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On the characterization of seismic signals generated by snow avalanches for monitoring purposes

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ABSTRACT. Seismic signals from artificially released avalanches were studied in an attempt to characterize them for avalanche-monitoring purposes. The seismic signals generated by different sizes and types of avalanches were recorded and analyzed in the time and frequency domains. Synchronized recordings of the corresponding seismic signals and the video images of the evolution of the avalanches were obtained together with a detailed cartography. Characteristic signatures in the frequency and time domains were found to depend on the characteristics of the avalanche path and measuring location, but to be mostly independent of avalanche size. The source of the different parts of the recorded seismic signals was determined. A relationship was observed between the avalanche size and the amplitude of the signals. Given the presence of local site effects, a prior seismic characterization of the avalanche path in relation to the recording sites is necessary for monitoring purposes. Moreover, it was found that sliding slabs in the early phase of acceleration produce little seismic energy, resulting in a time lapse between the observable start of the avalanche and the arrival of the detectable seismic waves at the receiving station.

INTRODUCTION

Seismic equipment has proved to be a useful tool for detecting various natural phenomena such as debris flow or avalanches (Sabot and others, 1995; Leprettre and others, 1996; Arattano and Moia, 1999). However, in contrast to the debris flow where the flux is very canalized, snow avalanches can occur on more open slopes. This, together with the varying size of the avalanches, poses a number of problems for their optimum detection. Medium-sized to small avalanches are more difficult to detect than larger ones. On the other hand, we believe that a deeper understanding of the sources of the seismic signals is necessary to improve the detection algorithms of automatic avalanche detection.

Our studies were initiated in 1994 in order to resolve the contradictions between the duration of the seismic signals (attributed to snow avalanches) obtained by means of an automatic seismic detector system, and their expected duration based on cartographic procedures (Sabot and others, 1995). An experimental procedure was set up in order to obtain further information about the seismic signals generated by avalanches. In most experiments avalanches were released artificially by explosives (using a cannon or a helicopter). Synchronized recordings of the seismic signals and video images of the explosion and the evolution of the whole avalanche were obtained. The seismic signals were obtained by means of one to three portable seismic stations distributed within a radius of <3 km from the avalanche path, with a geometry depending on the site characteristics.

The characteristics of the evolution and an accurate cartography (1:5000/1:25 000) of the avalanches were obtained in situ, and by analyzing the video images. Snow and avalanche characteristics (density, size and deposit distribution) were obtained, when possible, immediately after the experiments. The methodology used to determine site characteristics and the time shift between the video images and the seismic signals is reported in Sabot and others (1998) and Suriñach and others (2000). This study consists of

(a) determination of the actual ground motion (conversion mV to m s^{-1});

(b) control of the seismic noise of the recording site before, during and after the experiment (frequency and time domains);

(c) determination of the site seismic characteristics (estimation of wave propagation velocity, local effects);

(d) identification of the different signal wave trains in relation to the video images (time domain);

(e) time and frequency analyses of the different parts of the signals;

(f) study of the ground particle movement for each wave train.

In an earlier study we concluded that, in avalanches with a dense part, only some parts of the avalanche generated seismic signals. These signals correspond to changes in the flow regime of the avalanche and in the slope angle of the track, to interaction with obstacles and to phenomena associated with the stopping stage of the avalanche (Sabot and others, 1998). This conclusion was also reached in a study of avalanches carried out in Russia in 1990 (Firstov and others, 1991). The results account for the differences in duration between the avalanches and the corresponding seismic signals observed in records automatically obtained. In subsequent studies of small to medium-sized avalanches artificially triggered at the Boí-Taüll ski resort, Spain (Suriñach and Sabot, 1999; Suriñach and others, 2000), we showed that the wave trains generated by different mechanisms are different in the time and frequency domains. Changes in the path slope or in the type of flow generate long (>10 s) wave trains, whereas the

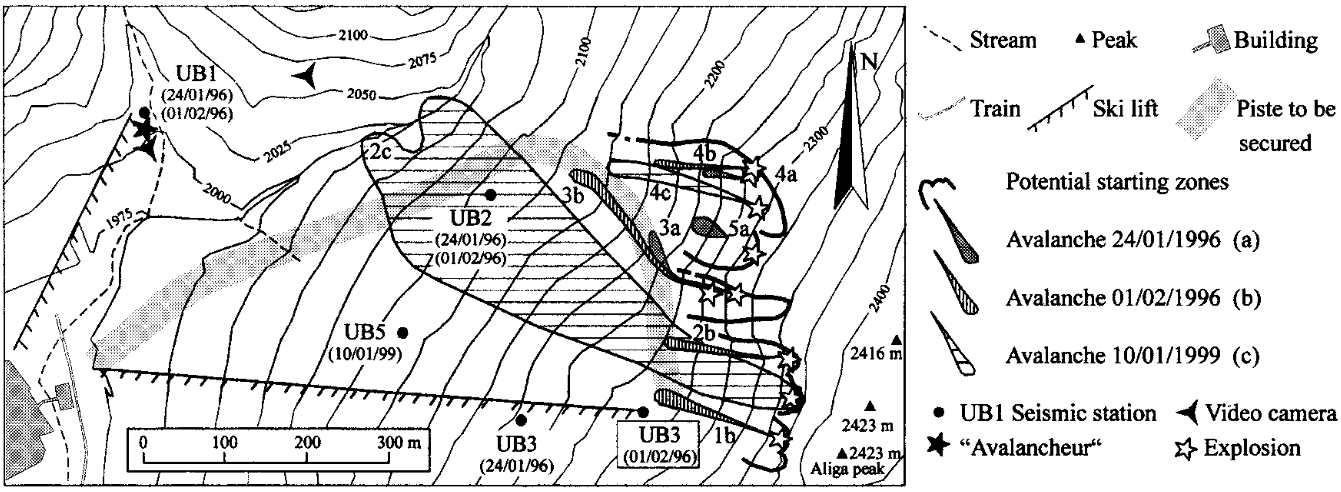

Fig. 1. Núria ski resort experimental site. Potential starting zones and cartography of the avalanches of the experiments of 24 January 1996, 1 February 1996 and 10 January 1999. The limits mapped are the maximum limits of the avalanches.

stopping stage and the impacts with obstacles generate short (1–5 s) wave trains with high amplitudes.

New experiments were set up to improve our understanding of the avalanche seismic signals with respect to their sources (origin). We used the infrastructure and facilities of the ski resort Vall de Núria (Ferrocarrils de la Generalitat de Catalunya) in the eastern Pyrenees, Spain (Suriñach and others, 1999), and those of the avalanche experimental site in Vallée de la Sionne, Switzerland (Issler, 1999).

SITES AND AVALANCHES

Núria site

The avalanches at the Núria site, which were of a small size, were triggered off in the 1996 and 1999 winter seasons and were recorded at different portable seismic stations never reached by the avalanches (Fig. 1; Table 1). The general topography of the site consists of an open slope of low surface roughness. In the highest part of the slope some cliffs and gentle channels that separate the different starting zones are present. The avalanche paths gradually decrease in inclination, from about 42° in the starting zone to 25° in the run-out zone. One ski run crosses the avalanche track zone. The 1996 avalanches did not produce aerosol, but had a flow that was not very dense (snow density before the release was 120–150 kg m^{-3}). The 1999 avalanche (2c, Fig. 1) was an aerosol avalanche which entrained cold, light snow (density <120 kg m^{-3}). No evidence for a deposit of a dense part was found.

Vallée de la Sionne site

The artificially released avalanches in Vallée de la Sionne presented here were recorded in the 1996, 1997 and 1999 winter seasons (Fig. 2; Table 1). The 1996 and 1997 Pointe des Tsarmettes avalanches (PdT-96 and PdT-97) ran over a similar path. The starting zone consists of a slightly irregular slope which is slightly canalized at the lower part. This start-

Table 1. Characteristics of the experiments

	Núria 3a *24 January 1996*	*Núria 2c* *1 February 1999*	*Sionne: PdT* *15 February 1996*	*Sionne: PdT* *16 February 1997*	*Sionne: CB2* *30 January 1999*
Path					
Length	600 m	735 m	1900 m	1900 m	3000 m
Vertical drop	320 m	350 m	1000 m	1000 m	1350 m
Starting zone inclination °	42°	40°	39°	39°	35°
Run-out zone inclination °	25°	27°	23°	23°	25–17°
Explosion	Canyon	Canyon	Helicopter	Helicopter	Helicopter
Seismic stations altitude	UB2: 2107 m UB3: 2205 m	UB5: 2112 m	S: 2260 m	S: 2260 m	T: 1900 m H: 1490 m
Horizontal distance from explosion to seismic stations	UB2: 350 m UB3: 310 m	UB5: 485 m	S: 1900 m	S: 1900 m	T: 1150 m H: 2360 m
Avalanche characteristics					
Vertical drop	120 m	355 m	900 m	1000 m	1300 m
Length	185 m	735 m	1585 m	1900 m	2770 m (hut)
Stopping position: horizontal distance to the stations	UB2: 250 m UB3: 285 m	UB5: 250 m	S: 850 m	S: 750 m	T: 1250 m H: avalanche reached hut
Type of avalanche	Dense	Powder	Mixed	Mixed	Mixed
Estimated volume (10^3 m^3)	1	20	50–100	100–150	480*

* SLF personal communication.

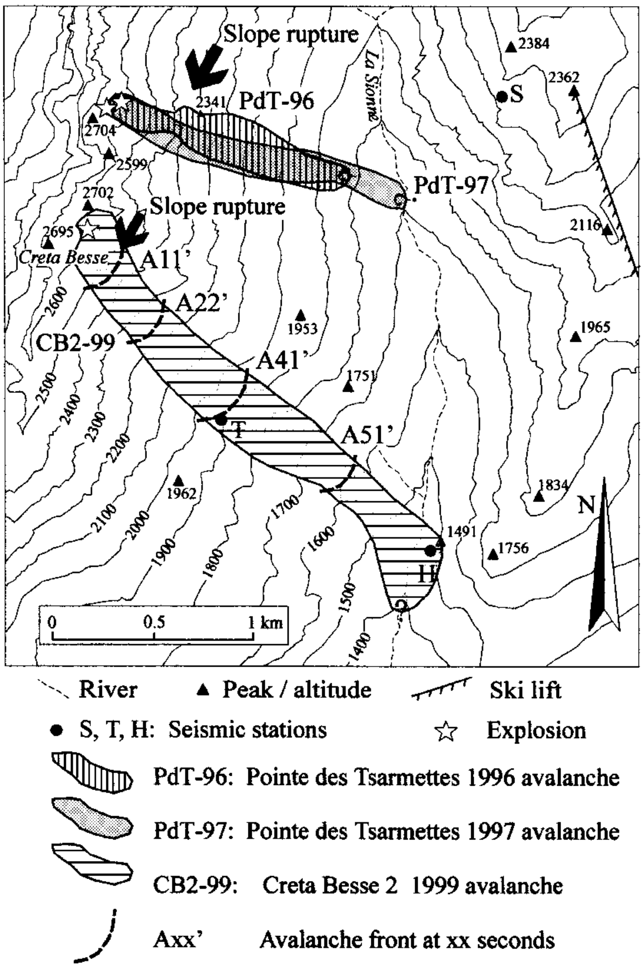

Fig. 2. Vallée de la Sionne experimental site. Starting zones and cartography of the avalanches in the experiments of 15 February 1996 and 16 February 1997 at Pointe des Tsarmettes (PdT) and of 30 January 1999 at Crêta Besse 2 (CB2-99). All the avalanches were mixed powder and dense flows. The limits mapped are the maximum limits of the avalanches and include both dense and powder parts. The slope ruptures generating seismic signals discussed in the text correspond to the cliffs indicated by arrows. The avalanche front A11' corresponds to the earliest energetic waves (E1) detected at station T, and the avalanche front A22' corresponds to the earliest energetic waves E2 detected at station H (see text and Fig. 7).

ing zone, approximately 480 m long and with an inclination of 39°, abruptly finishes on a convex slope rupture and on a cliff with a vertical drop of approximately 100 m. Below the cliff the open slope gradually decreases in inclination to about 23° in the run-out zone. The two avalanches were recorded at the same station (S) (same physical characteristics and geophone site) placed at a horizontal distance of 1900 m from the detonation point opposite the PdT path (Fig. 2).

The 1999 Crêta Besse avalanche (CB2-99) ran over a path which began with a relatively smooth, approximately 250 m long, open starting zone with an inclination of 35°. At the end of this area there is a cliff. The track is open in the highest part, but at about 2100 m a.s.l. it branches into two parallel V-shaped channels. At 2050 m a.s.l. there is a small convex slope rupture. At 1800 m a.s.l. the track opens again. The run-out zone decreases in slope from 25° to 17° and continues up the opposite slope. This avalanche was recorded by two seismic stations with the same physical characteristics at two different sites (Fig. 2). Station T was placed in a cavern in the track of the southernmost V-shaped channel, whereas station H was placed at the end of the path, 1200 m from T (Fig. 2). This avalanche, which was much larger than the PdT avalanches, passed over station T. All the avalanches in Vallée de la Sionne were mixed dense and powder-snow flows (Table 1).

SIGNAL STUDY AND INTERPRETATION

Data acquisition

The seismic signals were acquired in three dimensions by seismic stations with a velocity response of 0.5–40 Hz. The sampling frequency for the signals was 100 samples per second. Prior to the interpretation, all the seismic signals obtained were band-filtered (2–40 Hz order 2 Butterworth bandpass filter) to eliminate differences in the signal characteristics resulting from the different seismic equipment used for data acquisition.

PdT signals

Figure 3 shows the three component seismograms (vertical (Z), north–south (N–S) and west–east (W–E)) of the ground motion velocity corresponding to the PdT-97 explosion and avalanche recorded at station S, which is a typical recording obtained in our experiments. These seismograms consist of two parts: an earlier signal produced by the explosion and a later signal due to the avalanche. Note the lapse of time between them. The explosion signal is composed of two wave trains which are easy to identify in accordance with their arrival time: the waves propagating in the ground and the airwaves (high-amplitude sound waves caused by the blast). The avalanche signals initially consist of long wave trains which are uniform in amplitude (corresponding to a change in the path slope), and subsequently of short packets with higher amplitude (generated by the stopping stage of the avalanche). Figure 4 shows an example of the analysis of the seismic signals of the PdT-96 and PdT-97 avalanches recorded at station S. These two avalanches followed the same path, and the signals studied are those associated with the slope rupture located at 2300–2450 m a.s.l. (arrow in Fig. 2) (Suriñach and Sabot, 1999). Figure 4 displays a detail of 10 s of these signals for both avalanches (to show that they are composed of various and similar wave trains), the spectra of the signals (approximately 20 s) and the ground motion velocity diagrams of one of these wave trains. Regardless of the amplitude of the signals (larger for PdT-97 than PdT-96), the seismic energy and the frequency content of the three components are similarly distributed. The frequency does not exceed 10 Hz for all three components, but the spectra of component W–E have higher amplitudes than the others, showing a maximum at approximately 7 Hz. This frequency is also prominent in the two other components. Study of the ground motion velocity in the horizontal (N–E) and vertical (Z–E and Z–N) planes shows similar predominant directions in each of these planes for both avalanches. Figure 4 gives an example for a selected wave train. The predominant direction in the N–E plane with respect to the vertical axis is 105°, whereas in the Z–E plane the angle is 78°. In the Z–N plane the angle is 135° despite being less evident. These predominant directions are associated with the relative position of the source of the signals with respect to the recording station. Figure 4 also shows a relationship between the ava-

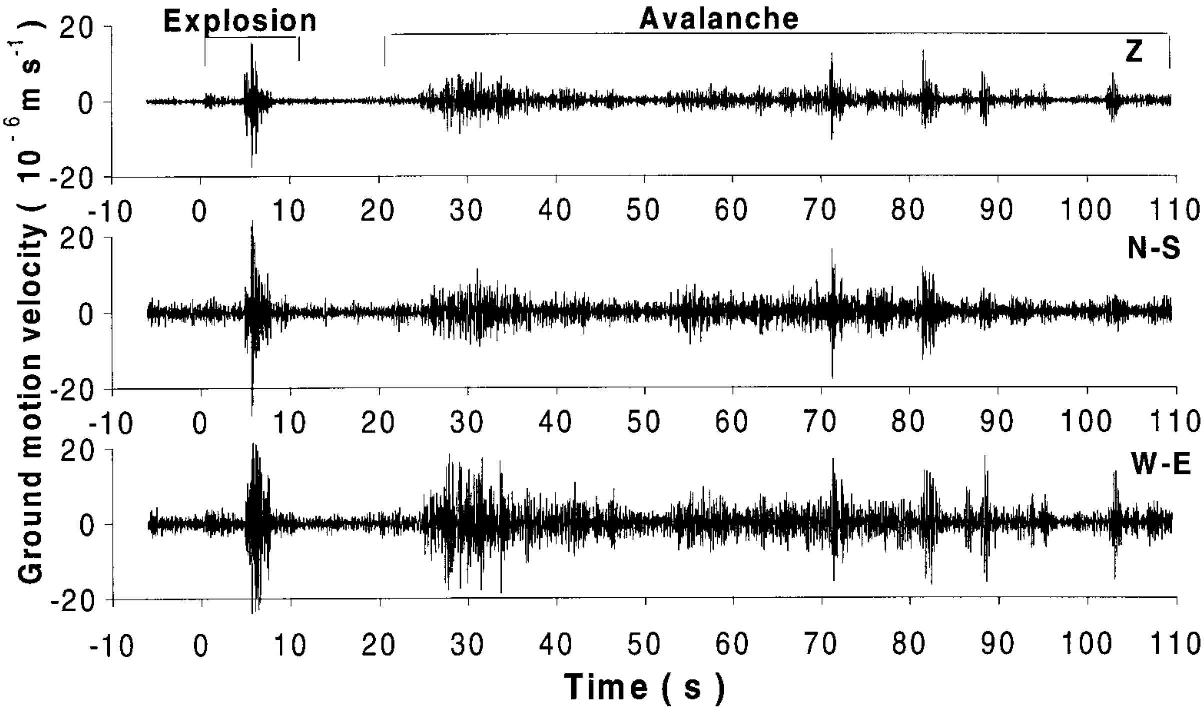

Fig. 3. Three component seismograms (vertical, N–S and W–E) of the 1997 Pointe des Tsarmettes avalanche recorded at site S (Fig. 2). Signals of the explosion and the avalanche are indicated. Origin of time: arrival time of the explosion waves propagating on the ground.

lanche size and the amplitude of the seismic signal generated: avalanche PdT-97, which was larger than PdT-96, had a ground-motion velocity signal whose amplitude exceeds (approximately five times) that of PdT-96, despite having a similar frequency content and ground particle velocity, as indicated above. This characteristic has also been observed in other avalanches.

1996/99 Núria signals

Comparison of the signals obtained in the 1996 Núria experiments reveals a different distribution of the seismic energy in the three components of the ground-motion velocities, depending on the recording site. Figure 5 shows this site effect. This figure presents the most energetic part of the signals generated by avalanche 3a recorded at stations UB2 and UB3, which were located at a similar distance from the avalanche, together with their spectra. At station UB2 the signals in the time domain show that the horizontal (N–S) component of the ground-motion velocity is the largest of the three components. By contrast, at station UB3 the ground-motion energy is similarly distributed in the three components. Moreover, the frequency content of the components is lower at UB3 than at UB2. The different features of the signals depending on the recording site indicate an energy shift from one seismic component to another, caused by partitioning of the seismic energy by refraction and reflection at the various surface and ground discontinuities and by scattering processes due to lateral heterogeneities of the ground (i.e. topography).

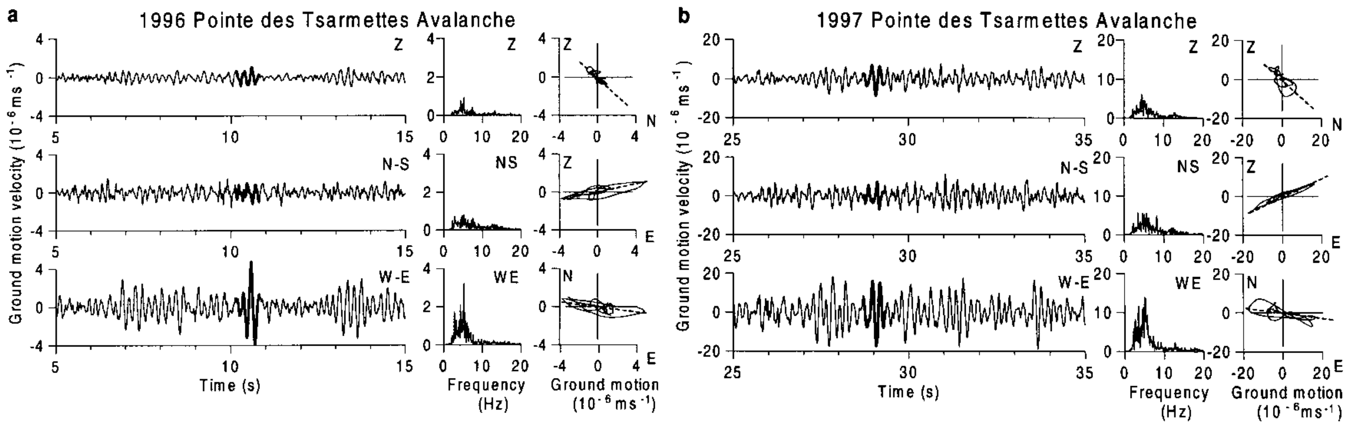

Fig. 4. Detail of the three component seismograms and their spectra of the avalanches at Pointe des Tsarmettes recorded in 1996 (PdT-96) (a) and in 1997 (PdT-97) (b) at station S. The signals correspond to changes in slope (arrow in Fig. 2). The time origin corresponds to the arrival time of the explosion waves propagating on the ground. The ground motion velocity in the vertical (Z–E and Z–N) and horizontal (N–E) planes of selected wave trains (in bold) are also depicted. Predominant direction in each of these planes is indicated by a dashed line.

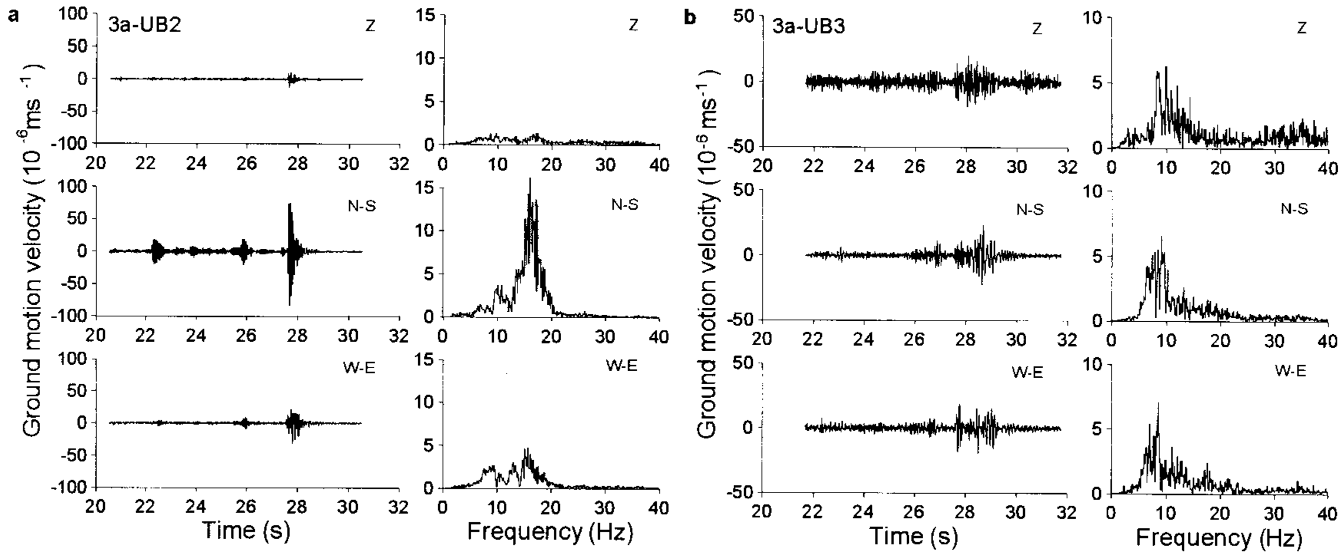

Fig. 5. Detail of the three component seismograms (Z, N–S and W–E), and their spectra, of the Núria avalanche 3a recorded at stations UB2 (a) and UB3 (b) (Fig. 1).

Figure 6 shows the signal from a pure powder-snow avalanche (2c, Fig. 1) obtained in the 1999 Núria experiment, recorded at station UB5 at a horizontal distance of 485 m from the explosion together with its spectra. Although this avalanche was larger than the one at Núria presented above, which was a dense avalanche, the signal obtained is small in amplitude. The spectra are fairly similar to those of the signals obtained from the dense avalanches.

CB2 signals

Figure 7 displays the first seconds of the most energetic component of the seismograms of the CB2-99 avalanche recorded at station T (N–S component) and at station H (E–W component) with a common origin of time. This figure shows that signals of the avalanche recorded at station T have larger amplitudes than those recorded at station H. A time lapse between the arrival of the explosion waves and of the earliest detectable signals from the avalanche (E1, E'2) is observed, although this time lapse is shorter at T (11 s) than at H (22 s). The energy observed (E1) in the seismogram recorded at station T corresponds to the passing of the avalanche over the slope rupture at 2500 m a.s.l. (A11', Fig. 2). The corresponding signal at station H is not observed at the same arrival time, although the waves must have arrived (wave propagation

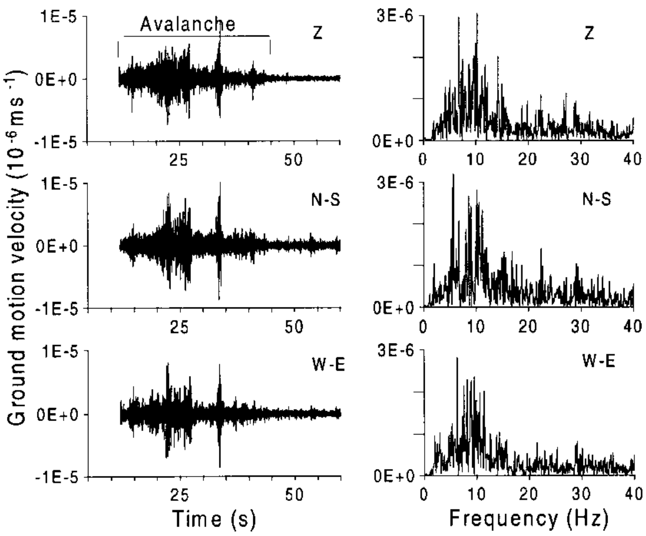

Fig. 6. Three component seismograms (vertical, N–S and W–E) of the Núria 1999 powder-snow avalanche recorded at station UB5 (2c, Fig. 1), and corresponding spectra.

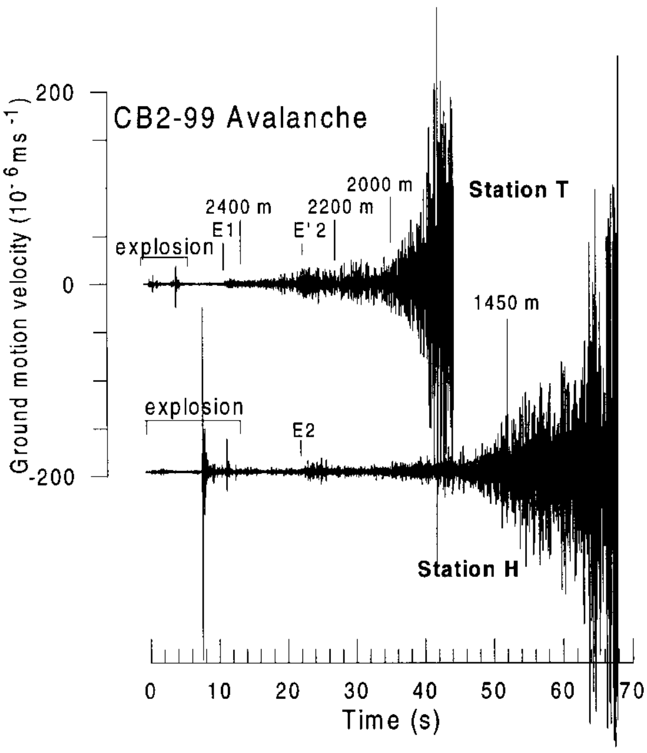

Fig. 7. First part of the seismograms of the 1999 Crêta Besse (CB2-99) avalanche recorded at stations T (N–S component) and H (W–E component). E1, E2 and E'2 correspond to earliest avalanche signals detected. The arrival times at different heights are indicated according to the arrival times deduced from Doppler radar and video measurements (personal communication from D. Issler, U. Gruber, N. Dawes and F. Dufour, 2000). Common origin of time: arrival time of the explosion waves propagating in the ground to each site.

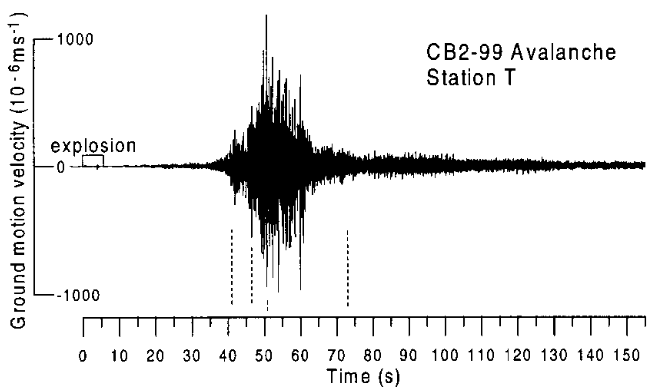

Fig. 8. N–S component seismogram of the 1999 Crêta Besse avalanche recorded at station T (Fig. 2). Signals of the explosion are indicated. Dashed lines correspond to the arrival times discussed in the text. Origin of time: arrival time of the explosion waves propagating in the ground.

velocity in the ground about 4000 m s^{-1}). The subsequent energetic waves (E2) observed at station H which are also observed at station T (E'2) correspond to a change of the type flow (aerosol is developed) at approximately 2250 m a.s.l. (A22', Fig. 2). We explain the delayed arrival of the energetic waves at the two stations as follows: a lapse of time is necessary (given the attenuation of the amplitude of the seismic waves as a function of the distance) for the avalanche to gain enough kinetic energy to generate sufficient seismic energy to be detected. The greater the source–station distance the longer the lapse of time before the avalanche is detected. Figure 8 shows the complete recording of the N–S seismic component obtained at station T, presented above. This recording presents a progressive increase in the amplitudes up to 41 s, with a subsequent decrease up to 46 s. Thereafter, an increase in the amplitudes is observed, with the highest amplitudes at approximately 51 s. Afterward, the amplitudes decrease, forming the avalanche "coda" wave (ringing of the ground) which lasts approximately 100 s. Comparison of the seismic signal with the video images shows that the maximum amplitudes (41 s) of the first packet correspond to the time when the avalanche front reaches station T (A41', Fig. 2). However, the absolute maximum amplitudes of the signal recorded are observed at 51 s, when the avalanche front reaches 1650 m a.s.l. (A51', Fig. 2). A possible explanation for this absolute maximum 10 s after the avalanche front passes station T is that the highest amplitudes correspond to the time when the main body of the avalanche passes over station T. Nevertheless, this hypothesis has not been confirmed to date given the presence of the avalanche aerosol part, which prevents the observation of the dense flowing avalanche part. The avalanche front reaches station H at 73 s. Note that the waves, recorded at station T, generated by the avalanche at this time and for >100 s have amplitudes that exceed those of the signal produced by the explosion and those of the start of the avalanche (approximately 40 s). This energy is produced by reverberations in the ground.

CONCLUSIONS

The analysis of the avalanche seismic signals in the time and frequency domains enables us to draw a number of conclusions that are worth considering for monitoring purposes.

1. Basic seismic signatures depend on path and measuring location but not on avalanche size. This reinforces our confidence in the use of seismic signals as a method of detecting avalanches in areas where human observation is not possible. Nevertheless, a prior characterization of the avalanche path with respect to the monitoring sites (from the seismic point of view) is necessary given the possible presence of local site effects.

2. The low level of seismic energy generated at the beginning of the avalanche flow, which accounts for the lapse of time between the observable start of the avalanche and the arrival of the earliest detectable waves at a distant station, must be considered in practical applications.

3. Possible focusing of the seismic energy in one direction has to be taken into account in cases where only a one-component sensor (frequently the vertical component) is employed to monitor an area. It is possible that the measured component of the ground motion does not have the largest amplitude, thereby resulting in delayed detection of the avalanche or even failure to detect it (for small-sized avalanches). This conclusion is more important for small to medium-size avalanches where the signal-to-noise ratio is usually lower than for large avalanches.

4. The relationship between avalanche size and the amplitude of the signals offers the possibility of estimating the size of the avalanche (volume and length) on the basis of the signal amplitude. Nevertheless, owing to the presence of local site effects, a prior monitoring of the different sites in relation to the avalanches is necessary. It was also observed that under similar conditions, powder-snow avalanches produce seismic signals, albeit with a smaller amplitude than dense avalanches but with a similar frequency content. Nevertheless, this result should be treated with caution since it is based on only one avalanche.

5. Although our conclusions focus on monitoring, we believe that the analysis of the seismic signals can also provide additional information on the dynamics of the avalanches, as envisaged for CB2-99 avalanches.

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