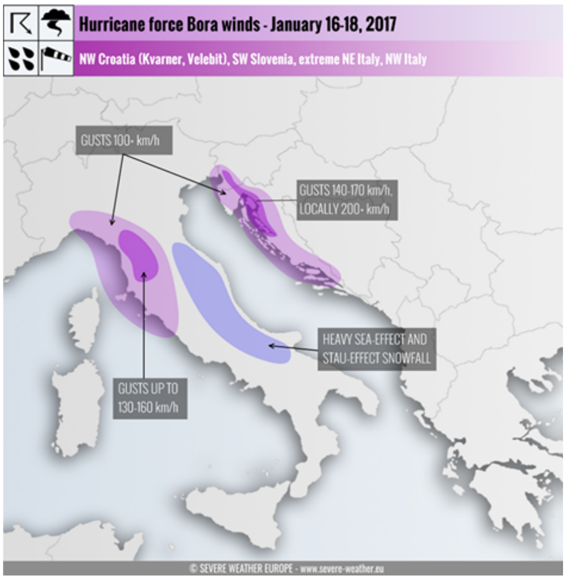


Figure 9 Overview of the wind and precipitation situation around central Italy on 2017-01-18. Retrieved from the website `http://www.severe-weather.eu/news/exceptionally-intense-snowfall-and-four-strong-earthquakes-in-abruzzo-central-italy-today-january-18-2017/` *on 2017-09-01.*

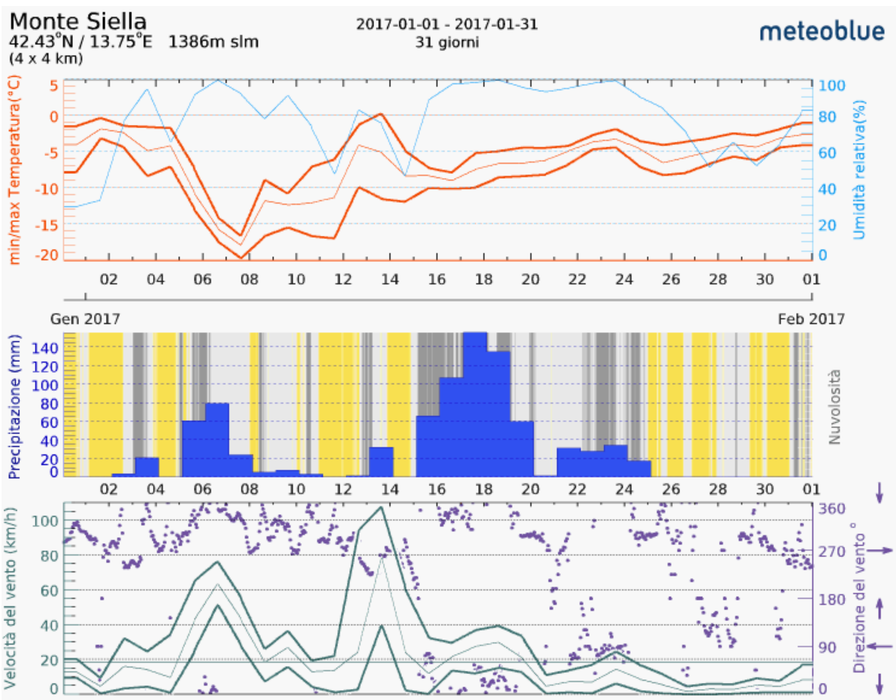
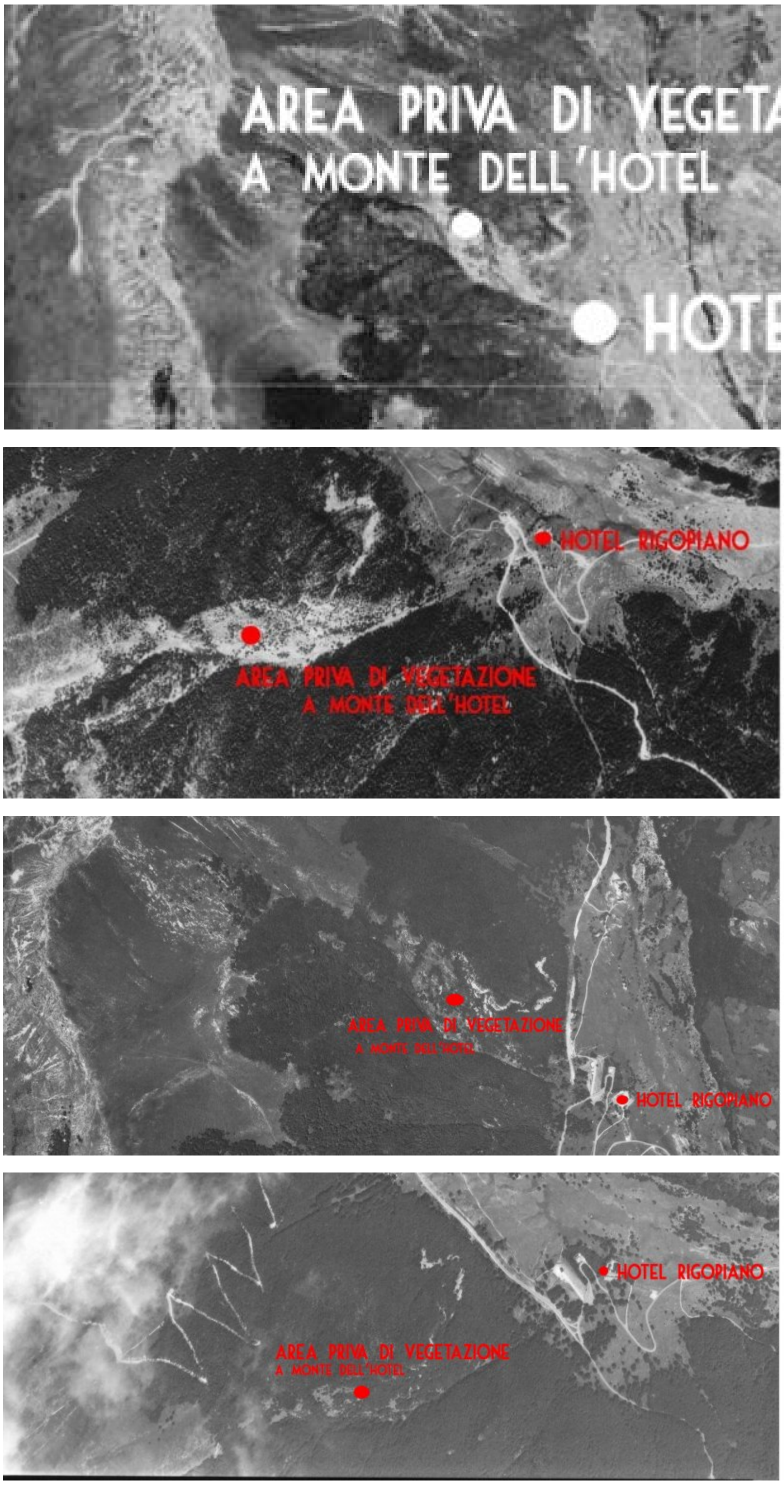


Figure 10 Simulated meteorological data (temperature, precipitation, wind) during January 2017 in the Monte Siella area at a representative altitude of 1386 m a.s.l.). Produced at the website `https://www.meteoblue.com/it/tempo/previsioni/archive` *on 2018-08-08.*



Ripresa	Volo IGM 1954
Strisciata	58
Fotogramma	2198
Data ripresa	14/09/1954
Committente	IGM
Ditta esec.	IGM
Focale	153.89 mm
Quota di volo	6000 m
Scala	1:33000
Formato	23 x 23 cm

Dettaglio fotogramma

Ripresa	Volo Cassa del Mezzogiorno 1974 1975
Strisciata	36
Fotogramma	449
Data ripresa	10/07/1975
Committente	Regione Abruzzo
Ditta esec.	CGR S.p.a.
Focale	153.15 mm
Quota di volo	3000 m
Scala	1:20000
Formato	23 x 23 cm

Dettaglio fotogramma

Ripresa	VIGM85
Strisciata	116
Fotogramma	2954
Data ripresa	25/07/85
Committente	IGM
Ditta esec.	IGM
Focale	152,34 mm
Quota di volo	5040 m
Scala	1:33000
Formato	23 x 23 cm

Figure 11 Aerial photos of Rigopiano and the Grava dei Bruciati in 1945, 1954, 1975 and 1985. Photos retrieved on 2018-08-03 from `http://www.repubblica.it/cronaca/2017/01/26/foto/rigopiano_forum_h2o-156964271`

Figure 12 View from a point to the south of the release area of the Rigopiano avalanche. The deposit area is clearly visible, but it is unclear whether the most distal debris was deposited by the dense/fluidized part of the avalanche or by the powder-snow cloud.

emerges: Depending on the wind direction during (or over a prolonged period after) the snowfall, avalanches release on the north-east or south-west-facing slopes of the mountain ridge between Monte Siella and Monte San Vito. Some of the avalanche paths release almost yearly, among them the Grava di Valle Savina, Grava di Valle Cupa and Grava di Costa Mercante paths. The Grava dei Bruciati path probably also releases quite frequently, but with limited run-out to an altitude of 1400–1500 m a.s.l. Other avalanches flowing in north-easterly direction also usually stop below timberline but well above the provincial road paralleling the ridge and leading from Rigopiano to Castelli. They prevent the forest from growing up where they reach very frequently (with return periods up to perhaps 10 years). Further down the path, avalanches with return periods up to approximately 30 years destroy the trees as soon as they have grown to a certain size and lost their youthful flexibility. The corresponding cuts seem to be quite narrow in this area, typically less than 50 m.

The potential of many of these paths is, however, much larger, given the extreme snowfall intensities and very substantial quantities of snow that occur with return periods of perhaps 30–100 years. According to a letter to the mayor of Farindola (Iannetti, 1999), an avalanche of somewhat smaller size than the 2017 event descended Grava dei Bruciati in 1959 (or 1956?). A narrow but very long cut is visible from Monte San Vito; in 1963 that avalanche crossed the provincial road that leads from Rigopiano across the ridge at Fonte della Canaluccia, joined the Grava di Varussale and stopped on the valley floor below 650 m a.s.l.,with a horizontal distance of approximately 2.5 km and a fall height exceeding 1200 m. Whether it released in 2017, is not clear, but in 2014 it stopped a short distance above the road just below 1300 m a.s.l., with a horizontally projected run-out distance of about 1100 m. In contrast, avalanches from Monte Siella through the Valle Savina do not usually reach the road at approximately 1220 m a.s.l., but the 2017 event did.

In the aftermath of the 2017 disaster, a sequence of aerial photographs of the Rigopiano area from the years 1945, 1954, 1975 and 1985 were made available on the Internet, together with the assertion that a large-scale avalanche event had occurred in 1936. The photos (Fig. 11) show that the forest, completely destroyed in the 1936 event, slowly recovers and becomes a dense, mature stand by 2017. In a letter to the mayor of Farindola, Iannetti (1999) warns of the threat from this avalanche path and mentions an event in 1959. That avalanche does not seem to have caused major damage to the forest—presumably due to its moderate size and the young age of the majority of trees in the path. According to other reports, an earlier quaternary map of the region showed that the hotel is located on an alluvial fan consisting of several meters of debris-flow and avalanche deposits.

2.4 Run-out distance

At the time of the field survey, the run-out area around the destroyed hotel was closed off by the authorities. Hopefully, enough data will eventually be released to allow a precise determination of the run-out distance and a reasonably precise estimate of the deposit volume. In the present situation, Fig. 12 can be used to estimate the most distal point of the avalanche from the debris that is still visible. Assuming that the avalanche front carried debris more or less until standstill, the horizontally measured run-out distance from the probable fracture line is close to 2200 m. Of this distance, the 750 m from 1400 m a.s.l. to 1200 m a.s.l. had an average inclination of only 15° and were covered with a dense, mature forest. It is unclear, however, whether the debris visible in Fig. 12 was deposited by the dense/fluidized part of the avalanche or carried by the snow cloud. A group from BFW Innsbruck will publish survey data from the run-out area, taken a few days after the accident and distinguishing between deposits from the dense/fluidized part and the powder-snow cloud (J.-T. Fischer, pers. comm.).

3 Field survey

For the field survey, one day (Saturday 2017-06-03) was available. Safety considerations (only one person, rapid nightfall in these latitudes, lack of mobile phone connection) together with the restrictions imposed by the sequestration of the area around the destroyed hotel and the road closures limited the choice of itinerary and the amount of data that could be collected. On advice from a resident of Farindola, the route shown in Fig. 2 was chosen on the way up. Unfortunately, the track could not be recorded by GPS. In the release area, it became clear that one could safely descend the upper track. At the upper end of the gully, the author decided to follow the avalanche path also through the lower track, despite the ubiquitous boulders and tree debris.

3.1 Observations in the release area

To the best of the author's knowledge, there are no direct observations of the fracture line of the 2017 avalanche because poor weather conditions and at times strong wind prevented reconnaissance flights by helicopter for several days. As Fig. 13 clearly shows, the potential release area is large and fairly uniform. There are, however, two depressions of 50–100 m in width and at most a few meters in depth in the upper part; they narrow in the downhill direction and become two channels at the lower end of the release area. Small-scale terrain roughness is easily evened out by moderate amounts of snow, but the mentioned depressions should be able to collect a fair amount of snow under (locally northerly or southerly) winds along the mountain side. Snowfalls with westerly winds are expected to deposit significant amounts of snow in the uppermost part of the release area around 1850 m a.s.l. There are a number of boulders or small rock faces in that part, which give rise to sporadic rock falls and may pin the fracture line.

The release probability must be much lower at the southern end of the potential release area than in its center part: There were no visible traces of avalanche damage along the upper border of the forest at an altitude of approx. 1600–1650 m a.s.l. where the trail from Rigopiano across the Vado di Siella approaches the Valle Siella. Avalanches descending the neighboring valley to the north and the Valle Cupa release significantly more often (with a frequency of more than $0.2\,\mathrm{y}^{-1}$ according to information from D. Borgheggiani, Club Alpino Italiano, Farindola section). The reason for such pronounced differences is not entirely clear, but may be related to the more pronounced concavity of those release areas or the wind patterns around the summit of Monte San Vito.

There are few signs of erosion in the release area, despite the heavy precipitation that may occur; this is probably due to the karstic nature of the mountain range, which limits surface run-off. The two depressions mentioned above seem to collect most of the limestone rocks falling out. During rain storms or avalanching, some degree of transport may occur since the boulders accumulate along some stretches of the depressions (Fig. 14, left panel). As one descends towards the lower end of the release area, the talus areas grow in size. A ridge dividing two shallow channels appears to have deflected the

Figure 13 Views of the release area of the 2017 Rigopiano avalanche. Pictures taken at approx. 1800 m towards northeast and 1700 m a.s.l. towards southwest, respectively.

Figure 14 Left: Gently inclined area in the upper track where the scree may be due to deposition by rockfall, a small rock avalanche or a particle-laden water flow. Right: Scree area that is most likely due to topsoil erosion by snow avalanches that are deflected by the small shoulder.

2017 avalanche (perhaps also earlier events), which eroded the topsoil (Fig. 14, right panel). Also, some shallow furrows of 2–10 m in length and less than 0.5 m in width are present where the vegetation and top soil apparently have been eroded and transported a short distance (Fig. 15). It is not clear whether they were formed during the 2017 avalanche descent (perhaps by a large boulder scraping the ground for a short distance before ascending to the flow surface) or are due to the action of water at a later time.

The vegetation in the release areas consists primarily of a dense grass cover with a wide variety of herbs and flowers and some ground-hugging juniper bushes interspersed. In the upper reaches of the track, a few willow or beech bushes can be found.

Based on the survey and map study, one may estimate the release area for the extreme Rigopiano avalanche to a little over 10 ha when projected onto the horizontal plane. Frequent events will likely release in one of the depressions and have a projected release area of about 2–4 ha. Rare but not extreme events are likely to occur when the fracture propagates from one depression to the other so that the combined release area may be 5–8 ha.

The forest damage pattern—or, rather, the absence of forest damage at the northern and southern parts of the forest line below the release area—suggests that neither the northernmost nor the southernmost parts of the potential release area were activated in the 2017 event. If this somewhat tenuous evidence is correctly interpreted, the projected release area would then likely be in the range 6–8 ha for this event. Assuming an average release height (measured vertically) in the range 1.25–2 m and a density in the release area of 150–250 kg m^{-3} (see Sec. 2.2), the release volume and mass would be in the range

Figure 15 One of the furrows observed in the upper track of the Rigopiano avalanche.

75,000–160,000 m^3 and 10–40 kt, respectively. Frigo and others (2018) estimated the fracture depth (measured perpendicularly) as 2 m, the average density as 250 kg m^{-3}, the release volume as 77,000 m^3 and the release mass as 19 kt. In contrast, a group from BFW Innsbruck found a projected release area of 125,000 m^2 and a fracture height of 2–2.5 m to lead to the most realistic simulations with the dynamical flow model SAMOS-AT. The corresponding release mass is 40–60 kt (J.-T. Fischer, pers. comm.).

3.2 Forest damage

At an altitude between 1000 and 1700 m a.s.l., the forest in this region of the Apennine is completely dominated by beech trees (*fagus*). They grow densely, often in clusters of three to seven trees. The typical distance between clusters varies, but appears to grow from 2–3 m at young age to 5–7 m as the trees approach maturity and some of them lose the race for light. Undergrowth is nearly absent. The average tree height varies strongly with location, from less than 10 m near timberline (1700–1800 m a.s.l.) to more than 20 m in avalanche-safe areas near the Rigopiano plateau. The reason for this difference is presumably a combination of rougher climate at high altitude and higher probability of damage due to small, frequent avalanches.

The topsoil above the limestone rocks is very thin in most locations. From the pits where

Figure 16 View of the trimline near the uppermost border of the forest in the Grava dei Bruciati at approx. 1600 m a.s.l. This beech forest stand is not quite mature, but shows the typical clustering of trees, an average distance of about 5 m between clusters, and little undergrowth. The trimline is rather sharp, with virtually no damage inside the surviving stand. In the denudated, stony area in front of the forest, trees of similar age were uprooted and partly carried away, partly deposited nearby. The bushes and young trees in the center of the gully were only slightly damaged. They indicate where minor avalanches occur frequently.

trees had been uprooted, one can estimate a typical soil depth of 20–30 cm. The top of the bedrock is strongly fractured, likely in part due to work of the tree roots that penetrate into small fractures, expand them and eventually wrap themselves around the rock fragments that originated due to fracture (Fig. 17, right panel).

All along the Grava dei Bruciati avalanche path below timberline, the trimline from the 2017 event was a rather smooth line. Inside the surviving forest, practically no damage was observed and only a few felled tree lie partially inside the forest, as Fig. 16 shows. This is in contrast to the observations from the neighboring avalanche path; possible reasons for this difference will be briefly discussed in Sec. 3.3.

In the upper track, there were a large number of young trees near the centerline of the

Figure 17 Damage patterns of beech trees hit by the Rigopiano avalanche: breaking and splintering (left) and uprooting (right). Note the considerable mass of limestone rocks that was pulled out together with the roots

channel that were bent and/or had been stripped of part of their branches, but were neither broken nor uprooted and produced plentiful foliage in the spring (Figs. 16 and 18). Very young trees up to 3–4 m in height and about 5 cm in diameter at breast height (DBH) mostly stood upright four months after the avalanche event. Trees up to about 10 cm in DBH and approx. 7 m in height were mostly bent to the ground; presumably, their root clusters were rotated and partially damaged.

Essentially all larger trees were either broken or uprooted (and possibly broken after uprooting), see Fig. 17. Only in special locations did a very few mature trees survive the avalanche (Fig. 18). The majority of fractures occurred 0.5–3 m above ground, which indicates that the dense or fluidized part of the avalanche was responsible rather than the suspension layer. Given that there was at least 2 m of snow on the ground when the avalanche occurred, fractures near the ground may indicate that the tree was broken, not by the fluidized front, but by the dense part of the avalanche that arrived after most of the new snow had been eroded. In the upper track, we estimate that less than 10% of the destroyed trees were broken and more than 90% were uprooted. In the run-out area, virtually all trees were uprooted.

As trees were uprooted, the root cluster carried along a substantial amount of limestone rocks with sizes from less than 10 cm to more than 30 cm. The hollows left by the uprooted trees had volumes of 0.5–2 m^3. This corresponds to roughly 500–3000 kg of rock eroded with each uprooted tree. Freshly exposed rock fragments were lying scattered over the entire lower track. It is estimated that the areal density ranges from about 20 $kg\,m^{-3}$ at the edges of the avalanche to perhaps 200 $kg\,m^{-3}$ along the centerline.

Lateral velocity gradients in the avalanche tend to quickly align oblong objects like tree trunks in the direction of flow. The orientation of tree debris along the lower track and in the run-out zone thus gives an indication of the flow direction of the avalanche immediately before it stopped. However, if motion ceases first at the front and compression

Figure 18 Upper track of the Grava dei Bruciati path at an altitude of about 1550 m a.s.l. The pronounced shoulder that was partially overflowed is seen to the left. Except for a lone survivor, all large trees were uprooted while young trees near the centerline recuperated from the avalanche. Tree height in the mature stand is estimated as close to 20 m. The forest is so dense and of uniform age that all trees are slender and have a small crown. The trees grow in clusters that are typically about 5 m apart. In contrast to most of the trimline, one can see two "bays", where the fringe of the avalanche ran into the forest and was stopped by it

ridges form as snow piles up from behind, tree trunks might get turned; moreover, the slower rear of the avalanche may follow different trajectories than the fast head. Despite these caveats, one obtains a plausible flow field in this way. Tree trunks deposited near the sides of the avalanche are oriented parallel to the trimline or pointing a little into the forest (Figs. 17 and 16).

As Figs. 18 and 19 show, there is a rather marked shoulder at about 1500 m a.s.l. protruding into the avalanche path from southwest. It can be considered a curved natural deflection dam at an angle of roughly 30° with the main upstream flow direction. Measured from, and perpendicular to, the thalweg, the height of the shoulder is 15–20 m. On the upstream side, the slope varies between 30° and 45°; on the downstream side, between 25° and 45°. The gully narrows from about 100 m at 1520 m a.s.l. to a mere 10 m at 1460 m a.s.l. Most of the mass of the 2017 avalanche overflowed the shoulder and eradicated the entire forest both on the upstream and downstream side. The felled trees visible in the left part of Fig. 18 are oriented oblique to the slope of the shoulder. Their orientation can be assumed to reflect the flow direction in the relatively slow rear part of

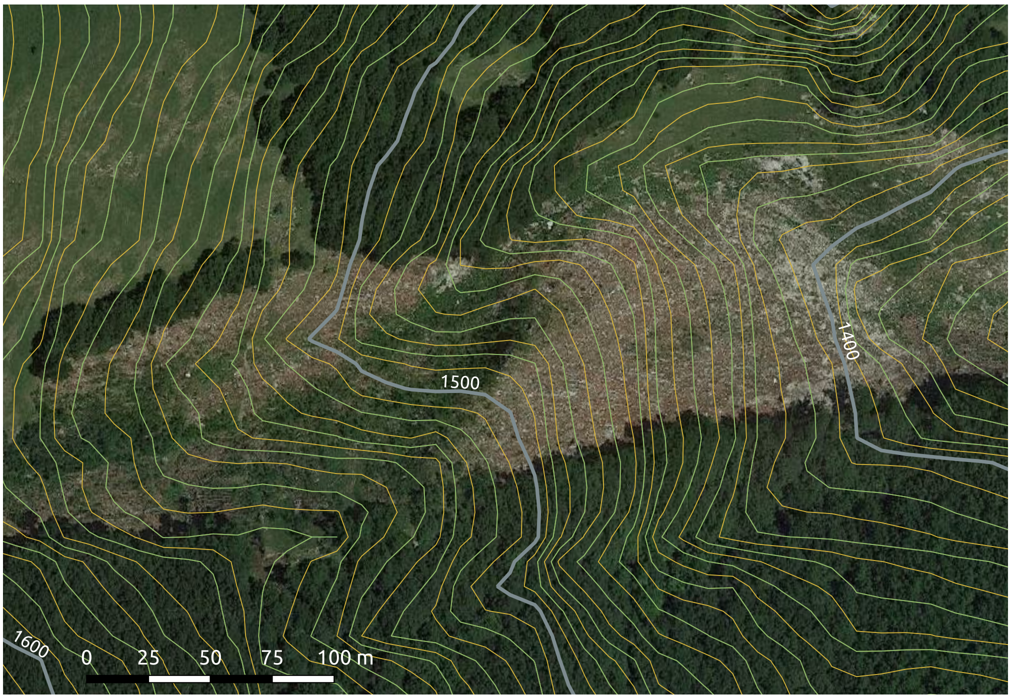


Figure 19 Detail of Fig. 3, showing the pronounced shoulder at 1500 m a.s.l. after the 2017 avalanche. Equidistance of isolines 5 m

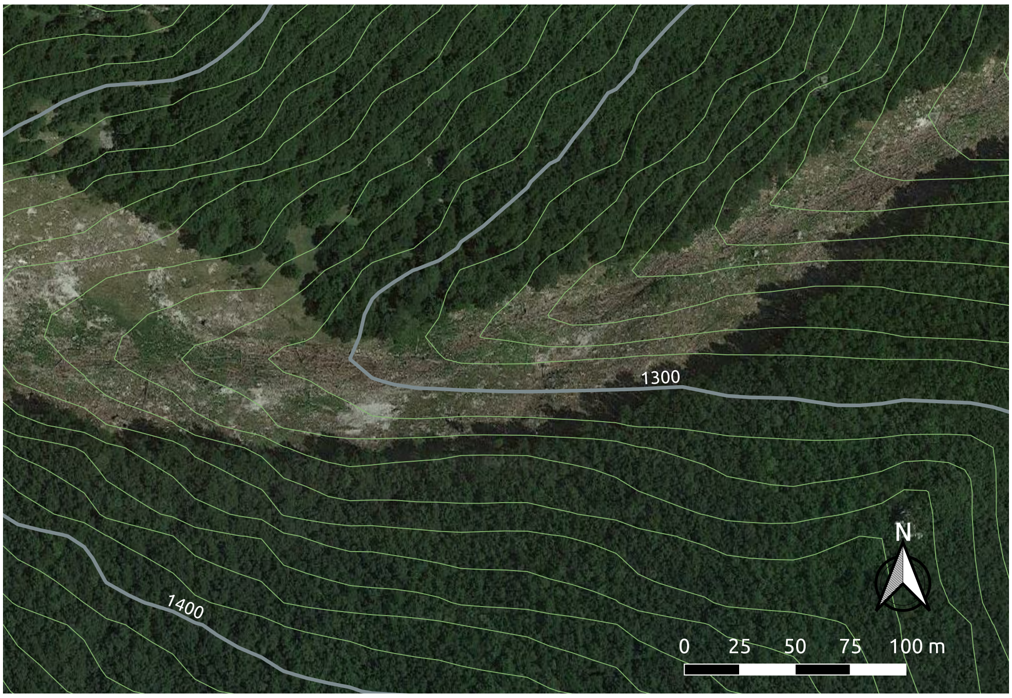


Figure 20 Detail from satellite image Fig. 3 around the left bend at 1300 m a.s.l. after the 2017 avalanche event. The trimline is at the transition from light foliage to dark green shadows. Equidostance of isolines 10 m

Figure 21 Trimline above the bend of the Grava dei Bruciati at approximately 1300 m a.s.l., seen from the trail at about 1530 m a.s.l. The superelevation is estimated as 30–40 m. In the right foreground the rock shoulder that was overflowed by the fastest parts of the avalanche and deflected slower-moving parts. The tree damage near the observer is likely not due to the 2017 avalanche event

the avalanche. The southern trimline, which is clearly visible in Fig. 19, shows that the fast avalanche front was very little deflected by this considerable obstacle. The presence of surviving bushes and young trees is a sign that avalanches reach this altitude frequently (perhaps on average once in ten years), but are usually stopped by the shoulder.

Below 1430 m a.s.l., the gully widens again, and the thalweg makes a right turn through an angle of approximately 90° with a radius of about 90 m. Outside this segment on the opposing slope below the forested cliff to the north, there was hardly any tree debris to be found. According to aerial photos taken before 2017, this area was not forested.

In the 45° left bend at 1300 m a.s.l., the gully narrows again, from a width of 100 m to 50 m (Figs. 20 and 21). The trimline along the southern edge is sharply defined and lies up to 40 m above the gully bottom on a 40° slope, with a (horizontally projected) curvature radius of 270–300 m. Further downstream, the width drops to 35 m at 1220 m a.s.l. and finally widens again when it approaches the Rigopiano area, which may be an up to 350 m wide alluvial fan.

In Figs. 16 and 18, one sees damaged trees lying in the avalanche path. One might therefore think that the avalanche was not able to transport them far. However, closer inspection shows that the trees near the upper edge of the forest (Fig. 16) are fairly young and have developed foliage, i.e., they were not completely uprooted. In contrast, the stand in the background of Fig. 18 is more mature. Most of the felled trees have been stripped of their branches. In some cases, the nearest upstream hollow seemed to match the root system of the felled tree fairly well, suggesting that these trees had been merely dragged a few meters.

3.3 Observations in neighboring avalanche paths

During the ascent, the trail first crossed the Grava di Valle Cupa and then the Grava di Costa Mercante. Clearly, avalanches had descended in either of these valleys in the winter of 2017, see Figs. 3 and 22. At an altitude of 1310–1350 m a.s.l., the Grava di Valle Cupa avalanche created a narrow cut, no wider than 15 m, in a thicket of young beeches (Fig. 23). From the trail, only 50–100 m of the cut above were visible; over this distance, its width did not change appreciably. In Fig. 22, the uppermost part of the 2017 cut is barely visible, but it appears that it is hardly more than 30 m wide at an altitude of approx. 1600 m a.s.l. The trees were less than 10 cm thick at the base and quite flexible; many developed foliage in the spring despite the severe damage they had taken. The beech trees tend to grow in clusters of typically 3–10 trees less than 0.5 m between trunks, and the distance between clusters is perhaps 2 m on average. This gives a tree density of about 10,000 ha^{-1} and a value for the product of tree density and average diameter at breast height $nD \approx 0.05\,\mathrm{m}^{-1}$. If the young trees were rigid, clusters would act almost as giant trees with breast-height diameters of 0.5–1.5 m; this would then give $nD \approx 0.1\,\mathrm{m}^{-1}$.

As the photo shows, the forest to the side of the avalanche cut is equally dense, but significantly older (perhaps some 50 years whereas the trees in the cut were 10–20 years old). This suggests that such an event is quite commonplace in this avalanche path, with a return period of at most 30 years, perhaps as low as 10 years. If this is correct, one has to assume that an avalanche event with a return period of 100 y or more may leave a much wider scar and descend to the vicinity of the road and the valley floor at approx. 1250 m a.s.l. The age of the forest to the sides of the cut is compatible with a large event perhaps around 1950. However, it could as well be that this area was used as pasture until around World War II or that an older forest stand was harvested around that period.

Perhaps the most surprising aspect of this avalanche is that it progressed so far despite its narrowness. Yet there is no pronounced channel to guide the avalanche, and it is hard to imagine that a narrow dry-snow avalanche would attain very high speed in such a setting. If the avalanche descended as a wet-snow avalanche, small disturbances such as

Figure 22 Release areas of the neighboring avalanche paths to the north of the Grava dei Bruciati seen from a ridge to the northeast of the Confini camping site. The wide bowl to the right is Valle Cupa. The uppermost part of the narrow cut created by the 2017 event is barely visible behind a beech tree in the foreground. To the left of the cut, the forest is quite young, indicating the potential size of rare avalanche events. The cut from the 2017 event in the Grava di Costa Mercanti path to the left is approx. 100 m wide in the upper part, widens to about 150 m in the middle and then narrows again. An island of only slightly damaged young beech trees extends from about 1530 m a.s.l. down to approx. 1450 m a.s.l, indicating the run-out distance of frequent events in this path

tree clusters could strongly deflect the flow; thus a straight trajectory as is observed here is fairly unlikely unless there is at least a moderately pronounced channel to guide the avalanche. One may speculate whether, to some degree, the trees that were broken by the avalanche front act analogously to a channel compared to the trees still standing to the sides of the avalanche. This can explain that the main body and tail of the avalanche follow in the trajectory of the front, but leaves the question open why the front is not randomly deflected by tree clusters.

The release area above Valle Cupa extends from about 1700 m a.s.l. to 1950 m a.s.l.

Figure 23 Forest damage from the 2017 Valle Cupa avalanche. The cut created by the avalanche is only 10 m wide near its end about 30 m beyond the trail, at an altitude of approx. 1310 m a.s.l.

(Figs. 2 and 22). The potential release area has a projected area of about 10 ha, but except in extreme situations, one expects only one sector of the bowl-shaped area to release, depending on the dominant wind direction during the snowstorm. To judge from its narrow width, the 2017 avalanche probably was of medium size relative to the potential of the release area, with a release area perhaps of the order of about 5 ha. Given the massive snowfall and the bowl-shaped release area, the fracture depth may have been more than 1 m, however, so that the release volume and initial mass probably exceeded 50,000 m^3 and 10 kt, respectively.

In the neighboring valley to the south, an avalanche released that attained close to maximum size relative to the potential of the path. As Fig. 22 shows, it created a 50–150 m wide cut in the mature beech tree stand down to an altitude of about 1320 m a.s.l. In the upper part of the track, a narrow tongue of young trees withstood the onslaught of the avalanche only lightly damaged. The extent of this young stand most likely marks the width and length of frequent avalanches in this path, with a return period in the range 5–20 y. Note that the width of the young stand is similar to the width of the 2017 cut in the Valle Cupa path.

Most of the trees that were taken down by this avalanche had breast-height diameters between 15 and 30 cm. Timber was selectively harvested a few years ago so that sections of several trees of different sizes were available for age determination. However, weathering made it difficult to reliably count the growth rings, see Fig. 24. Our best estimate is

Figure 24 Beech tree cut by chainsaw some years before the 2017 avalanche in the Grava di Costa Mercante avalanche path. The notebook measures $15 \times 21\,\mathrm{cm}^2$

that in this area and at an altitude of 1400 m a.s.l., beech trees with a breast-height diameter of 20 cm are about 50 y old. It would be useful to obtain more reliable information on this point from, e.g., local forestal engineers as it is important for assessing the frequency of avalanche releases in the area.

As in the case of the Rigopiano avalanche, the majority of the trees were uprooted. The topsoil was again seen to be very shallow, but the limestone underneath was strongly fractured by the tree roots. The terminal area of the deposit could not be visited either for this avalanche or the Rigopiano avalanche. Therefore it is difficult to assess whether the rocks from uprooted trees were transported over a long distance or deposited close to their original location. The fact that freshly exposed rocks were strewn almost evenly about the area where trees were uprooted, but were not deposited in large quantities in locations where there had been no forest, suggests that the average transport distance was not very long—perhaps a few tens of meters.

An interesting observation from this avalanche concerns the lateral distribution of forest damage. In the author's observations from (channelized) avalanche paths in the Alps, the trimline from snow avalanches appears very sharp, i.e., almost all trees within the path are destroyed, but there is almost no damage to the trees beyond that sharp line. The same obvservation was also made along the Grava dei Bruciati avalanche path (see e.g. Fig. 16). In the present case as well, there is a clear trimline, within which only young, flexible trees survived. However, in the run-out zone in the vicinity of the survey track (cf. Fig. 2), uprooted, cut or damaged trees were lying around some 20–30 m into the forest on either side of the avalanche (Fig. 25). It seems that all of the tree debris stemmed from the cut and was rafted into the surviving forest by the avalanche, which

Figure 25 Avalanche damage beyond the trimline, i.e., inside the forest, at the northern edge of the Grava di Costa Mercante avalanche

sustained some damage from felled trees or stones hitting the bark of the standing trees. The unusually far lateral penetration of this avalanche into the forest appears to be due to the reduction of slope in this zone and the absence of a channel that guides the avalanche.

4 Data for use in back-calculations of the Rigopiano avalanche

The data that will be described in this section are prepared with a view towards use in NGI's quasi-3D dynamical avalanche model MoT-Voellmy, but it should be relatively easy to adapt it the data format requirements of other models, in particular RAMMS, Titan2D or GeoClaw.

4.1 Topographic information

A digital elevation model (DEM) with a spatial resolution of 10 m can be obtained in GeoTIFF format from `http://opendata.regione.abruzzo.it/opengeodata/Dati_raster/2007%20-%20DTM%2010x10/350140_DTM10x10.rar` (tile 35140 covers the entire area). The EPSG code is 32633. There appear to be marked differences from the topographic map at scale 1:25,000 (Fig. 2) if one compares the contour lines. It should be assumed that the modern DEM is more precise than the map produced manually from geodetic surveys and orthophotos in the 1950s and 1960s. However, we did not notice any apparent deviations from the real terrain during our field survey.

The DEM is stored in the directory `P:/2017/01/20170131/WP4_Deteksjon_og_undersøkelse_av_snøskredhendelser/Skredhendelser_2017-2019/2017-01-18_Rigopiano/Kartdata` as file WGS84_DTM10x10_350140.tif. Two rectangular areas encompassing, respectively, the entire Grava dei Bruciati path and both the Grava di Valle Cupa and Grava di Costa Mercante paths, have been cut out and stored in ESRI ASCII Grid format as files Grave_bruciata.asc and Valle_Cupa.asc; they can be used directly in simulations with RAMMS or MoT-Voellmy.

4.2 Initial and boundary conditions

There are no direct observations of the release area and the fracture depth. Based on the terrain characteristics, the available information on the wind direction and strength, and the observed forest damage patterns, three different possible release areas are proposed (GB_rel_area_S.shp, GB_rel_area_M.shp, GB_rel_area_L.shp) in ESRI shape file format.

As discussed in Sec. 2.2, the density of the released slab was probably in the range 150–250 kg m^{-3}, while the release depth most likely was between 1.5 and 2.0 m, but values in the ranges 1–1.5 m or 2–2.5 m cannot be excluded on the basis of the available information.

The erosion model of MoT-Voellmy requires the spatial distributions of the erodible snow depth (measured perpendicular to the ground) and the characteristic shear strength of the snow cover as input. The latter may correspond to the strength of the weak layer, whereas the new snow above it may be considerably stronger. In such a situation, the simple erosion model of MoT-Voellmy, which assumes continuous erosion at the snow–avalanche interface rather than intermittent detachment of thick slabs, may not give the correct erosion rate. Disregarding this potential problem, the following qualitative rules should be taken into account when creating these raster files: (i) The amount of erodible snow tends to increase with altitude. In the vicinity of the release area, the erodible snow depth will be comparable to the fracture depth, but probably somewhat smaller. (ii) Where blowing snow is not a strong effect, the local new-snow height multiplied by the cosine of the local slope angle may be a reasonable approximation. (iii) Due to the higher temperature at lower elevations, the density of the erodible snow layer is expected to decrease with altitude. (iv) The shear strength of snow at constant density decreases significantly with increasing temperature (Mellor and Smith, 1966), but it increases about exponentially with density at constant temperature. Moreover, weak layers like buried surface hoar will more rapidly metamorphose into non-weak layers at elevated temperatures. (v) The dense beech forest may reduce the erodible snow depth somewhat. The snow density may also be higher inside the forest than outside, except where snow drift compacts the new snow. It is an open question whether the shear strength of the snow inside the forest is larger or smaller than in a comparable location outside the forest.

Given these uncertainties, three scenarios with different distributions of erodible snow depth and shear strength have been devised and provided as raster files. Table 1 shows the heuristic formulas by which they were created. The estimated temperature distribution is also indicated as a reference for models that vary the friction parameters as a function of temperature. The qualitative properties of the proposed formulas are the following:

Temperature The vertical profile of temperature is well approximated by a linear function of altitude, Z, parameterized by the temperature at sea level, T_0, and the lapse rate $\Lambda < 0$:

$$T(Z) = T_0 + \Lambda Z. \tag{1}$$

Erodible snow height It is assumed that b increases linearly with altitude Z and with contour-line curvature κ, i.e., snow accumulates in depressions and is eroded from ridges and shoulders by the wind. Moreover, the curvature effect is assumed to increase with altitude because wind speeds tend to increase with altitude. Less snow tends to accumulate in a forest stand, even if it consists of deciduous trees. The best indicator of this effect would be (winter) crown coverage, but here the number of trees per unit area, n, times the average trunk diameter at breast height, D is used as a proxy. The simplest function with these properties can be written as

$$b(Z, \kappa, nD) = b_0 + \Gamma \cdot (1 + \kappa/\kappa_r) Z - \Delta n D. \tag{2}$$

Snow density A standard average value for new snow is $100\,\mathrm{kg\,m^{-3}}$. Under its own weight, the new snow will densify rapidly. This process occurs the faster the warmer the snow and the larger the overburden. As temperature drops with altitude, the snow remains light for a longer time at higher altitude. However, larger snow depths at high elevation and stronger wind packing counteract this tendency. Here, we assume

$$\rho(Z) = \rho_0 + \Sigma Z. \tag{3}$$

Shear strength For a given snow type and constant density, the shear strength is known to decrease when the temperature approaches the melting point (Mellor and Smith, 1966). At fixed temperature, however, the strength increases exponentially with density (Mellor, 1975). In Nature, the lower temperatures at higher altitude cannot generally compensate for the effect of higher density at lower altitude, except where wind-packing occurs. In forest stands, the complex wind field and snow clods falling from branches tend to pack the snow more densely and to interrupt the formation of extended weak layers. We tentatively set

$$\tau_c(Z, nD) = \tau_{c,0} + \Xi Z + \Omega nD. \tag{4}$$

On the basis of observations and photos, a rough map of nD (stand density times mean breast-height diameter) has been elaborated. Given the large uncertainties, it is advisable to conduct numerical simulations with different distributions of nD.

Table 1 Scenarios for estimating erodible snow height and strength for the 2017 Rigopiano avalanche. κ is the planform curvature, taking positive values in gullies, Z is the altitude, n the number of trees per unit area. The erodible snow depth *is obtained by multiplying the erodible snow* height *by the cosine of the local slope angle. For each quantity, the range of values from the release area to the run-out area is indicated*

Scenario	1	2	3
Erodible snow height	$1.0\,\mathrm{m} + 0.0005\cdot(1+10\,\mathrm{m}\kappa)Z - 10.0\,\mathrm{m}^2\,nD$	$1.0\,\mathrm{m} + 0.0005\cdot(1+10\,\mathrm{m}\kappa)Z - 10.0\,\mathrm{m}^2\,nD$	$0.5\,\mathrm{m} + 0.001\cdot(1+20\,\mathrm{m}\kappa)Z - 10.0\,\mathrm{m}^2\,nD$
	$2.4\,\mathrm{m} > b > 0.5\,\mathrm{m}$	$2.4\,\mathrm{m} > b > 0.5\,\mathrm{m}$	$4.3\,\mathrm{m} > b > 0.2\,\mathrm{m}$
Temperature	$7.0°\mathrm{C} - 0.006°\mathrm{C\,m^{-1}}Z$	$7.0°\mathrm{C} - 0.007°\mathrm{C\,m^{-1}}Z$	$5.0°\mathrm{C} - 0.007°\mathrm{C\,m^{-1}}Z$
	$-4.4°\mathrm{C} < \vartheta < -0.2°\mathrm{C}$	$-6.3°\mathrm{C} < \vartheta < -1.4°\mathrm{C}$	$-8.3°\mathrm{C} < \vartheta < -3.4°\mathrm{C}$
Density	$200\,\mathrm{kg\,m^{-3}} - 0.05\,\mathrm{kg\,m^{-4}}Z$	$200\,\mathrm{kg\,m^{-3}} - 0.05\,\mathrm{kg\,m^{-4}}Z$	$200\,\mathrm{kg\,m^{-3}} - 0.05\,\mathrm{kg\,m^{-4}}Z$
		$105\,\mathrm{kg\,m^{-3}} < \rho_s < 140\,\mathrm{kg\,m^{-3}}$	
Shear strength	$1200\,\mathrm{Pa} - 0.2\,\mathrm{Pa\,m^{-1}}\,Z + 10^4\,\mathrm{Pa\,m}\,nD$	$1200\,\mathrm{Pa} - 0.3\,\mathrm{Pa\,m^{-1}}\,Z + 10^4\,\mathrm{Pa\,m}\,nD$	$1000\,\mathrm{Pa} - 0.2\,\mathrm{Pa\,m^{-1}}\,Z + 5\cdot10^3\,\mathrm{Pa\,m}\,nD$
	$820\,\mathrm{Pa} < \tau_c < 1960\,\mathrm{Pa}$	$630\,\mathrm{Pa} < \tau_c < 1840\,\mathrm{Pa}$	$620\,\mathrm{Pa} < \tau_c < 1260\,\mathrm{Pa}$

5 Concluding remarks

What can we learn from the tragedy of Rigopiano? Besides the technical issues discussed in the previous sections, the event raises questions concerning the methodology of hazard mapping and the legal and political procedures and conditions. Discussing them in depth is far beyond the scope of this Technical Note and the author's competence, but it may nevertheless be useful to raise them briefly here.

Consequences for hazard mapping methodology One of the important questions raised by this tragic avalanche event is whether the methods usually applied in avalanche hazard mapping—by NGI or other consultants—would have been able to reveal the potential for catastrophe in advance. When making such a statement a posteriori, one is always in danger of being influenced by the knowledge about the event that has in fact happened. However, in the author's opinion, there are a number of reasons that suggest an affirmative answer can be given:

- Collecting information on past avalanche events from the local population is a crucial step in a serious avalanche hazard mapping effort. It was not particularly difficult to find knowledgeable local persons who know that avalanches release very often in paths in the vicinity of, and quite similarly exposed as, the Grava dei Bruciati. It is difficult to say whether an external expert would have obtained knowledge of the report written by a mountain guide for the procedure to grant the building permit for Hotel Rigopiano around 1999. According to press reports, that report contained information on an avalanche event of somewhat smaller size in this path, which took place in 1959.
- Forest damage due to the 1963 avalanche in the Grava di Varussale, less than 2 km to the southeast of the Grava dei Buciati, is visible to the naked eye from Farindola. A survey of the area or the analysis of aerial photos would easily reveal recent forest damage caused by snow avalanches in the Grava di Valle Cupa and the Grava di Costa Mercante. Avalanche damage is also visible on the southwestern slope of the mountain chain between Monte Siella and Monte San Vito. In the Grava dei Bruciati itself, the tree population at the center of the gully was clearly much younger than to the sides down to an altitude between 1300 and 1400 m a.s.l. The more mature trees to the sides have an estimated age of 50–80 years, while significantly older trees can be found in areas that are not endangered by avalanches. This observation strongly suggests that medium-size avalanches occur quite frequently and that a large-scale event may have happened around the middle of the 20th century.
- There are a number of ski areas with lifts and other infrastructure not too far from Rigopiano, indicating that there are considerable amounts of snow in winter. An analysis of the climate of this region shows immediately that there can be extremely intense snowfalls, the most extreme measured in March of 2015.

Moreover, the Apennine being the major obstacle for winds between the eastern and western Mediterranean and the Gran Sasso massif being the highest range and the divide, one has to expect that strong winds occur often and may transport massive amounts of snow into potential release areas.

- The release area above the Grava dei Bruciati is vast, has the "right" inclination and at least two slight depressions that will collect snow under winds along the mountain side, yet are gentle enough for weak layers to be continuous over large distances.

Thus a careful investigation of the avalanche hazard in this path, using state-of-the-art methods, should conclude that large avalanches can release in this path and that they will reach the location of the hotel. The critical question then concerns the return period of avalanches reaching Rigopiano. Without a detailed analysis of climate data, no definite answer can be given, but in the author's opinion, most avalanche experts would probably estimate the return period to be in the range 50–200 years. (With a posteriori knowledge of the 1959 and 2017 events, experts would presumably set an upper limit of about 100 years.)

According to Norwegian regulations, the Hotel Rigopiano would definitely be in the endangered area for security classes[1] S2 and S3, perhaps even for S1. Applying Swiss regulations, Rigopiano would be assigned either to the "blue" or "red" hazard zone, depending on the details of the estimate of the return period and the maximum avalanche pressure. In Italy and France, the maximum return period for avalanches to be taken into account is essentially 100 y, in Austria 150 y; with these criteria, it would depend on the details of the expert's assessment whether Rigopiano would be considered an endangered area or not.

Such dependence on subjective judgment is, of course, troublesome. However, in the author's opinion avalanche science is still far from being able to determine the return period in a given avalanche path objectively. The expert's subjective judgment is unavoidable in such situations, but it is important to keep in mind that it can have grave consequences. In situations of doubt and with potentially high risk to human life, one may consider basing the final decision on a number of independent assessments by different experts or charging a panel of experts with the assessment.

In view of the massive forest destruction one may ask to which degree the forest was able to reduce the run-out distance and velocity of the avalanche and how this effect can be captured in avalanche models. Clearly, the available data does not directly reveal the braking effect of forest in Rigopiano because no comparison of the run-out distance

[1] Buildings in security class S1 comprise garages, boat sheds and similar constructions where people are only sporadically present. They must not be exposed with a frequency larger than $0.01\,\mathrm{y}^{-1}$. Cabins and single-family homes or small condominiums fall into security class S2, with an upper avalanche frequency limit of $0.001\,\mathrm{y}^{-1}$. Public spaces with many people present like schools, hotels, factories are assigned security class S3, where the maximum tolerated avalanche frequency is $0.0002\,\mathrm{y}^{-1}$.

between avalanches through forest and in non-forested terrain under otherwise identical conditions is possible. However, in one carefully observed and analyzed event in Japan, such immediate comparison is possible (Takeuchi and others, 2011, 2018). This question will be investigated further in [II], where it will be shown that an avalanche of the size of the 2017 Rigopiano event indeed should be expected to traverse and destroy a moderately strong forest over a distance of 1 km. Moreover, if an avalanche is expected to destroy forest above some built objects, its destructive power will be much higher than that of a corresponding pure-snow avalanche.

Political issues Also at the political level, several questions are brought into focus by catastrophes like this one. A major problem—treated very differently in the European countries—concerns the frequency threshold for taking avalanches or other gravity mass movements into account, as already mentioned in the paragraph on consequences for hazard mapping methodology. In Norway, buildings like the destroyed Hotel Rigopiano must not be reached by avalanches more frequently than once in 5000 years. In Italy, there is presently no national law regulating this. The recommendations issued by the (private) organization of Italian regions and avalanche professionals, AINEVA (Interregional Association for Snow and Avalanches), and adopted by several of Italy's regions, set the threshold return period as low as 100 y. Similar thresholds are adopted in France and Austria.

The difficulty and ensuing large uncertainty of estimating the return period of very rare events was a major reason why AINEVA adopted the 100-year threshold (M. Barbolini, private communication, 2001). This difficulty is especially pronounced in areas where the avalanche cadastre is poor or non-existent or there are no long time-series of nivo-meteorological measurements. However, a majority in society may well consider the *risk* due to avalanches with return periods between 100 y and 1000 y to be unacceptably large in cases where there is high exposure or high vulnerability of exposed persons. The first case comprises all buildings that fall under Norwegian security class S3; high vulnerability is due to high impact pressure relative to the strength of a structure. The latter varies over perhaps two orders of magnitude for different widely used types of construction, but our knowledge about these limits is still rather limited. In the author's personal opinion, the Swiss threshold return period of 300 y is the minimum for achieving adequate protection through hazard mapping.

At this point, only Norway and Iceland have thresholds that depend on human exposure to the avalanche hazard. From a societal risk perspective, it appears mandatory to take into account exposure, but at the same time one is faced with the problem that exposure can change much over a short period of time, and the state entities in charge of avalanche safety often have few or no means available to limit exposure. The Norwegian approach, essentially employing building use as a proxy for exposure and categorizing it into three levels, appears as an effective and easily applicable solution.

On the other hand, experience from Norway shows that a regulation based purely on run-out may be overly restrictive where the risk to human lives and property could be reduced economically by adequate dimensioning of the exposed structures. The Swiss approach, which is based on building restrictions linked to both the return period and the maximum expected impact pressure retains the necessary flexibility in land use without sacrificing security. Combining the two criteria, i.e., specifying different pressure–frequency limits for different building categories, would provide an even more suitable framework. The Norwegian regulations TEK10 and TEK17 have begun to open the way for such a practice, even though there are some ambiguities in the present formulation and this option is rarely used in practice.

Finally, experience from many countries shows that the restrictions on land use imposed by effective avalanche hazard mapping often collide with strong economic interests. In the political process that leads to the establishment of legislation on hazard mapping and land-use planning, these interests have to be weighed against each other. Once they are established, however, they need to be enforced uniformly within the area of jurisdiction. Whether this is the case or not, depends strongly on the political culture in a country, a region or even a municipality. In the case of large disasters like the one at Rigopiano, the economic interests tied to the location are often rather strong. The court procedure that usually follows the disaster, may shed light on the question to which degree existing legislation was followed or not.

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