




Article

The Avalanche of Les Fonts d'Arinsal (Andorra): An Example of a Pure Powder, Dry Snow Avalanche

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Abstract: On 8th February 1996, in the north-western part of Andorra in the Pyrenees, the Les Fonts d'Arinsal (LFd'A) pure powder avalanche was triggered, descending some 1200 m to the bottom of the Arinsal valley and continuing up the opposite slope for about 200 m. This size 4–5 avalanche reached velocities of up to 80 ms^{−1}, devastated 18 ha of forest, involved a minimum volume of up to 1.8 × 10⁶ m³ and caused major damage to eight buildings. Fortunately, no one was injured thanks to an evacuation, but 322 people lost their properties. This study describes the physical characteristics of the LFd'A avalanche path and provides data on earlier avalanches, the meteorological synoptic situation and snowpack conditions that generated the avalanche episode, the warning and preventive actions carried out, the effects and evidence of the large avalanche, and the defence system implemented afterwards. A discussion of the avalanche dynamics based on observations and damage, including the role of snow entrainment, the total lack of characteristic dense flow deposits, as well as the evidence of a two-phase flow (fluidisation and suspension), is presented. This case study is an example of a paradigmatic large, pure powder, dry-snow avalanche, which will be useful for model calibration.

Keywords: snow avalanches; powder snow avalanche; field observations; snow entrainment; case study; Pyrenees

1. Introduction

The winter of 1995 to 1996 was unusually intense in the Pyrenees. Six heavy snowfall episodes extended over two thirds of the length of the mountain range, from the Central Pyrenees in Aragon [1], across Andorra [2,3], to the Eastern Catalan Pyrenees [4,5]. In the Catalan area of the range, from December 1995 to March 1996, the snowfalls doubled and even tripled the means calculated over a period of thirty years at half a dozen observatories, and the avalanche situation of 1996 was considered the most catastrophic of the second half of the 20th century [4]. Furthermore, the episodes of 22nd to 23rd January and 6th to 8th February attained the highest Major Avalanche Activity Magnitude Index values ever recorded (this index records quantification of the magnitude of episodes during which major avalanche events have occurred [6]). In Andorra, on 8th February 1996, large avalanches

occurred on the slopes of the Valira del Nord valley, including Arinsal and the Casamanya peak; in the Madriu and Valira d'Orient valleys, including the Incles, Ransol, Vall del Riu and Montaup valleys [7,8] and above Andorra la Vella [9]. The day before, 7th February, the snowstorm halted traffic on all roads in the high valleys of Andorra; not even snowploughs could operate. The villages of El Serrat, Soldeu and Canillo were isolated and some recently built residential complexes were evacuated. Traffic was prohibited on all access roads to ski resorts [2].

At the time, two different institutions were jointly responsible for nivometeorological monitoring and avalanche control in Andorra. The Meteorological Service of the government's Department of Industry under the leadership of Francesc Areny was in charge of snow and meteorological observations. The firm ASI consultants was the government contractor for avalanche control and maintenance of roads and infrastructures, and Arinsal was one of their control points. Margaret Baró, an employee of ASI at that time, had been in contact with the authorities at the "Comú (municipality) de la Massana", which was administratively responsible for Arinsal. Aware of the potential risk posed by the situation, especially after the artificial release of several large avalanches on 6th and 7th February and a few natural releases on the night of the 7th to the 8th [7], she alerted the Comú at 8:00 a.m. and urged them to evacuate the area. Simultaneously, Areny informed the minister in charge of territorial planning of the situation and of the need for urgent intervention to avoid fatal consequences. These alerts led the national and local authorities and the police to close the road at 8:30 a.m. on 8th February to prevent more people accessing the area at risk. Just one hour later, around 9:30 a.m., the Percanela avalanche released and cut off the access road to the Arinsal ski resort, leaving a 4 m thick snow deposit on the road [2,8]. The 322 people who at that time were in the hotels, residential buildings and at the bottom of the ski resort facilities had to be urgently evacuated; however, the avalanche deposit blocked the only evacuation road available, complicating any rapid intervention before a possible second avalanche, while the rescue teams had to probe the area looking for potential victims buried under the snow. As well as ensuring that no victims were buried, the rescue teams had to look for evacuation alternatives through the buildings and the paths above and between them. Finally, 11 buildings were evacuated via the deposit above the main road and via buildings located at the side. All areas had been successfully vacated by around 5:30 p.m. after several hours of effort. Only an hour and a half later, at 7:00 p.m. on 8th February, the Les Fonts d'Arinsal (LFd'A) powder avalanche was triggered, descending to the bottom of the Arinsal valley and continuing up the opposite slope, devastating the forest and causing major damage to eight buildings (Figure 1). Thanks to the evacuation, no one was injured, but 322 people lost their properties.

The avalanche event at LFd'A on 8th February 1996 was a paradigmatic case of a pure powder, dry snow avalanche. The main aim of this study is to provide an updated compendium of published and unpublished data about this event with a view to exploiting it as an interesting example for model calibration.

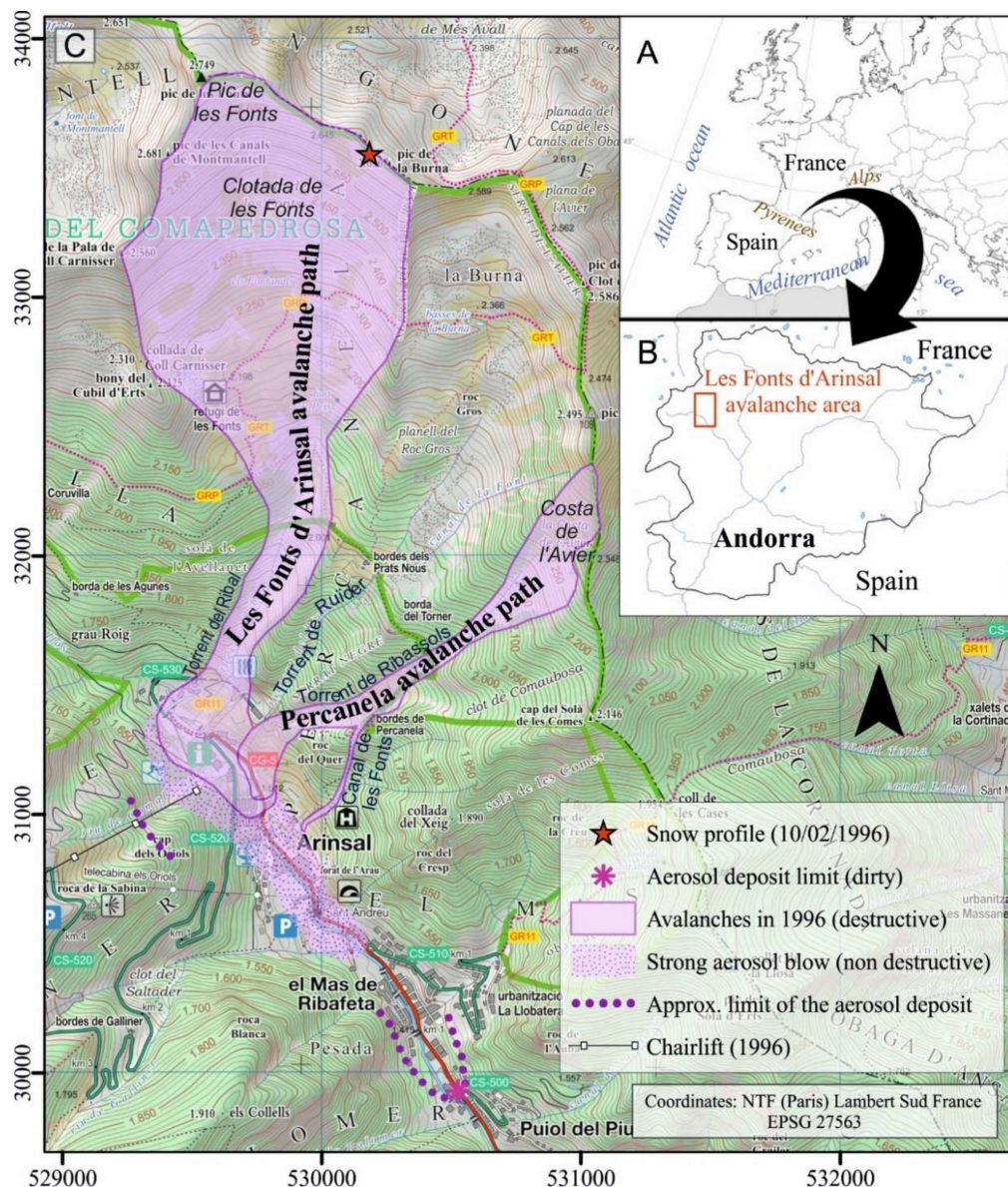


Figure 1. Geographical location of the study area: (A) location of the Pyrenees and Andorra in Europe; (B) location of the area of interest in Andorra; (C) locations of Les Fonts d'Arinsal-Torrent del Ribal (LFD'A) and Percanella-Costa de l'Avier avalanche paths, Arinsal village, the tourist complex and ski resort and the location of the snow profile on 10th February, 1996, marked with a red star.

In the following sections, we describe the physical characteristics of the LFD'A avalanche path, present a summary of data on earlier avalanches, and report on the meteorological synoptic situation and snowpack conditions that generated the avalanche episode. We also review the warning and preventive actions carried out, the effects and evidence of the large powder avalanche, and the defence system implemented afterwards.

2. The Site

The village of Arinsal is located in the heart of the valley of the same name, in the north-west of Andorra. Access to the village is via the CG-5 road and also to the tourist complex of hotels and apartments just upstream and the entrance to the Arinsal ski resort with its facilities: a car park, the CS-520 Comallempla road that goes up to the ski resort and the cable car (a chairlift in 1996) which also ascends to the resort. The Arinsal valley lies on a north-west-to-south-east axis. The LFD'A and

Percanela avalanche paths are on the left margin, on the south-south-west-facing slope (Figure 1). By convention, the following path descriptions (starting, track and run-out zones) refer to the paths as a whole [10].

The LFd'A avalanche path reached its maximum altitude at pic de les Fonts (2749 m), descending 1200 m through the Clotada de les Fonts cirque and Torrent Ribal stream until its confluence with the Arinsal river at the valley bottom (1543 m a.s.l.), crossing it and continuing on to the opposite slope for about 200 m, where it reached a height of more than 50 m above the river crossing (Figure 1). As the entire ridge lies above 2560 m a.s.l., there is a permanent snowpack in the catchment area during the winter months. Meadow covers the area from 2150 m a.s.l. to the crest. Below, pine forests and bushes predominate down to the bottom of the valley, which is occupied by pastures and infrastructure (Figure 2). The area of the basin, extending to the channel of the Torrent Ribal and corresponding to an ancient glacial cirque, covers about 136 ha, with a vertical drop of more than 700 m of and a 1850 m long path. The slope angle in the highest part of the basin exceeds 30° , reaching values up to 50° in the western part and 45° in the east (Figure 3). The combination of these slope values and the presence of the alpine meadow makes the basin a perfect potential avalanche release area when the snowpack conditions are appropriate. Most of the frequent avalanches stop at the bottom of the cirque (from 2300 to 2100 m a.s.l.), where the slope levels out to values of about 14° . The main avalanche track zone, the Torrent Ribal stream, is 1000 m long and has a vertical drop of 450 m. In the upper part of the channel, the slope ranges from 30° to 40° , while in the lower half it increases to between 35° and 47° and ends in a waterfall. The run-out zone starts at a well-defined slope break at 1600 m a.s.l., where the slope decreases abruptly from values of over 40° in the channel to a much gentler area of less than 20° and often about 12° , crossing the river and continuing upstream for about 200 m, where the slope increases again to more than 30° .

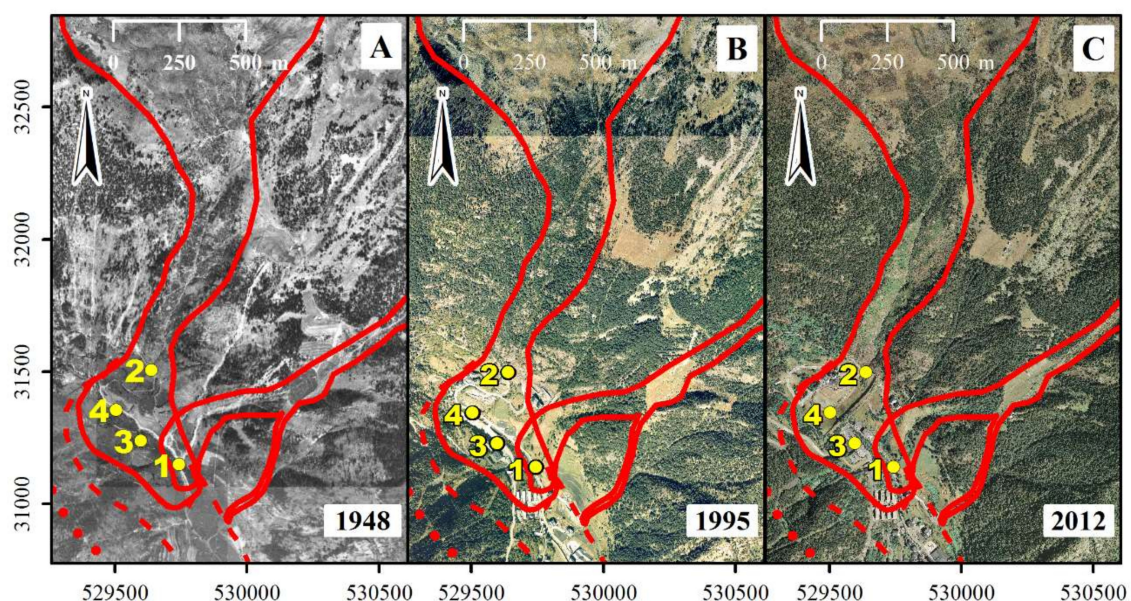


Figure 2. Orthophotographs covering the track and run-out zones of the avalanche paths of LFd'A (west red contour) and Percanela (east red contour) (Coordinates: NTF (Paris) Lambert South France, EPSG 27563). Changes in vegetation in the track zone, especially forest density, can be clearly seen mostly due to avalanche activity: (A) in 1948, after an avalanche that occurred earlier in the decade); (B) in 1995, with the regenerated forest, just before the 1996 avalanche; (C) in 2012, showing the effects of the 1996 avalanche on vegetation. Yellow dots and numbers indicate the approximate run-out of the historical avalanches: (1) the reach of the wet avalanche in the early 1940s; (2) the reach of the avalanche that occurred between the first avalanche and the last one in the 1960s; (3) the minimum run-out of the last avalanche in the 1960s; (4) the reach of the 2015 wet avalanche.

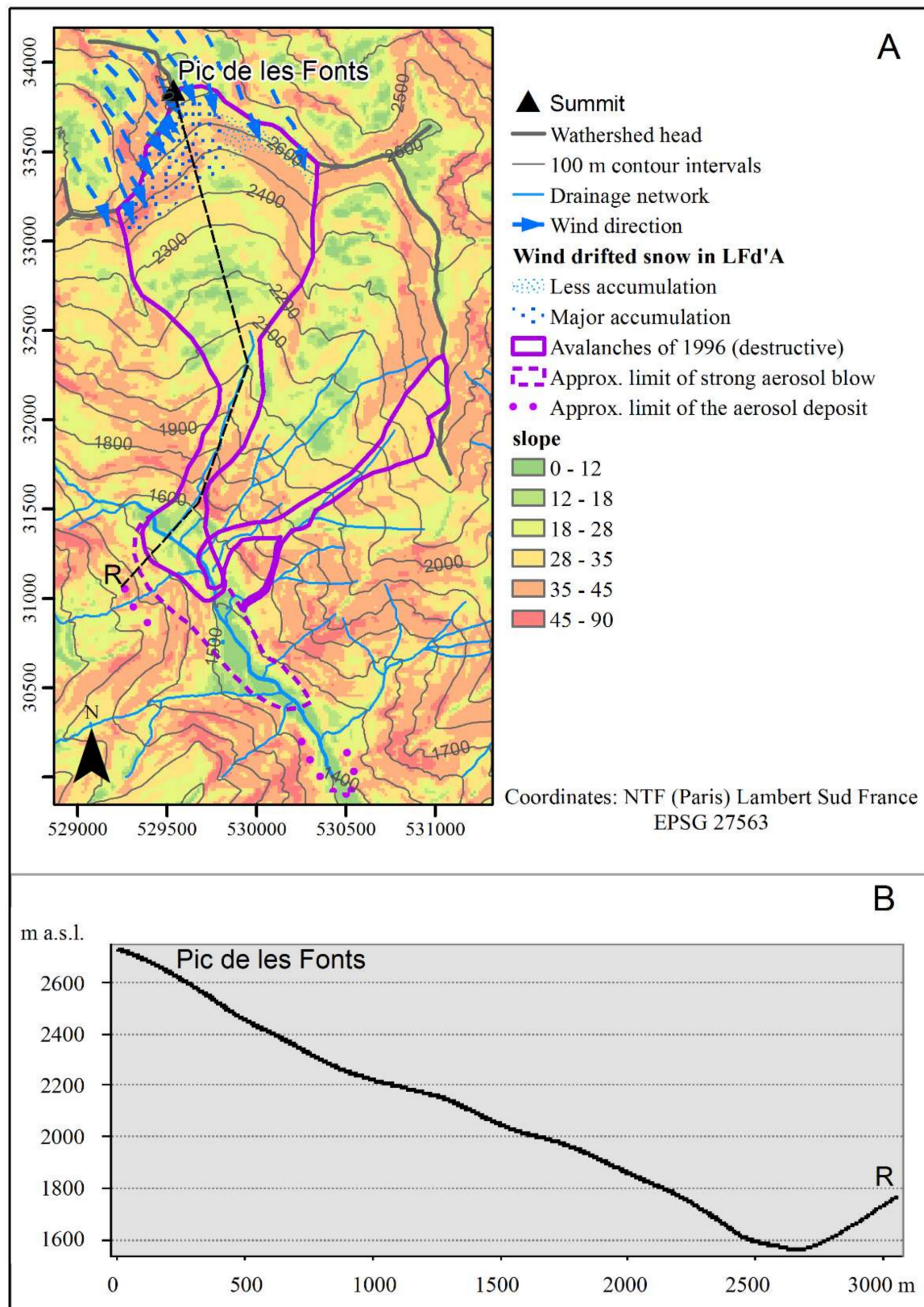


Figure 3. (A) Main wind direction and wind-drifted snow accumulation zones during the snowfall episode in the LFd'A avalanche path on a slope map. (B) Avalanche path profile indicated in (A).

The Percanela avalanche path descends through Costa de l'Avier and presents a vertical drop of 940 m from its highest point, at 2460 m a.s.l., down to the valley bottom, located at about 1500 m a.s.l. The slopes are much more regular, with values of 30° to 35° in the starting zone, which was partially covered by some isolated trees and bushes prior to the 1996 avalanche, and decreasing to values of between 30° and 25° in the first half of the track zone that runs through the Costa de l'Avier channel, previously completely tree-covered (Figure 2B). The channel drains to a relatively flat meadow, at about 18°, which breaks the slope. After this flat area, the 1996 Percanela avalanche split into two steeper branches: the wider one, in the north, used the Torrent de Ribassols path to arrive at the valley bottom and then crossed the Arinsal river, while the narrower one, in the south, descended via the Canal de les Fonts in at a gradient of up to 42° and stopped at the opening of the channel, creating a small, narrow deposit (Figures 1 and 2). Together, they completely destroyed the forest (Figure 2).

The LFd'A avalanche path has a known history of avalanches reaching the floor of the valley. In the early 1940s a wet avalanche descended to the valley bottom and ran downstream for about 150 m, as far as the Torrent de Ruider, just in front of the current cable car station (Figure 1). The effects of this avalanche on the vegetation can be inferred from the lack of dense forest covering the track zone in the 1948 orthophotograph (Figure 2A). On another, undated occasion, the avalanche stopped at about 1600 m a.s.l., at the bottom of the waterfall of the Ribal stream. The largest known avalanche occurred in the late 1960s: the starting zone incorporated the whole cirque snowpack and the avalanche extended over the fields of the opposite slope, transporting a large number of trees into what is now a parking area. Moreover, during the construction of the parking lot in front of the Peu de Pistes building detritus from trees and trunks was found buried close to the chairlift station [2,8,11] (Figure 1).

In February 2015, a wet avalanche triggered by the Gazex@system (see Section 7) reached the valley bottom, continuing as far as the Arinsal river, without causing any damage. None of the previous events in the LFd'A path achieved the amplitude, extension and power of the avalanche of February 1996.

3. Meteorological and Snowpack Conditions

Between 28th January and 8th February, two successive and well-differentiated meteorological episodes were recorded in the Pyrenees. This meteorological sequence contributed to form a snowpack with a high intrinsic instability that triggered many major avalanches in the Pyrenees [6,12], among them the Percanela and LFd'A, in Andorra. Previously, at the Arinsal ski resort (1927 m a.s.l.), from the beginning of the winter season until 21st January, a succession of precipitations had built up a height of snowpack which was, on average, slightly above the mean for the period between 1980 and 2016 (Figure 4). From 22nd January, several snowfalls accumulated more than 0.85 m of new snow in Arinsal, and then a gradual drop in minimum temperature (−6 °C on 26th January; Figure 5) completed the snowpack prior to these two episodes [13]. The snow–rain limit had fluctuated through the winter between 1500 and 2200 m a.s.l. and so, until that moment, the snowline had been strongly dependent on the aspect of the slope. The snowpack persisted in the Clotada de les Fonts cirque (Figure 1), but there was no snow along the main torrent (avalanche track zone) or in the valley bottom.

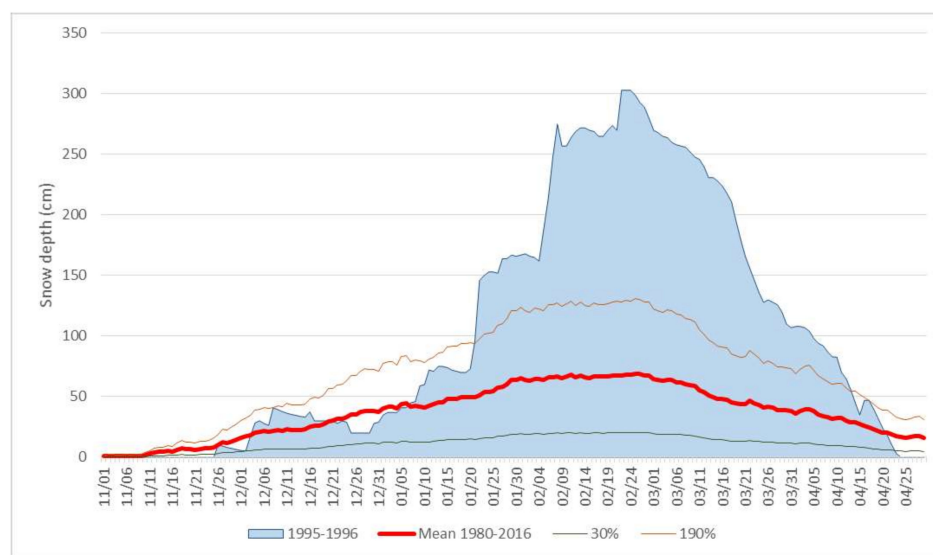


Figure 4. Blue polygon shows the daily snow depth (cm) data recorded at the manual weather station in Arinsal ski resort (1927 m a.s.l.) during the winter season, from 1st November 1995 to 30th April 1996. Red, green and brown lines correspond, respectively, to the mean, 30% and 190% values of snow depth (cm) for the 1980–2016 reference period. Gaps in the long-term daily snow depth series have been reconstructed by means of the Safran–Crocus reanalyses generated within the framework of the CLIMPY 2016–2019 project.

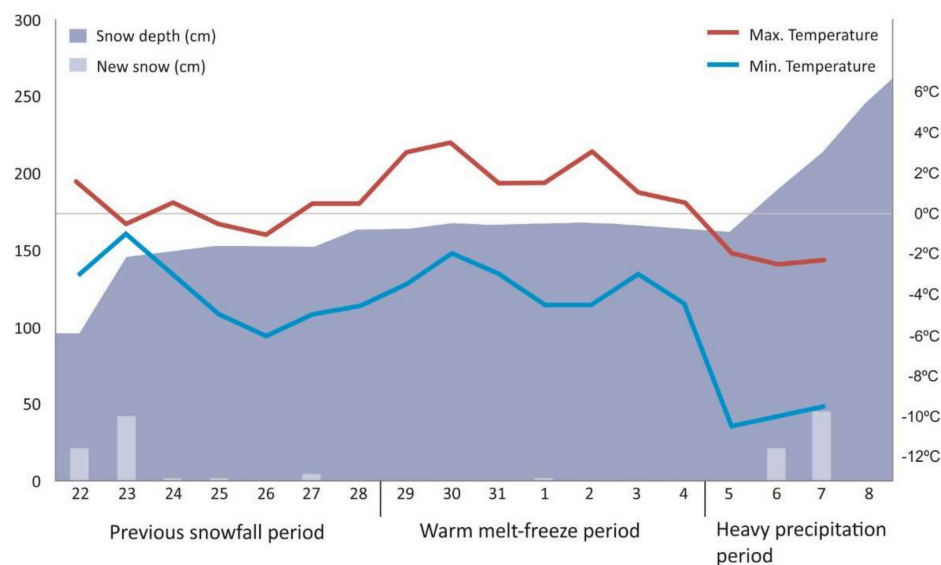


Figure 5. Snow depth (cm), new snow (cm) and minimum and maximum daily temperatures from 22nd January to 7th February 1996, observed at the manual weather station at the Arinsal ski resort (1927 m a.s.l.).

The synoptic atmospheric situation and main characteristics of the two episodes are described as follows:

3.1. Episode 1: Warm Melt–Freeze Period (28/1/1996–4/2/1996)

Between 28th January and 4th February, a stable atmosphere predominated over the Iberian Peninsula with relative anticyclonic conditions and weak geopotential gradient at high levels. This circulation pattern favoured weak SSE winds and the advection of a warm air mass up to the northern part of the Pyrenees. This winter period was characterized by mostly sunny days and

mild temperatures. At high altitudes, above 1900 m a.s.l., temperatures reached positive values during sunlight hours, facilitating the snow melt, while subzero temperatures during the night froze the previously melted snow [4,13], as shown by the atmospheric weather observations at the Arinsal ski resort (Figure 5). This persistent melt–freeze process gave rise to the formation of a melt–freeze crust. During the events of 8th February, the crust acted as a bed surface of the avalanches in Costa de l’Avier-Percanella and in Clotada de Les Fonts-LFd’A cirque.

3.2. Episode 2: Heavy Precipitation Period (5/2/1996–8/2/1996)

On 5th February, a low-pressure system located near Iceland was growing progressively deeper, while the Azores anticyclone remained stationary in its habitual position. This synoptic configuration favoured a NW circulation affecting the northern part of the Iberian Peninsula and allowed several cold frontal systems to cross over the Pyrenees up until the early morning of 8th February. The dominant northerly polar flow caused a sudden drop in temperature on 5th February, with a minimum of -10°C recorded at the Arinsal ski station (Figure 5). The snowfalls began on 6th February, at about 5:00 a.m., accompanied by strong NW winds across the northern part of Andorra [7,14]. As shown in Figure 5, heavy snowfalls intensified with the crossing of a cold front on 7th February [4] and persisted throughout the episode, depositing fresh snow cumulatively in the valley bottoms, including Arinsal [13]. Although no wind observations were available at Arinsal, ASI consultants reported a strong snowstorm with NW winds and large snowdrifts on the east- and south-facing slopes all over Northern Andorra. On 6th and 7th February, there was no visibility over the LFd’A starting area, and the surveillance helicopter could not fly due to the strong blizzard [7]. Wind data were also reported from the automatic weather station at la Molina (2270 m a.s.l.), located on the southern slope of the Pyrenees, 40 km south-east of Arinsal. Instantaneous wind observations showed an increasing trend in the wind speed, from 20 km/h on 2nd February to more than 100 km/h on 8th February, with two peaks exceeding 160 km/h on 6th and 8th February and another 193 km/h on 7th February [4]. At the same time, a peak of 145 km/h was registered in Vaqueira-Beret (2500 m a.s.l.), 45 km east-north-east of Arinsal [4]. The very strong NW winds extended from high atmospheric levels to the surface, as shown on the 850 hPa synoptic map, impinging perpendicular to the Pyrenees mountain ridge (Figure S1 in the Supplementary Materials), until about 4:00 p.m. on 7th February [7]. The highly effective drifting snow process resulting from this situation led to major accumulations on SE facing slopes, as in the starting zone at la Clotada de les Fonts (Figures 1 and 3).

Integrating data from multiple sources and observations at altitudes between 1600 m a.s.l. and 1800 m a.s.l. across Northern Andorra, the new snowpack was about 0.3 m deep on 6th February [7]; on 7th February, at about 9:00 a.m., ASI consultants reported a total snowfall of about 0.5 m at 2000 m a.s.l.; specifically, 0.47 m of new snow at the Arinsal ski resort (1927 m a.s.l.), 0.5 m and 0.7 m at Soldeu ski resort (~2000 m a.s.l.), 0.4 m at Grau Roig and 0.5 m at Pas de la Casa (different altitudes), respectively [7]. As a rough estimation for the northern part of Andorra, from the morning of the 6th February to the evening of the 7th (at about 9:00 p.m.), ASI reported an approximate snowfall of about 1.5 m to 2 m at 2500 m a.s.l., stressing the difficulty of obtaining a more precise calculation due to the strong winds and snowdrifts. At the Arinsal ski resort, from 4th to 10th February, the snowpack height was reported to have increased from 1.64 m to 2.57 m, although no measurements were taken between the afternoon of 7th February and 9th February because the ski station was closed; the last observation was made two days after the avalanches and the cessation of the snowfalls, when the thickness had reduced to some extent due to settlement. The Les Fonts starting zone ranges from 2748 m a.s.l. to approx. 2050 m a.s.l.: therefore, as ASI had estimated, the fresh, cold, drifted snowpack must have been thicker.

On 6th February, the temperatures at about 2000 m a.s.l. at various locations in Andorra were between -1°C and -9°C and fell to between -8°C and -10°C on 7th February. According to radiosonde data from Nîmes, Bordeaux and La Palma, the temperatures at 700 hPa (approx. 3000 m a.s.l.) were

between -10°C and -13°C [7]. The result was a new, very cold and light snowpack deposited as far as the bottoms of the valleys of Northern Andorra, including Arinsal.

On 10th February, two days after the LFD'A avalanche, a snow profile was made by L. Rey and M. Baró (Figure 6) close to and above the crown scar, at 2650 m a.s.l., on a south-west facing slope (Figures 1 and 3). The snow thickness above the crust was 1.10 m and the snowpack temperatures ranged from -5.1°C to -9.1°C , after two days' settlement. It was composed of a fine layer of a few centimetres of faceted grains, which might have formed either during the first episode, when a distinct temperature gradient generated near the crust might have produced a thin layer of near-surface faceted crystals, or during the beginning of the second episode, when the newly fallen snow might have been transformed due to the temperature gradient among the crust and the low atmospheric temperatures. Above this layer, there were rounded grains with some wind-broken and partly decomposed precipitation particles, with densities ranging from 210 kg/m^3 to 370 kg/m^3 . In summary, a snowpack thicker than 1 m of cold, new, wind-accumulated snow was lying on top of a weak layer of poorly bonded, faceted crystals, which in turn was lying over the melt-freeze crust developed during the previous warm period. Furthermore, it has to be pointed out that the slopes were covered with new snow right to the bottom of the valley (Figures 7 and 8), thus favouring the entrainment of snow all along the avalanche descent and feeding it.

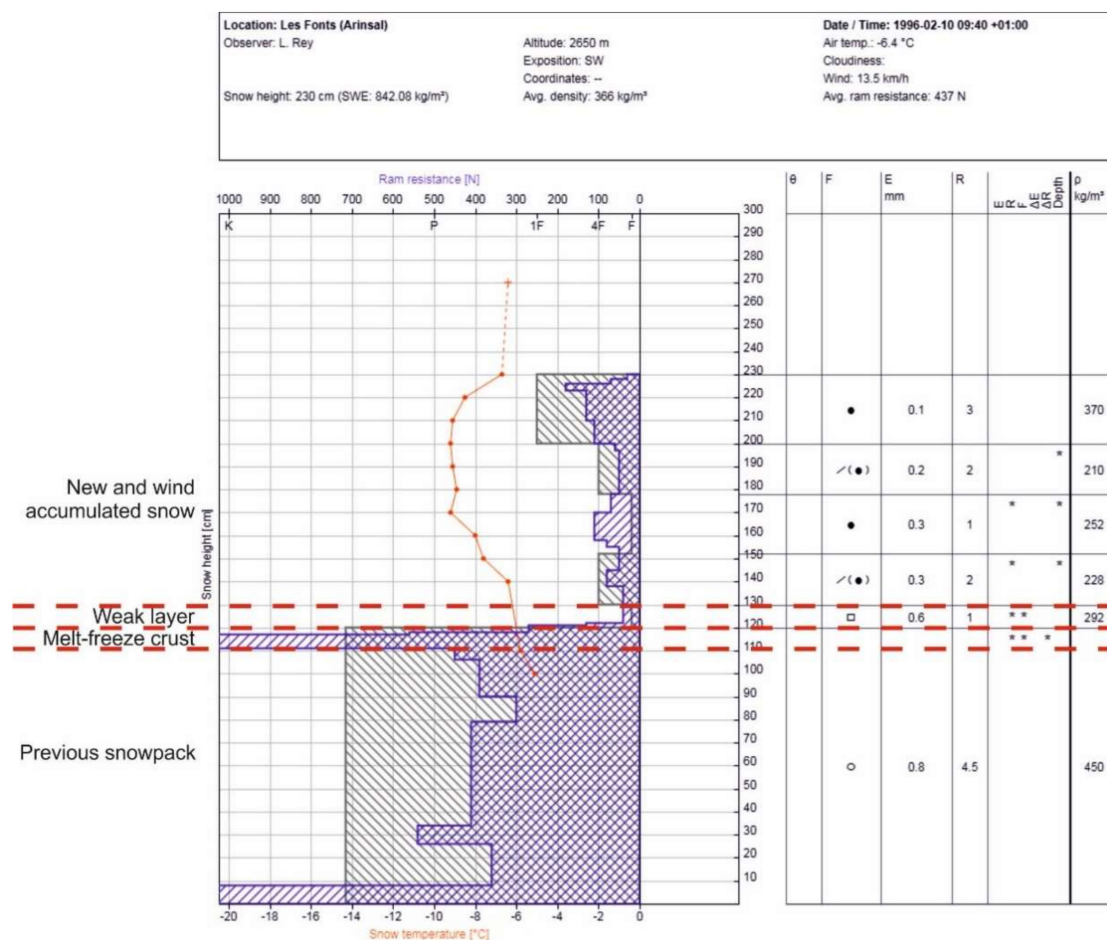


Figure 6. Snowpack profile made by Laurent Rey, accompanied by Margaret Baró, at 9:40 a.m on 10th February. See Figure 1 for location.



Figure 7. Photographs taken from a helicopter the day after the avalanche (Dept. d'Indústria). (A) track and run-out zones of Les Fonts (left) and Percanela (right) avalanches; the LFd'A avalanche entrained the whole snowpack in the track zone, completely destroying the forest and partially eroding the soil; (B) run-out zone view from downstream to upstream in the main valley; the main aerosol trajectory direction can be observed in the plastered snow on the ground.

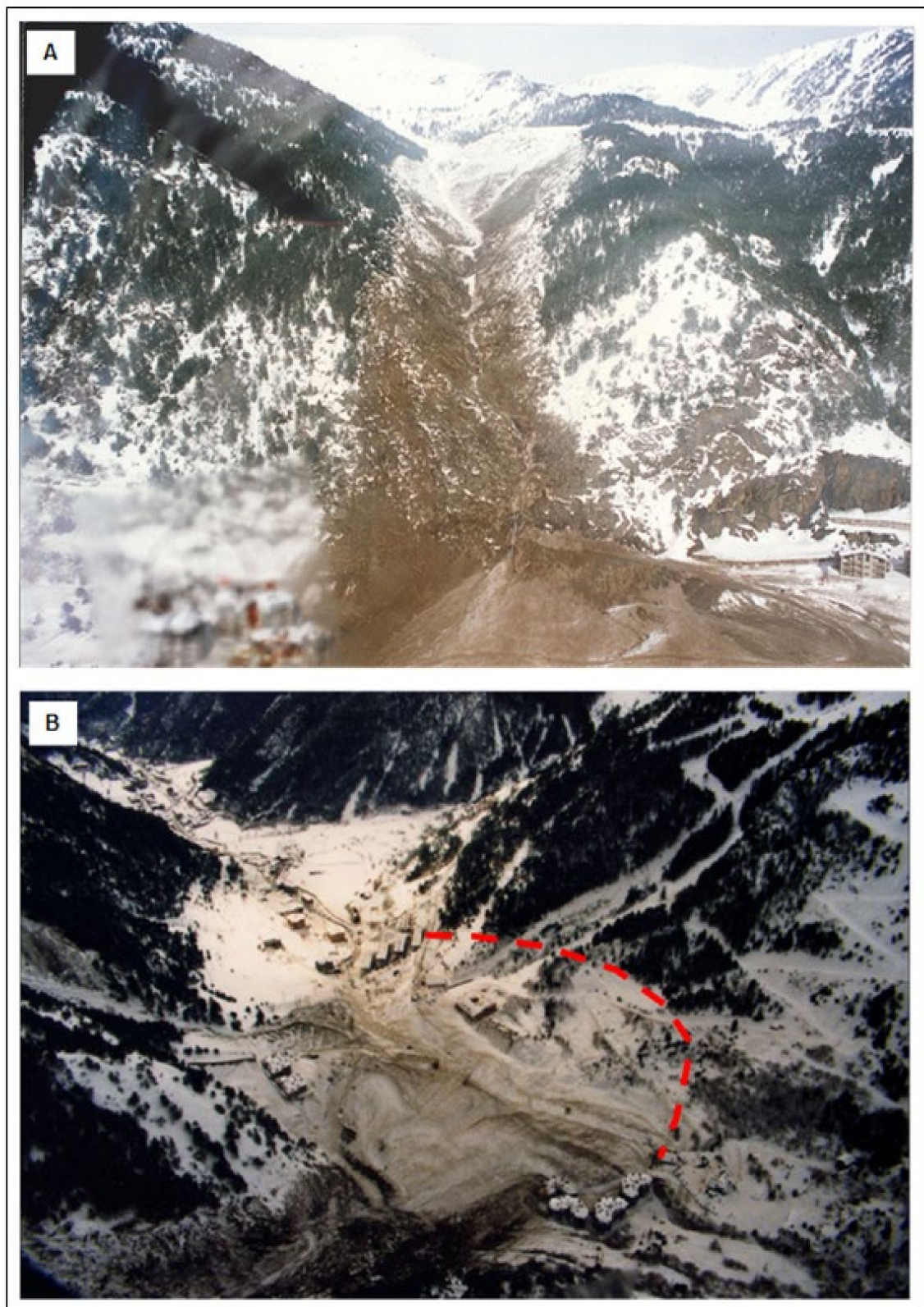


Figure 8. Photographs of the avalanche showing (A) the LFd'A track zone after the pure powder avalanche of 8th February 1996 (photo: A. Reyes); (B) the run-out zone, whose destructive limits can be mostly mapped by observing the damaged forest (red dashed line) (photo: Dept. d'Indústria).

4. The Avalanche, Its Effects and Damage

The LFd'A avalanche of 8th February descended about 1200 m. following a straight trajectory along the track zone (Figure 1, Figure 7A, Figure 8A), climbed up the opposite slope for about 200 m (Figures 1 and 7B) and then turned downstream towards Arinsal village for approximately 1 km (Figures 1 and 8B). It appeared as a dirt-brown cloud, accompanied by a loud noise that was heard all the way to the centre of the village, and was described as being “like a bomb”, at Mas Ribafeta, about 1500 m down the valley. The dominant winds during the snowfall blowing from the north and north-west eroded the snowpack on the slopes adjacent to the cirque ridge. Thus, the SE to SW basin orientation favoured overaccumulation of the drifted snow (Figure 3). The crown height of the released slab was estimated at between 1.1 and 1.5 m. The minimum snow volume released and involved in the avalanche ranged from $1.5 \times 10^6 \text{ m}^3$ (rapidly estimated by the experts in 1996) to $1.8 \times 10^6 \text{ m}^3$, according to release area drawings and a few helicopter observations made a couple of days after the avalanche and through GIS analysis. The whole cirque was considered as the starting zone for these estimations, as no stauchwall could be identified. Moreover, snow was entrained all along the track. In a rough estimation, the mass involved in the avalanche may have ranged from $300 \times 10^6 \text{ m}^3$ to $550 \times 10^6 \text{ m}^3$. The avalanche velocity was estimated by technical experts to be over 300 kmh^{-1} (or approximately 80 ms^{-1}) [15].

The avalanche entrained the whole new snowpack down to the valley bottom, destroying 18 hectares of forest and incorporating all the vegetation and portions of the soil along the track (Figure 7A, Figure 8A), where intact trees of about 50 years old and older trees with avalanche impact scars were uprooted and mixed into the flow [8]. Thus, the avalanche was composed of a mixture of snow, soil, small rocks, pine needles, fragments of branches and trunks.

The destructive avalanche flow affected an area of about 16 ha in the run-out, but the area affected by the strong, non-destructive aerosol blow went 1 km further downstream into the main valley (Figure 1). At about 1600 m a.s.l., at the beginning of the run-out zone where the slope angle abruptly decreases (Figure 3), the avalanche plastered the dirt snow against the snowpack and ground, leaving a very hard deposit of snow, earth and vegetation fragments, all less than 1 m thick (Figures 7–9, Table 1 and Figure 10i,j,o,p) and with a roughly estimated mass of $<50 \times 10^6 \text{ m}^3$. This deposit represents between 10% and 15% of the avalanche mass. Locally, where the slopes present a greater leeward inclination, the snow was not plastered but entrained (Figures 9 and 10o,p). Between the Amadeus and Prat Sobirans buildings (Figure 9), the trees growing along the road and protruding over it were trimmed by the blow at the slope roadside height. At the valley bottom, the compact dirt snow deposit locally reached a maximum thickness of 6 m (Figure 9). A few days later, Dr. J. Becat mapped the avalanche and distinguished two zones: one with major destruction and deposits, and the other with evidence of shock wave and strong blow. His map is reproduced in [8]. The outer and inner limits of this map, modified and improved as shown in the Avalanche Cadastre of Andorra [16], are replicated here (Figures 1 and 9). It is confirmed that the inner limit corresponds to the zone with major damage, including forest destruction (Figure 8B) and the very hard deposits of plastered snow on the ground, and the outer limit corresponds to the area affected by the aerosol blow which threw people to the ground, displaced parked cars and also plastered up to 0.2 m of snow on the facades of the houses oriented upstream along the valley towards Arinsal [8], with snow that was not plastered on the ground but just deposited as snowfall. However, faint deposits of dirt snow, pine needles and small fragments of branches were found as far away as the Sant Gothard hotel, about 1750 m downstream the Arinsal valley and small pieces of furniture and appliances up to half way to the ski resort chairlift line (Figure 1). The main damage, as described below, and the referenced buildings and locations are summarised in Figures 9 and 10. Figures S2–S9 in the Supplementary Materials show several pictures taken from a helicopter.

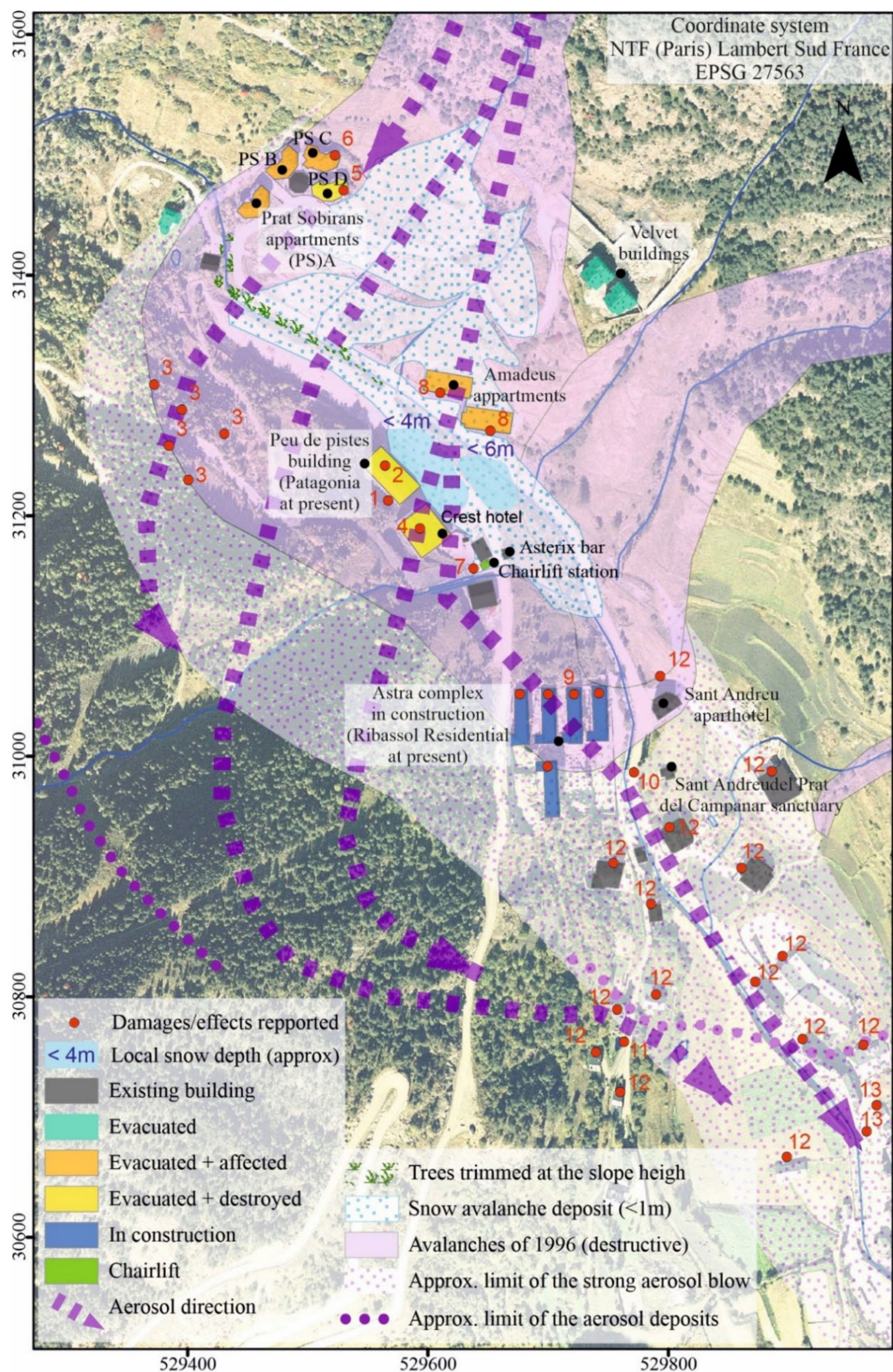


Figure 9. Map of the LFd'A avalanche run-out. In violet, the main zone with destruction; the purple dotted plot area corresponds to the strong aerosol blow affected area, and the violet thick dotted line the limit where dirt (pine needles and fragments of branches, small pieces of furniture, etc.) were found. In purple arrows, the main trajectory of the avalanche. The numbers related to the red dots represent the damage and evidence of elements displaced by the avalanche and are explained in Table 1.



Figure 10. Cont.



Figure 10. Pictures of damage in the run-out zone: (a) Peu de Pistes (PdP) building with the roof lifted and destroyed; (b) PdP building with the roof lifted and destroyed displaced backwards; (c) PdP and Crest Hotel with plastered snow filling the ground floor; (d) PdP apartment with window glass broken; (e) PdP apartment filled with dirt snow; (f) car smashed in front of PdP; (g) Crest Hotel roof skylights burst; (h) van wrapped around a chairlift pylon; (i) Prat Sobirans (PS) buildings destroyed; (j) PS D block with structural damage; (k) PS D block, top apartment, roof and partitions destroyed; (l) PS D block, ground floor; (m) aerial view of the ski lift area, the bottom right-hand corner points to the Astra complex; (n) Astra complex building in construction, protruding parts of the reinforced concrete's iron rods bent by the aerosol blow; (o) run-out slope, Velvet and Amadeus blocks; (p) Amadeus buildings.

Table 1. Summary of the damage mapped in Figure 9 and related pictures in Figure 10 that illustrate some of this damage, arranged by zones and groups of buildings.

Group of Buildings/Zone in Figure 9	Red Points in Figure 9	Damage Reported	Related Pictures in Figure 10
Peu de pistes building	1	Roof lifted and displaced to the back of the building.	a, b
	2	1st floor slab raised till the 2nd floor; snow with earth and pine debris and needles clogged the lower floors; window glass blasted. Cars smashed in front and inside the building.	c, d, e, f
West of Peu de pistes building	3	Furniture and appliances from Prat Sobirans apartments found.	
Crest hotel	4	Snow-clogged staircase and ground floors; roof skylights burst by the blow.	c, g
Prat Sobirans apartments	5	Structural damages to pillars; 2 floors destroyed at terrain level.	i, j, k, l
	6	Doors and windows destroyed; fallen partitions; external damage to decorative elements.	
Chairlift station	7	Van rolled up to chairlift tower; car displaced to the roof of the chairlift station.	h, m
Amadeus apartments	8	Windows opened outwards and curtains hanging outside (depression effect).	o, p
Astra complex in construction	9	Protruding parts of the reinforced concrete iron rods bent by the aerosol blow.	n
Main road: St. Andreu sanctuary	10	Police car displaced by the blow about 30 m along the road until this point.	
North-west Arinsal main village	11	A holding on to the wall so as not to fall; he thought the avalanche (not the LFd'A one) was coming from the east facing slope.	
	12	Snow plastered on all the facades (no damage) (approx. 0.2 m).	
	13	People walking in the street knocked over by the aerosol blast.	

Mr. X. Siurana, a policeman who was patrolling the closed road on the afternoon of 8th February at the Sant Andreu Aparthotel level, explains that he was in a small 4 × 4 vehicle with his colleague when they heard a loud noise and saw a brown cloud behind them. Their vehicle was pushed by the blow and glided about 30 m along the road; covered in plastered snow, completely battered and with the wheels twisted, the 4x4 was a write-off, but the occupants were not injured [15] (Figure 9).

Eight of the eleven evacuated buildings were affected, to differing degrees (Figure 9). The hundreds of transported trees acted as battering rams [2]. The avalanche passed over the Amadeus apartment buildings, whose roofs had been designed and built as avalanche galleries [2] (Figure 10o,p). It caused minor damage to protruding ornamental features but produced a depression effect downwards: the windows were opened outwards (rather than inwards) and the curtains were found hanging outside; the snow entered and reached the second floor via the staircase [14].

The avalanche crossed the river and ran uphill, hitting the Peu de Pistes and the Crest Hotel (Figure 10c). It entered the Peu de Pistes building directly through the ground floor, lifted the entire first floor slab to the second floor, filling both levels with dirt snow (Figure 10e) (the slab descended slowly during the snow melt) [2], exiting through the sixth floor lifting part of the roof and displacing it to the back of the building and destroying the rest (Figure 10a,b) [15]. Most of the windows burst (Figure 10d) [2]. At the Crest Hotel, the avalanche also entered through the ground floor, clogged the ground floor and staircase and left by bursting the roof skylights (Figure 10g). In front of these two buildings, about 40 cars parked in the parking lot were smashed (Figure 10f), mostly by being crushed against the buildings; some even ended up inside the Peu de Pistes bar [14,15]. The smashed cars were

filled with snow so hard that it was impossible to insert a knife into the deposits. A van was wrapped around a chairlift pylon (Figure 10h) and another car was lifted to the roof of the chairlift station [15]. The compacted dirt snow deposit at the parking lot surpassed 4 m in height (consistent with the ground floor clogging of Peu de Pistes and Crest Hotel buildings). Due to its high density and hardness, it had to be removed mechanically by bulldozers. Further down, at the Astra complex buildings (now the Ribasol Residencial), under construction at that time, the protruding parts of the reinforced concrete's iron rods were bent by the aerosol blow (Figure 10n). About 300 m downwards, a man gripped onto the wall of a house so as not to fall (Figure 9); he thought an avalanche (not the LFd'A event) was coming from the east-facing slope, thus confirming that the avalanche turned downwards towards the valley. Traces of the turn of the avalanche can be clearly observed in Figure 10m.

At the right margin of the run-out, the Prat Sobirans buildings were also hit (Figure 9). The worst affected was the six-floor block D, where the avalanche completely destroyed the two floors closest to the ground level, resulting in structural damage to the supporting pillars (Figure 10i,j,l) [15]. The avalanche entered and exited the building through the brick walls which did not resist (Figure 10i,j,l); however, some stone clad walls, not perpendicular to the flow, did resist [2,15]. Part of the roof was also destroyed (Figure 10i,k). Damaged household appliances and pieces of furniture were found up to the run-up at the opposite slope (Figure 9). Later, only the two lower floors were reconstructed, as they are below ground level and are protected by a new dike. In block C the doors and windows were destroyed, and the partitions fell (Figure 10i,m); in blocks A and B, there was only non-significant external damage to decorative features.

The devastation was extensive, and feelings of astonishment and anger were generalised among the population [15].

5. Les Fonts d'Arinsal Avalanche Dynamics Derived from Observations and Damage

Powder snow avalanches (PSAs) like the LFd'A event may be hundreds of metres high and descend at high speeds of up to 100 ms^{-1} [17]. Fundamental information about their dynamics can be derived from the description and classification of the evidence of their effects and damage.

Firstly, the LFd'A avalanche of 8th February 1996 can be classified by its size, according to the Canadian system [10,18] and the system of the European Avalanche Warning Services [19]. Both describe five levels, based on the estimated potential destructive effects and other typical factors. In both classifications, LFd'A corresponds to somewhere between levels 4 and 5 (5 being extremely large), as it destroyed several buildings and 18 ha of forest. The released area involved a huge volume of snow. The run-out reached the valley floor, and it was the largest known avalanche along this path. This classification is consistent with the history of the path, where none of the previous avalanches achieved the amplitude, extension and power of the 1996 event (Figure 2).

In the literature, there is currently no unified view of the structure and behaviour of PSAs, even though great progress has been made in recent years [17] (and references therein). PSA videos reveal that they typically release across a wide slab; this was the case with the LFd'A avalanche, which released as a huge slab. PSAs then begin moving downslope as a dense flow; as the resulting slide descends, it grows, accelerates and gradually incorporates more material. When it reaches a certain speed, particles are launched on high ballistic trajectories while turbulent air eddies scour further material from the surface, thus turning the slide into a mixed PSA [17]. In well-developed PSAs with a well-developed snow dust cloud, an air blast can precede the avalanche [20].

Snowpack entrainment is fundamental to the dynamics of PSAs, because they decay once they can no longer entrain snow; their suspension density drops as they engulf air at the interface, the turbulence loses intensity and particles settle. This decline occurs mostly in a widening run-out zone or as soon as the erodible snow supply disappears [17,20,21]. PSAs typically involve dry, cohesionless snow. Because freshly deposited surface snow is cold, its ability to sinter is limited, and it may be brought into suspension more easily [17].

At the LFd'A avalanche path, the new, cold snowpack covered the entire slope and bottom of the valley. No measures or estimations of snow entrainment could be made, although the volume of new snow entrained must have been huge. In the cirque, it was impossible to distinguish the main released area from the area with entrained snow: no stau wall observations were reported, nor could any be derived from the photographs. No secondary slab releases feeding the avalanche, as described by Köhler et al. [22], could be identified. Due to the quality of the snow and the angle of the slopes at the top of the path, between 40° and 45°, it is most likely that some small, dry snow avalanches descended to the bottom of the cirque on the two preceding days (6th and 7th February) and the deposits were entrained by the large avalanche of 8th February [7]. The released volume, estimated roughly, must have included the main cirque snowpack. Certainly, entrainment occurred all the way along the avalanche's descent up to the slope rupture at the valley floor (1600 m a.s.l.) and even further downwards. Below the cirque, where no previous snowpack existed, visual observations corroborate that all the available new snow deposited since 6th February was entrained into the avalanche (Figure 7A, Figure 8A).

Along the main track zone, two features merit particular comment. The first is that the avalanche broke off and completely uprooted mature trees all the way along its track. The second is that the path steepens at its lower part (Figure 3), a circumstance that may have caused an increase in avalanche velocity counteracted by an increase of air incorporation along the dry waterfall area. Whatever the case, the avalanche reached the sharp, concave slope rupture, i.e., the run-out zone, at a very high velocity.

The avalanche then impacted against the ground due to the sudden decrease of the slope (Figure 3); this can be inferred from the very dense, dirt snow deposit in this area, which showed traces of the avalanche direction (from the orientation of the mineral contaminants such as soil and of the fragments of vegetation). This deposit was most likely formed partly from the existing snowpack, compressed by the avalanche air blast and impact (due to the abrupt slope reduction) and partly due to the avalanche snow plastered against the ground. Interestingly, there were only minimal deposits: only very hard snow on gentle slopes at the run-out (a few decimetres thick, up to the valley thalweg) and inside or around obstacles (houses and favourable terrain counter-slopes and depressions). A large part of the snow involved in the avalanche was dispersed and deposited as light snowfall across a very large area, or even sublimated.

Regarding avalanche structure and flow regimes, Gauer et al. [23] indicate that avalanche dynamics have traditionally distinguished into dense flow avalanches (DFAs) and powder snow avalanches (PSAs), but it has been recognised for a long time that dry snow avalanches are often not pure, but mixed-motion. Ancey [21] describes three zones in the structure of large, dry, mixed, aerosol avalanches: a rapid and dense zone, typically 1 to 3 m thick, which can generate impact pressures of up to 500 kPa; a less dense transition zone, typically ~5 m thick, which can produce significant impact pressures (50–100 kPa), and a very diluted zone, corresponding to the cloud, which can produce lower impact pressures (1–5 kPa). Gauer et al. [23] and Issler et al. [24], emphasising flow regimes, also describe a simplified structure of mixed, dry snow avalanches in three layers, as identified in 30 years of full-scale avalanche experiments in Canada [25], Japan [26], the USSR [27], and Europe [28,29]: a dense flowing core, a fluidised layer that develops ahead of and over the core (previously referred to as the saltation layer by Norem et al. [30] and Issler [31]), and a suspension cloud.

Sovilla et al. [17] describe dry PSAs. They suggest a more complex structure, with spatial transitions perpendicular and parallel to the slope dimensions. Their work, of undeniable value, compiles years of full-scale experiments at Vallée de la Sionne (VdS) in Switzerland. They assert that a fast, low density dilute front is tailed by an energetic and turbulent, suspension region, which together form the so-called intermittent frontal region defined by Köhler et al. [22]. This is followed by a slower, dense core at the bottom that evolves into a dense tail; a powder cloud of small, suspended particles that can reach a height of more than a hundred metres envelops the whole avalanche. At the front, surrounding the avalanche, a laminar overpressure is followed by a less turbulent underpressure,

where the fluidised avalanche front entrains large parts of the light, low-density snow cover in the head region and deeper snow layers below the energetic region. In fact, measurements made with FMCW radar [32] on VdIS [33–37] and [17] revealed that many avalanches studied developed a distinct fluidised front, and clearly showed that snow entrainment was produced by this fluidised front or “nose” of large, cold, dry avalanches.

Several hypotheses regarding the mechanisms involved in entrainment have been proposed by Gauer et al. [33], Carroll et al. [38] (and references therein), Sovilla et al. [17] (and references therein) and Köhler et al. [22] (and references therein), where very rapid entrainment is related to the existence of this frontal, fluidised flow. Ploughing, turbulent fluctuations at the surface, the instantaneous failure of snow slabs and rapid erosion-deposition waves related to roll-wave flow instabilities can be complementary mechanisms, as the authors cited above propose.

In general, a cold and light snow cover typically fluidises [17]. Since the surface (i.e., new snow) is cold, a PSA maintains its dynamics from surface entrainment; as it entrains warmer snow, its dynamics (i.e., the flow regime) changes, and transition to a denser flow occurs as soon as the temperature of the flowing snow reaches $-1\text{ }^{\circ}\text{C}$ and above [39].

Issler et al. [24] were able to identify the existence of different flow regimes from the snow avalanche deposits. The present study takes their work as a fundamental reference. Observing 20 avalanches in the Davos area of the Swiss Alps, those authors found (1) that most of the avalanches, whatever their size, deposited snow along the entire path, the deposited mass being similar to the eroded mass; (2) that in areas overflowed only by the fluidised part of the avalanche, deposition was absent or significantly less than erosion, as long as the terrain was sufficiently steep; and (3) that in an extreme avalanche occurring in 1995, the densities from deposits corresponding to the fluidised flow reached values above 500 kg m^{-3} [40]. They concluded that it appears likely on physical grounds that dry snow avalanches in very steep terrain or of very large size will fluidise to a much higher degree.

As noted above, in the very large LFd'A avalanche entrainment occurred all the way along the steep track and the top of the run-out zone and incorporated all the existing new snow cover, hence indicating the existence of a diluted, fluidised layer or flow. This entrainment may also have been enhanced by turbulence and other processes.

Köhler et al. [39] observed that nearly every large powder snow avalanche in VdIS has undergone a partial transition to denser flows, evolving from a cold regime flow (involving cold snow $>-1\text{ }^{\circ}\text{C}$) to a warm regime (involving warm snow $>-1\text{ }^{\circ}\text{C}$). In all their GEODAR data, acquired over seven years and covering 20 PSAs, only one large PSA without a clear partial transition occurred. Pérez-Guillén et al. [41] recorded 30 avalanches at the VdIS with seismic sensors, FMCW radar and other complementary devices. Nearly half of the avalanches studied were PSAs, and in all of them they identified the frontal, energetic and dense characteristic parts of the typical dry, mixed, powder snow avalanches, as described by Sovilla et al. [17]. This suggests that large, purely cold-dry, powder snow avalanches are very rare, as Köhler et al. note [39]; these authors think that purely cold-dry avalanches do exist, but perhaps only as long as they remain small and thus only entrain layers of cold snow close to the surface. In the case of the LFd'A avalanche, (a) no old, warm snow was available; therefore, the avalanche entrained the entire new snowpack, which was cold, and fed the avalanche; (b) no deposition was observed in the cirque or along the torrent, so no deposits were left by a dense core or tail; (c) there was no evidence of dense flow: no snowballs, levees or any other typical feature of dense flow were observed, even in the run-out zone. There is no evidence of a dense core or a dense flow transition; therefore, according to the hypothesis of Köhler et al. [39], the LFd'A cold-dry, pure powder avalanche entrained just cold snow. However, contrary to the premisses of these authors, it was a very rare, extremely large event that is likely to have involved a fluidised front, an energetic, turbulent suspension zone in the head and a huge suspension cloud.

Clear evidence of pressure depression related to the avalanche descent can be seen in the Amadeus buildings (Figure 9o,p, Figure 10), where windows facing downslope were opened outwards and curtains were found hanging outside. This depression could have been caused by the step effect

produced by the buildings, originating in the angle between the roof and the facade, which disengages the flow and generates depression and upward eddy next to the facade, and, to a much lesser extent, by the pressure drop in the front of the PSA. The same effect can be deduced at the steepest short slopes in the run-out zone (Figure 9o,p, Figure 10), which were completely clean after the avalanche because all the snow cover had been entrained. The snow deposits found on the staircase in the Amadeus buildings may be related to both depression and upward eddies created by the edifices themselves.

Regarding velocity and impact pressure, the LFd'A avalanche broke off and uprooted mature trees right along the track, indicating that impact pressures there may have reached (or even exceeded) ~ 100 kPa [17,21]: there were no “silent witnesses” that might have recorded higher pressures. Below, at Prat Sobirans block D (Figure 9i-l, Figure 10), the severely damaged brick partitions and wood frame structures indicate impact pressures of up to 45 kPa [17]. Even though most concrete walls resisted, some pillars suffered structural damage, probably due to the ramming impact of the trees entrained in the flow, suggesting even higher punctual impact pressures. It can thus be inferred that the trees were transported into the energetic, turbulent region of the avalanche front defined by Sovilla et al. [17].

Köhler et al. [39] indicate that impact pressures in cold-dominated flow regimes have a dominant velocity-squared contribution, and the hydrostatic term vanishes due to small densities. Gauer et al. [23] present data from 30 years of measurements at the lower third of the Ryggfönn experimental site, where average speeds reached a maximum of about 45 ms^{-1} for a dry snow event. These authors assume velocity values of $60\text{--}80 \text{ ms}^{-1}$ at the bottom of the VdLS experimental path (1999-02-25 avalanche). Steinkogler et al. [37] present data from VdLS, where several avalanches reached speeds of over 50 ms^{-1} . Later, Köhler et al. [22] concluded that internal surges of large avalanches, mostly produced by the entrainment of secondary released slabs, can reach significantly higher velocities than the avalanche leading edge or lower edge of the moving snow on the terrain (in the LFd'A avalanche, roughly corresponding to the “main avalanche front”). Suriñach et al. [42] estimate maximum velocities of over 80 ms^{-1} for powder avalanches at VdLS. McClung and Gauer [43] present data from 89 flowing avalanches that had a dense core of flowing material which dominates the dynamics by serving as the driving force for downslope motion. For avalanches of sizes 4 and 5, maximum frontal speed measurements reached values from 40 ms^{-1} to 70 ms^{-1} . For avalanches with α angles ($\tan \alpha = H_0/X_0$; H_0 the measured total vertical drop and X_0 the measured total horizontal reach considering the distal end of the avalanche run-out position and the top position of the starting zone) close to 20° , like the LFd'A one, velocities were of about 70 ms^{-1} . Their set of data probably included the avalanche presented by Gauer et al. [29]. In that study, for two VdLS dry flowing avalanches of sizes 4–5, Doppler radar measured velocities were of 70 ms^{-1} and $60\text{--}65 \text{ ms}^{-1}$, and these speeds were reached along the track. The LFd'A avalanche could, then, have reached speed values of around 80 ms^{-1} , as estimated by the experts in 1996. This velocity is in accordance with both the impact pressures proposed by Ancey [21] for the avalanche transition zone and the rough impact pressures deduced from studying the damage. No large particle cluster deposits were observed, probably due to the total disintegration of the released slab along the avalanche descent and to the quality of the light, cold, entrained snow. Thus, the LFd'A avalanche effects also coincide with the density measurements described by Sovilla et al. [17] for the dilute, fluidised front and possibly for the energetic, turbulent suspension region.

Due to the topography of the terrain, the distribution of the deposits was highly irregular. Their thickness varied from 6 m at the river thalweg, to 4 m piled in front of the buildings at the run-up slope and less than 1 m in general all over the run-out. The height of the fluidised flow cannot be deduced, in this case, from the deposit's height (as Issler et al. were able to do for a giant avalanche occurring in 1995 [40]), as the thickest ones accumulate in front of obstacles and the thinnest ones were plastered. The flow height, thus, must be inferred from the amplitude or “height” of the damage.

In Prat Sobirans and Peu de Pistes, the main damages and snow clogging affected two storeys of apartments. In Prat Sobirans, the two most seriously affected floors were in block D (Figure 9i–l, Figure 10) at ground level. In the avalanche path run-up, the lower two floors of Peu de Pistes and the Crest Hotel (Figure 9a,c, Figure 10) were the most affected, especially in the first building, where these two floors were filled up with snow. This, as well as the 4 m of snow piled up in the parking lot in front of these buildings, suggests that the denser part of the LFd'A avalanche might have had a height similar to these two floors, which would correspond roughly to the ~5 m thick transition zone, as defined by Ancey [21], the fluidised layer of Gauer et al. [23] and Issler et al. [24] or, more precisely, to the intermittent frontal region defined by Sovilla et al. [17] and Köhler et al. [22]. Thus, the fluidised flow height would be around 5–6 m. The high densities of these deposits (see Section 5) are in accordance with the density of the fluidised flow deposits measured by Issler et al. [24] in the giant avalanche of 1995. The frontal air blast injected into the buildings produced the overpressure which burst the roof and skylights.

It seems clear that the LFd'A cold-dry, pure powder snow avalanche was made possible by the absence of a previous, warm snowpack and the new, cold, dry snow cover that was entrained along the avalanche's descent. As is often the case, the coincidence in time and space of different factors that do not usually occur together gave rise to this extreme avalanche event.

6. The Present: Defences Implemented

Before the 1996 avalanche, protection measures in the LFd'A avalanche path were based on local avalanche forecasts. Situations of high danger prompted the evacuation of the buildings under threat. After the LFd'A event, when the evacuation of 322 people was completed just 90 minutes before the avalanche, the need to change the protection strategy was abundantly clear. Moreover, most access routes to the Arinsal ski resort are in the avalanche run-out zone, and so the government was convinced of the need to keep the area safe and open during the whole winter.

The new protection system consists of (a) a Gazex® system in the release zone of LFd'A avalanche, (b) a system of two dikes and flat area in the run-out zone, and (c) avalanche nets in the Percanella release zone.

In the LFd'A release zone, nine Gazex® tubes and four Gazex® shelters were installed (Figure S10). Snowpack monitoring was improved, thanks to an automatic weather station (Les Fonts d'Arinsal, 2681 m a.s.l.) that measures temperature, wind, and snowpack height, and a FlowCapt sensor which allows precise control of the drifted snow.

In the run-out area, an 18 m high dike with a flat area upstream was built, designed to hold back the denser part of the avalanche and to deflect the aerosol. The overall aim is to protect the infrastructures located below (the parking area, buildings and lower chairlift of the ski station, Amadeus apartments, Patagonia building, Velvet building, Crest Hotel and Astra complex) from the direct impact of the avalanche. A smaller dike in the opposite part of the run-out area was constructed to protect block C of the Prat Sobirans apartments and the access to the Velvet building (Figure 11). Most buildings were reinforced, and the structure of the Prat Sobirans block D was modified with the removal of three flats.

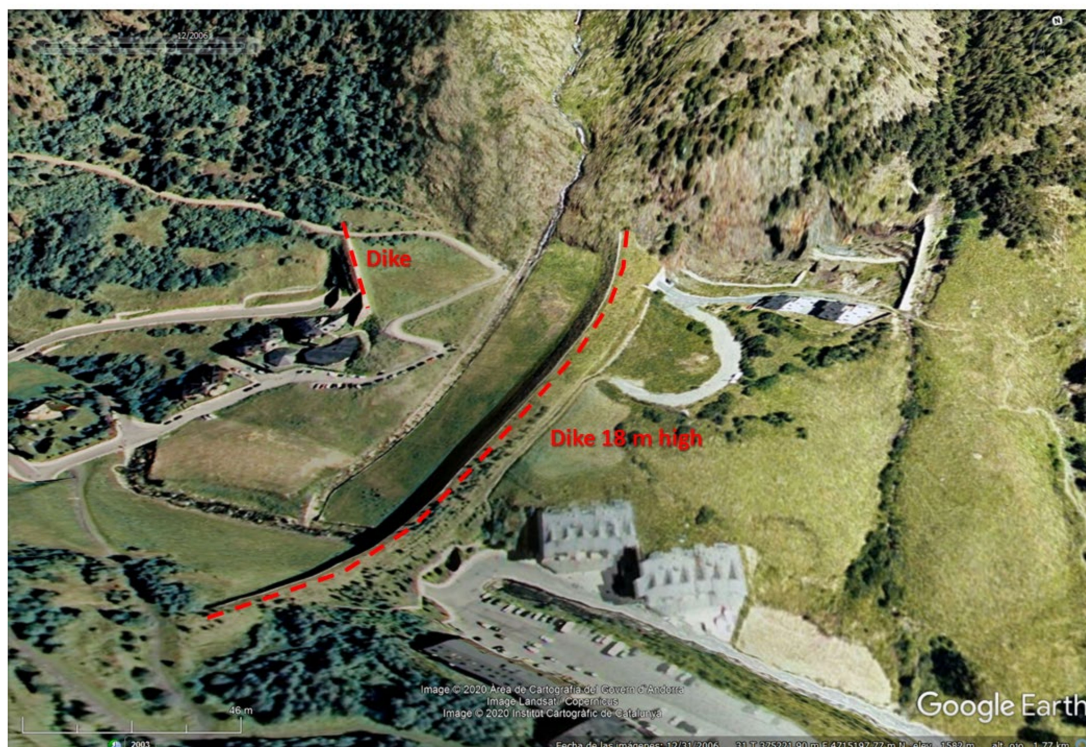


Figure 11. System of dikes in the run-out zone of Les Fonts d'Arinsal avalanche path.

In the Percanella release zone, 2300 linear metres (580 nets) of Dk3 mono anchorage net fences were installed in order to retain the snow and to permit the regeneration of a protective forest.

The strategy adopted, therefore, was to protect the infrastructures.

7. Final Remarks

The LFd'A event of 8th February 1996 was a paradigmatic case of an extreme dry, pure powder snow avalanche. It was the largest avalanche ever known along this path, and its effects exceeded all the previsions.

As is often the case in extreme events, a rare combination of circumstances coincided in time and space to make this avalanche possible: (a) the winter season began with no snowpack at the lower altitudes, and so no dense, warm snow was available for the event to evolve into a denser avalanche; (b) over two days, the generalised, heavy snowstorm, with large snowfalls, was accompanied by strong winds that generated large snowdrifts susceptible to release; and (c) the decrease in temperature kept the new snowpack cold right down to the bottom of the valley, facilitating the entrainment and, thus, the growth of the avalanche down to the main valley bottom.

In the context of climate change, scenarios of this kind may become more frequent. The first reason for this is that the snowpack will be reduced at low altitudes and may even disappear. According to the results obtained by the CLIMPY project (for more information, see <https://opcc-ctp.org/ca/climpy>), even though climate projections show a significant spatial variability among the Pyrenees massif in terms of precipitation, the rise in mean winter temperatures (December–April) is ubiquitous in the area. Climate projections of the future snowpack in Andorra [44–46] show a distinct fall in the mean snow height at 1500–1800 m altitudes at mid-term horizon (2041–2070) (Figure S11). In terms of numbers of days with a height of snowpack above 5 cm the most pessimistic scenario, without climate policies (RCP8.5), indicates that the continuous snowpack from 1800 m to the peaks is likely to endure until mid-century, but that the expected normal snowpack will correspond to the current winter seasons with lower snowpack accumulation. Winters will present a median of less than 70 days with 5 cm at 1800 m, limiting continuous snowpack at altitudes above 2100m, where the number of days with

height of snowpack >50 cm will be reduced by almost 70 days. Such conditions are similar to the ones projected in the Southernmost French Alps and also comparable to expected patterns in the Swiss-Austrian Alps [47], where more reliable and larger changes in snow depth are expected in low elevation regions. The second reason is that heavy snowstorms may continue to occur and may be accompanied by low temperatures, allowing cold snowfalls to cover the slopes sporadically as far as the valley bottoms. As for heavy snowfall episodes, the study by López-Moreno et al. [48] in the Pyrenees found that they had not changed above 1000 m a.s.l. Changes in extreme snowfalls, their frequency and magnitude are still very difficult to predict [49] (and references therein), but scenarios like the LFd'A path in 1996 cannot be ignored. In this context, surveillance and forecasting are crucial for the activation of defence measures in possible similar scenarios and must be enhanced. The knowledge acquired from this event must be capitalised upon in order to minimise risk situations in the LFd'A avalanche path (in addition to the defence measures already implemented there) and in other similar paths with exposed infrastructures.

The main objective of this study is to provide the most complete data set possible and the best possible description of the effects of this paradigmatic, cold-dry powder avalanche. The authors believe this case study could be useful for calibrating existing or developing numerical models. Basic topographic data for the area can be found in [16].

In Andorra, the LFd'A event marked a “before-and-after” in avalanche investigation and data collection. The *Cartes de Localització Probable d'Allaus* (Maps of Probable Avalanche Paths [8]) were revised and completed, the *Cadaastre d'Allaus d'Andorra* (Andorra Avalanche Cadastre [16,50]) was initiated and the *Plans de Prevenció de Riscos d'Allaus Previsibles* (Prevention Plans of Predictable Avalanche Risks [16]) were launched within a few years. The country's land use management and planning were vastly improved. Efforts to increase knowledge of avalanches and their management are ongoing and will continue in the future in this small, mountainous country.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3263/10/4/126/s1>, Figure S1: Streamlines and wind intensity (kt) at 850 hPa (around 1500 m) from February 8th at 00h UTC from NOAA Reanalysis; Figure S2: Helicopter view of the track and part of the run-out zones of the Les Fonts d'Arinsal and Percanella avalanches; Figure S3: Helicopter view of the Les Fonts d'Arinsal avalanche run-out zone taken from above the track zone; Figure S4: Helicopter view of the Les Fonts d'Arinsal avalanche run-out zone. Downstream Arinsal valley perspective; Figure S5: Helicopter view of the Les Fonts d'Arinsal avalanche run-out zone. Detail of Prat Sobirans buildings; Figure S6: View of the Les Fonts d'Arinsal avalanche run-out zone. Closer detail of Prat Sobirans buildings; Figure S7: Helicopter view of the Les Fonts d'Arinsal avalanche run-out zone. Upstream Arinsal valley perspective; Figure S8: Helicopter view of the Les Fonts d'Arinsal avalanche track zone. Downstream perspective; Figure S9: View of the Les Fonts d'Arinsal avalanche run-out zone. Detail of Amadeus buildings. Track zone in the background; Figure S10: Gazex@system in the release zone of Les Fonts d'Arinsal avalanche path; Figure S11: Anomaly of mean snow depth during the winter season for scenario RCP 4.5 (scenario including climate policies aiming to stabilize CO₂ concentrations) at near, mid-term and long-term horizon and different altitudes (1500, 1800, 2100 m).

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