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Field observations of a debris flow event in the Dolomites

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Abstract

A debris flow event occurred in June 1997 in the Dolomites (Eastern Alps, Italy). The phenomenon was directly observed in the field and recorded by a video camera near its initiation area. The debris flow originated shortly after an intense rainstorm (25 mm in 30 min) whose runoff mobilised the loose coarse debris that filled the bottom of the channel in its upper part. The analysis of the steep headwater basin indicates a very short concentration time (9–14 min) that fits the quick hydrological response observed in the field. The debris flow mobilisation was not contemporaneous with the arrival of the peak water discharge in the initiation area probably due to the time required for the saturation of the highly conductive channel-bed material. Channel cross-section measurements taken along the flow channel indicate debris flow peak velocity and discharge ranging from 3.1 to 9.0 m/s and from 23 to 71 m^3/s, respectively. Samples collected immediately after deposition were used to determine the water content and bulk density of the material. Channel scouring, fines enrichment and transported volume increase testify erosion and entrainment of material along the flow channel. Field estimates of the rheological properties based on open channel flow of Bingham fluid indicate a yield strength of 5000 ± 400 Pa and relatively low viscosity (60–326 Pa s), probably due to a high percentage of fines (approx. 30%).

Keywords: debris flow; failure mechanism; physical properties; Bingham fluid

1. Introduction

Debris flows are found in a wide variety of environments worldwide. Main characteristics of these phenomena are the initial transformation from solid to flowing debris slurry which shows fluid-like macroscopic behaviour and the transport mechanism characterised by the interaction of solid and fluid forces (Iverson, 1997).

In the Dolomites Mountains (Northeastern Italy), debris flows commonly occur in channels draining small steep rock basins. Most debris flows occur in the summer during short, localised and high-intensity rainfalls. Channels are incised in thick talus slopes that ensure a large availability of poorly sorted debris.

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Similar conditions for debris flow occurrence have been previously observed and described in Canada (VanDine, 1985) and Japan (Takahashi, 1991) and are common in areas of high relief and high precipitation. The initial failure typically involves the channel bed material and the flowing mass progressively increasing its volume along the initial part of the channel, mainly by bed scouring. Since the material is cohesionless, or only poorly cemented, and needs to be close to saturation to mobilise, slope gradients in the initiation area are usually close to half the friction angle. Triggering conditions can be represented by a critical channel discharge caused by intense rainfall and/or by a temporary damming of the channel (bank sliding, build-up of debris on the bed) with subsequent failure (Cojean and Staub, 1998). Hillslope debris flows can originate at higher slope angles (Iverson et al., 1997) and they are often initiated by Coulomb failure of colluvial soils with water table below the ground surface. Materials are usually finer and less permeable; this implies the importance of antecedent moisture conditions and storm duration (Cannon and Ellen, 1988; Wilson and Wieczoreck, 1995).

Acquabona Creek, near Cortina d'Ampezzo, Eastern Italian Alps (Fig. 1), was selected as an observational and experimental site because debris flows occur almost annually and because the geomorpho-

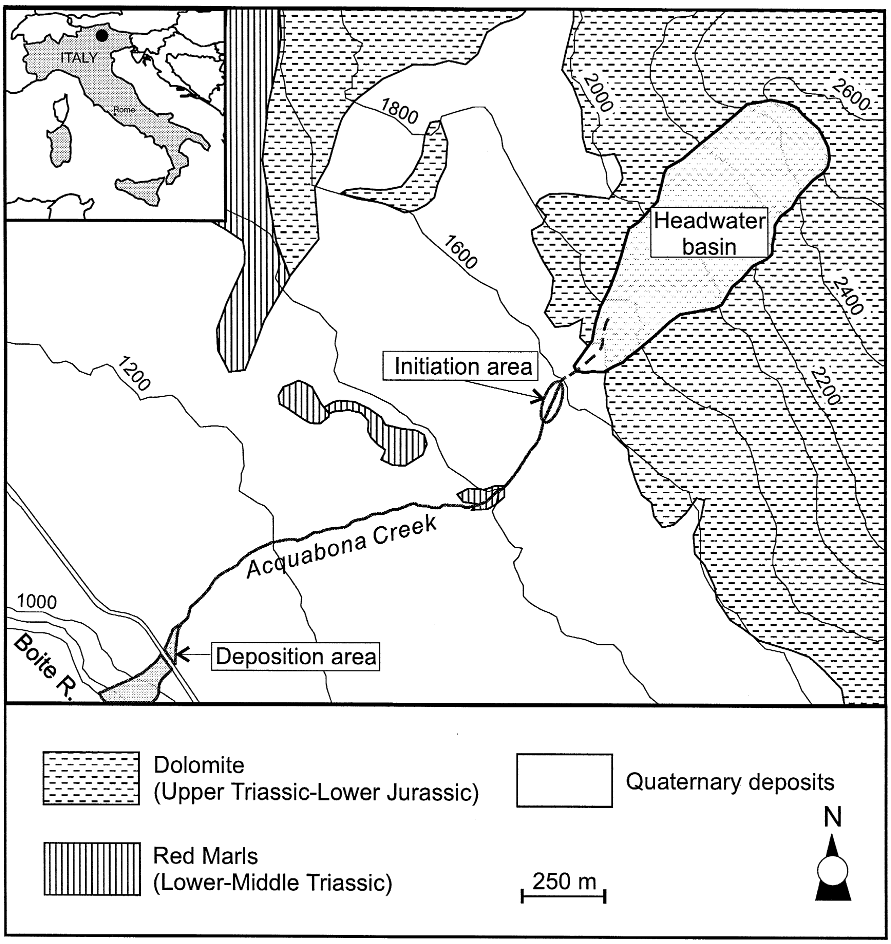

Fig. 1. Overview map of the study site.

logical and hydrological conditions of the area are quite typical of other debris flow-prone areas in the Dolomites.

On June 12, 1997, during the installation of a monitoring network, a debris flow was witnessed and recorded by a video camera near the initiation area. The flow was triggered by a short duration, high-intensity rainfall that produced free water surficial flow in the channel bed. Immediately after the event, material was sampled for grain size analysis, density and water content measurements. Channel morphometric measurements were completed in order to estimate peak velocity and discharge of the flow, yield strength and viscosity of a representative Bingham fluid.

2. Area description

The study site is located in the eastern part of the Dolomites (Fig. 1) and is characterised by massive rock cliffs made up of Upper Triassic to Lower Jurassic dolomites and limestones underlain by red marls of Lower–Middle Triassic age (Raibl Formation). Slopes below massive dolomite cliffs consist of thick talus deposits of poorly sorted debris including boulders up to 3–4 m in diameter. Recent alluvial deposits including postglacial sediments blanket the lower parts of the valley.

Slope angles below the subvertical dolomitic cliffs range from about 30–40° on the upper parts to 10–15° on the lower parts. Elevations range from 1000 to 3200 m above sea level.

The Acquabona drainage basin is characterised by an upper rock basin consisting of dolomitic rocks and of a deep channel cut in heterogeneous talus deposits. Debris deposits are exposed all along the channel bank except in the upper-intermediate part of the channel (at elevation of about 1400 m a.s.l) where stratified red marls outcrop along a 150-m reach.

The channel is rapidly deepened by the debris flows, as testified by maps and photographs which date back to the last century and confirmed by previous field surveys, and its depth has reached more than 30 m in the intermediate part. The incised channel has an average slope of 18°, ranging from 30° in the initiation area to 7° in the deposition area, the channel length is 1632 m and the steep rock basin that represents its effective drainage area has an area of 0.30 km^2.

The climatic conditions are typical of an Alpine environment. Annual precipitation at Cortina ranges from 900 to 1500 mm. Precipitation occurs as snowfall from November to May. Intense summer thunderstorms are common and give a maximum to the seasonal precipitation regime.

3. The 12th June 1997 event

3.1. Direct observations

On June 12, 1997 a debris flow was triggered by an intense and localised thunderstorm. The event was directly observed by two researchers, and recorded with a video camera from the left side of the channel, near the source area of the debris flow (point O in Fig. 2). Following is a description of the event as directly observed in the field and recorded by the video.

At 3:15 PM, approximately, just a few minutes after the rainfall stopped, a waterfall was observed near the outlet of upper rock basin (point I in Fig. 2; Fig. 3a). After a 150-m fall, the water ran through a narrow rocky channel that delivered it straight to the beginning of the Acquabona debris flow channel, where loose debris filled up the bottom of the gully. In the meanwhile, very little surficial runoff was observed in the channel.

At 3:19 PM, a loud rumbling announced that a debris flow had started. A channel bend obstructed direct view of the initiation area from the observation point. Field evidence revealed that the flow was initiated immediately downstream of a boulder-field (point II, Fig. 2; approximately 1590 m a.s.l.) that distinguishes the debris gully downstream from the rocky channel upstream. No evidence of precursory bank failures was detected and only the channel bed debris was mobilised.

A first surge of flowing debris appeared from behind the bend and came to rest at point III (Fig. 2) depositing coarse debris, 1–2 m thick, that almost clogged the channel. Coarse clasts were present at the snout, sides and on top of the surge. Water initially seeped out of the base of the debris snout and after approximately 30 s, the sediment-laden

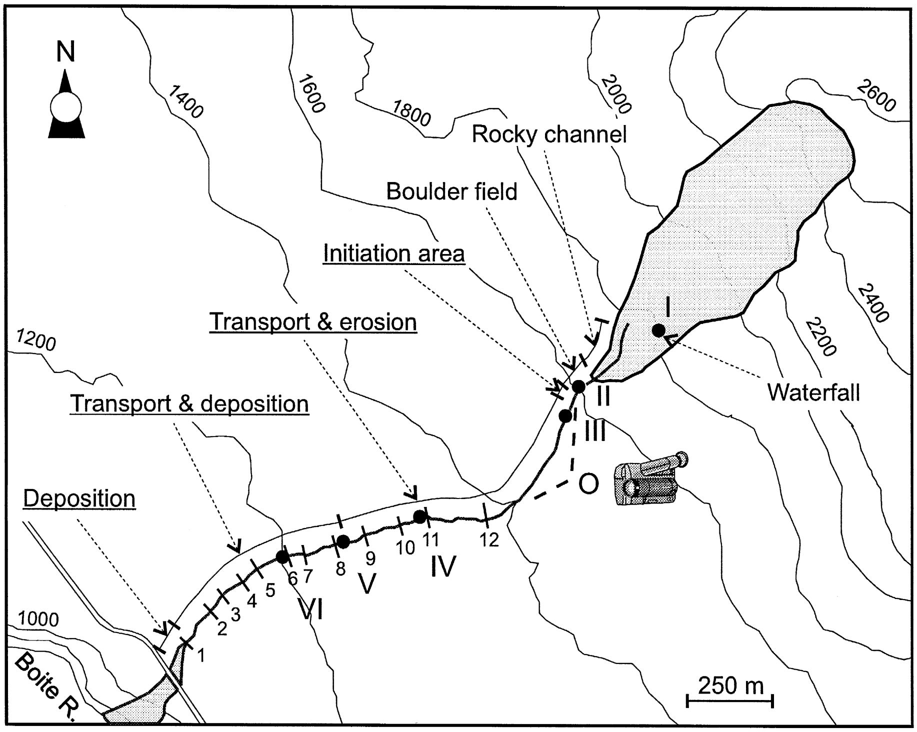

Fig. 2. Schematic map of the 12th June 1997 debris flow event (see text for explanation).

water overtopped the fresh deposit, the temporary dam failed and the deposit was remobilised. The stony snout appeared unsaturated, and the flow was not turbulent, segregating coarsest material at lateral sides, but becoming turbulent at steep channel steps (Fig. 3b). Large boulders, up to 1.5 m, were transported by rolling, and pushed by the oncoming flow (Fig. 3c). Additional debris was supplied both by channel bed scouring and channel banks undercutting with consequent localised bank failures. This initial surge was followed by a more dilute turbulent tail.

In the following 10 min, two more surges with similar characteristics were observed. Although the flow was somewhat ‘immature’ (Takahashi, 1991) due to the proximity to the initiation area, severe channel bed scouring was caused and a mean deepening of the channel of about 1 m was estimated. Eleven minutes after the debris flow initiation, the water fall discharge was significantly less. The actual debris flow finished and only hyperconcentrated flow continued for a few minutes in the channel.

Going downstream after the event ceased, debris flow traces and deposits were carefully examined. Only erosional processes were observed along the first 1000 m below the initiation area. Channel bed deepening was in the order of 0.5–1.5 m and bank undercutting had caused surficial bank failures on the external part of the channel curves. Erosion and incorporation of the material was particularly severe in the red marls outcrop (1400 m a.s.l.): channel steps up to 2 m high were created and the flowing mass became completely reddish in colour. At point IV (Fig. 2; approximately 1350 m a.s.l.), fresh mud on banks recorded a maximum flow depth of about 2.5 m.

Lateral and channel bed deposition occurred downstream from point V (Fig. 2; approximately 1240 m a.s.l.). At point VI (1210 m a.s.l.), the flow depth was about 1.6 m and coarse clasts, up to 20 cm size, were observed on the top of the deposits of debris flow levees inset within the channel (Fig. 3d).

Terminal lobate debris deposits (1130 m a.s.l.) were about 50 m wide and 60 m long on a slope of

Fig. 3. (a, upper left) The waterfall that delivers water to the debris flow initiation area. (b, upper right) The debris flow at a steep channel step. (c, lower left) A large boulder (1.5 m) pushed by oncoming flow. (d, lower right) Fresh mud marks recording the maximum flow depth are well-visible after the event.

7°, with an average thickness of 1.8 m. The total volume of the debris deposit was about 6000 m^3. Subsequent stream flow partially eroded the channel bed. Coarser clasts (up to 30 cm) were concentrated at the top of the deposit and the alignment of the clast major axis with the flow direction suggests that sorting occurred during deposition. Subsequent stream flow partially eroded the channel bed and the terminal deposit, transporting finer sediment beyond the coarse debris lobe. The deposited material, still in a liquid state an hour after motion ceased, did not show water losses at the front or in any other parts.

Along the channel, the flow incorporated debris at a rate of approximately 6 m^3/m, determined from the total volume of the deposited debris (6000 m^3) minus the estimated volume of the material mobilised from the source area (600 m^3), and averaged over the length of the erosion zone (942 m). Previously determined yield rates at Acquabona Creek, based on an event in 1992, averaged 5 m^3/m (Marchi and Tecca, 1992).

3.2. Rainfall

Rainfall data of the June 12, 1997 storm were recorded at the rain gage of Mt Faloria (2230 m a.s.l.), located 1.3 km N of the debris flow initiation area. The main part of the localised thunderstorm that preceded the debris flow had a duration of 35 min, with an average rainfall intensity of 0.65

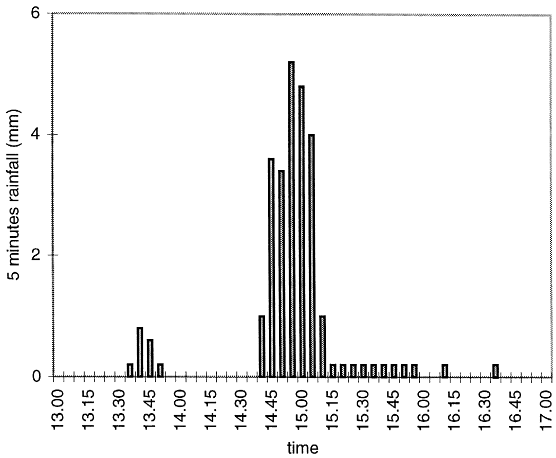

Fig. 4. Five minutes rainfall at the rain gage of Mt. Faloria (2230 m a.s.l.) on 12 June 1997.

mm/min (39 mm/h). The peak rainfall intensity exceeded 1 mm/min (60 mm/h) measured over 10 min. (Fig. 4).

The recurrence interval for the June 12, 1997 storm, calculated using the available one-day storm precipitation data of the last 20 years in Cortina, is approximately 5 years. Historical recurrence for medium-size debris flows may be estimated from existing records to be one event every 2 to 3 years, but a comparison of these two recurrence intervals should consider that factors like spatial rainfall distribution and wind effects affect the actual precipitation that reach the basin.

On the other hand, the availability of debris material in the upper part of the channel, where debris flows initiate, does not seem to represent a limiting factor for the occurrence of the phenomenon, since the channel is deeply incised in young weakly cemented heterogeneous slope deposits. The channel banks are very steep (up to 50°), thanks to the contribution of a certain degree of cementation of the dry material. Once wet, it looses its cohesion causing accelerated erosion and bank failures with subsequent accumulation of loose debris on the bottom of the channel.

3.3. Headwater basin characteristics

The basin that feeds the debris flow channel is almost entirely constituted by moderately fractured outcropping dolomite not affected by significant karst phenomena. Slope gradients are very high and colluvium is limited to a few areas of lower gradient. Such characteristics determine a quick hydrological response as confirmed by the direct observations on June 12.

Lacking direct measurements, an estimate of the water inflow at the initiation area of the debris flow (Q) has been made using the rational method:

$$Q = kCh_c A/t_c,$$

where k is a conversion factor, C is the runoff coefficient, h_c is the amount of rainfall in the concentration time t_c, and A is the drainage area.

The concentration time has been estimated by two different empirical formulae, both suitable for steep mountain catchments (Tropeano et al., 1996):

$$\text{Giandotti:} \quad t_c = (4A^{0.5} + 1.5L)/0.8(H_m - H_o)^{0.5}$$

$$\text{Tournon:} \quad t_c = 0.396L/i^{0.5}\left[A/L^2(i/i_v)^{0.5}\right]^{0.72},$$

where L is the headwater basin length, H_m is the average basin elevation, H_o is the basin outlet elevation, i is the average channel gradient, and i_v is the average slope gradient.

The morphometric parameters used in the calculations are listed in Table 1.

The estimated concentration times are 14 and 9.5 min and apparently agree with the time elapsed from the onset of the rainfall and the waterfall appearance near the basin outlet. Considering a representative concentration time of 15 min, a conversion factor (k) of 0.278 and a runoff coefficient (C) of 0.8, the water inflow to the initiation area of the debris flow peaks at 3.35 m^3/s (Fig. 5).

The total volume of water inflow can be estimated integrating the discharges for successive 5 min steps (rainfall data resolution). The result is 4900 m^3 before the debris flow initiated (Fig. 5). The delay between theoretical peak discharge arriving from the

Table 1
Morphometric parameters of the headwater basin

A (km^2)	H_m (m)	H_o^a (m)	L^b (km)	i	i_v
0.3	2158	1650	1.3	0.78	0.96

[a] Basin outlet at the channel head.
[b] Distance from the watershed divide to the watershed outlet.

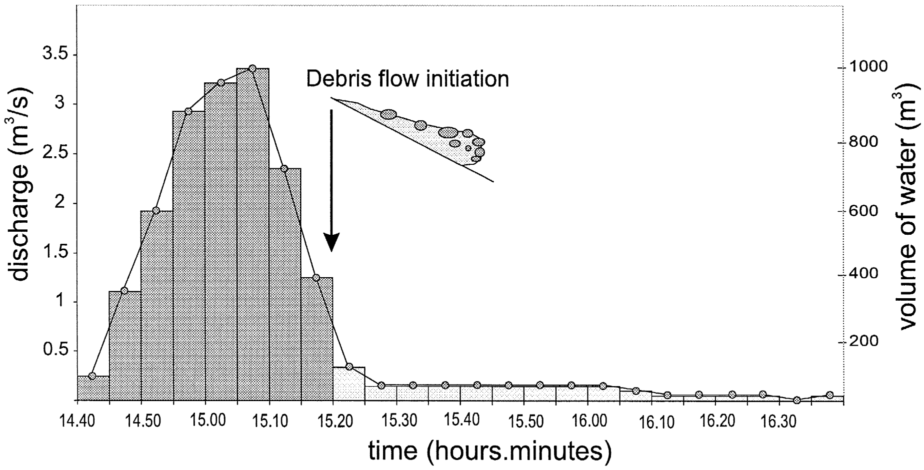

Fig. 5. Inferred water inflow from the upper rocky basin compared, on a temporal scale, with the actual debris flow initiation. Dark gray: water inflow before the event; light gray: water inflow after the event.

upper basin and the actual debris flow initiation (about 12 min) could correspond to the time required to saturate the loose debris that fills the channel in the initiation area. Such material has a very open structure with a thickness limited to few meters and rests on less permeable slope deposits: water coming from upstream circulates preferentially in the surficial debris horizon and eventually flows above the surface, if its capacity is exceeded.

3.4. Cross-section measurements

The day after the event, 12 cross-sections of the debris flow channel were measured (Fig. 2 and Table 2). The velocity of the debris flow was estimated from superelevations of lateral deposits or mudlines left by the peak discharge at 6 of the 12 sections. Following Johnson (1984), for channel slope less than 15°, the mean velocity (v) of the debris flow at bend sections can be estimated from:

$$v^2 = g\psi\Delta h / W,$$

where g is the acceleration due to gravity, ψ is the radius of curvature of the centerline of a channel bend, Δh is the superelevation of the flow, and W is the flow width.

Velocity and peak discharges (Q) values, estimated as the product of average velocity and the flow cross-section area (A), are reported in Table 2.

Velocities ranged from 4.5 to 7.2 m/s in the middle channel (Sections 9, 10, 11) and from 3.1 to 9.0 m/s in the lower channel (Sections 3, 5, 6). Debris flow peak discharge varied between 23 and 71 m^3/s.

Iverson et al. (1994) analysed the error involved in the superelevation method and found estimates to be within 30% of measured velocity values, with errors mainly due to the passage of the frontal bore in which conditions of steady and uniform flow are

Table 2
Morphometric measurements along Acquabona channel[a]

Section no.	D (m)	Δh (m)	ψ (m)	β (°)	v (m/s)	Q (m^3/s)
12	2.4	0				
11	2.5	0.76	24	5.0	4.5	60.9
10	2.5	0.29	40	4.0	5.2	27.9
9	2.3	0.46	68	4.5	7.2	47.5
8	1.9	0				
7	1.6	0.38				
6	1.5	0.60	21	7.0	5.0	23.9
5	1.8	0.33	159	3.0	9.0	70.6
4	1.9	0.12				
3	1.8	0.52	11	5.0	3.1	23.0
2	2.2	0				
1	1.5	0.20				

[a] L: distance from the initiation area; δ: channel slope; W: flow width; D: flow depth; Δh: elevation difference between inner and outer lateral deposit; ψ: radius of curvature of centerline of channel; β: flow surface tilt angle; v: estimated peak flow velocity; Q: estimated peak flow discharge.

violated, particularly at sharp bends. Moreover, splashing at the bend could exaggerate mud marks, and the assumption of a linear surface profile may overestimate the flow cross-section (Jakob et al., 1997). Surveys of multiple bends reduce these errors, but the available data of the essentially straight Acquabona channel cannot be corrected for bore effects. Velocity and discharge estimations must therefore be considered approximate.

4. Physical characteristics of the material

The Acquabona debris flow transported poorly sorted material, including boulders with diameters up to 1–2 m. Grain size distribution analyses have been performed on material sampled in the deposition area (15 samples) and in the source area (15 samples). The grain size distributions, obtained on the fraction passing the 20 mm sieve, show a remarkable difference between the two areas (Fig. 6). The percentage of fines (finer than 0.065 mm) did not exceed 10% in the source area, whereas it is about 30% in the deposits. This fines enrichment is essentially due to the passage of the flow on the Raibl Formation cropping out in the intermediate reach of the channel. Such formation is constituted mainly by highly erodible pelites and of thin-bedded silty–sandy layers and produce an increase in fine sand and silt fraction; the clay fraction reaches at most 5%.

The bulk density and water content of debris was measured on material sampled in the deposition area within half hour of the debris flow deposition. Referring to the fraction finer than 20 mm, bulk densities range from 24.2 to 25.5 kN/m^3 and water contents vary from 9.6 to 11.9%. The choice of such a fraction for the physical characterisation of the material was suggested by practical considerations; however, the fraction represents 70–75% by weight of the total grain size distribution.

Atterberg limits classify the deposited material as inorganic silt with low plasticity (Plastic Index equals 3–4%) and a liquid limit of about 20%. The mean water content of the sampled fresh material, if referred to the fraction finer than 0.42 mm, results to 28%, well above the liquid limit.

5. Field estimated rheological properties

A back-calculation of debris flow rheological properties based on field measurement of channel

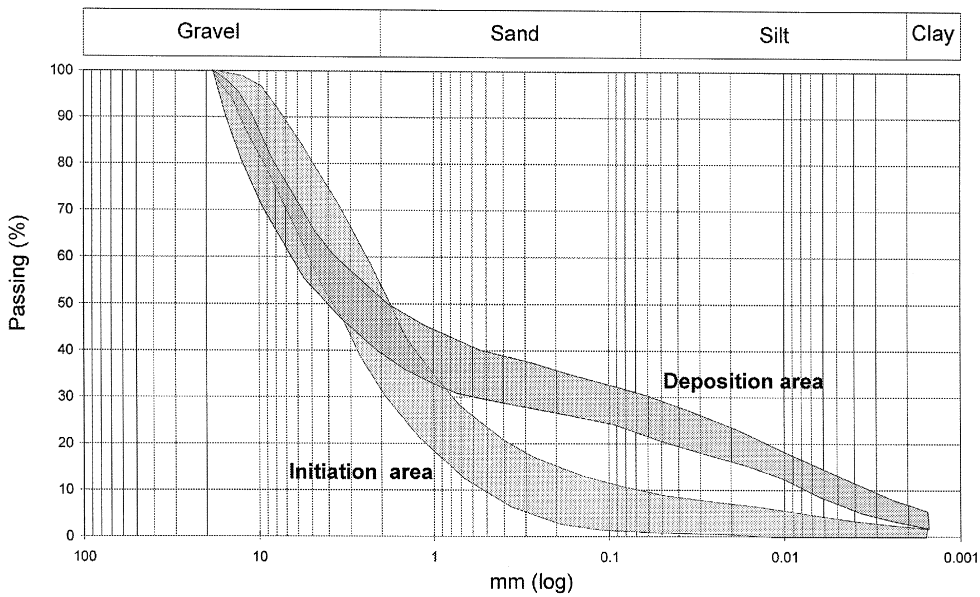

Fig. 6. Particle size distribution of debris.

geometry, channel slope, deposit thickness, deposit slope, debris bulk density and peak discharge estimates has been performed based upon the method recently proposed by Whipple (1997) which supplies general solutions for flow of Bingham fluids in channels with realistic shapes. In our case, the channel shape was assumed trapezoidal, yield strength (5000 ± 400 Pa) was estimated from deposit thickness and slope, while peak discharge estimates were derived from the cross-section measurements cited above. The back-calculation procedure requires also cross-section measurements of straight channel reaches (possibly located between two of the surveyed bends) because they represent the closest approximation of steady, rectilinear flow.

Viscosities resulting from the calculations refer to the six different sections considered (1, 2, 4, 7, 8, 12) and range from 60 to 326 Pa s. Reliability of the data is mainly affected by errors associated with peak discharge and yield strength estimates and with reconstruction of flow cross-sectional area. Estimates of the effective Newtonian viscosity were also obtained by repeating the viscosity calculation for the case of a zero yield strength; they range from 524 to 1609 Pa s. Also in this case, the scatter is significant, but the data represent one of the few examples of field-estimated rheological properties. In cases like Acquabona, where the coarse (gravel and boulder) fraction play a significant role in the rheology of the debris flow, field estimation remains the only way to provide rheological parameters that are representative of the real material.

6. Discussion and conclusions

Field survey and direct observations of the 12th June 1997 debris flow event in Acquabona Creek allow a preliminary consideration of debris flow initiation mechanisms and behaviour.

(1) The debris flow channel collected water from a very small and steep rock basin characterized by a short concentration time. The sequence of events indicates that the incoming water took a few minutes to saturate the channel bed material, before excess water began to flow in the initiation area and the debris flow originated. The complete saturation of the material and the presence of flowing water on the surface appear then to be necessary for the initiation of the debris flow; this condition is reached only after intense rainstorms which generate a peak inflow exceeding the capacity of the highly permeable channel bed material.

(2) Erosion and entrainment of material were very active in the upper and middle parts of the flow channel (approx. 1000 m) as demonstrated by the fines enrichment and volume increase of the flowing mass along the channel itself. The high fines content could explain the relatively high value of yield strength and low Bingham viscosity estimated from field measurements in the lower part of the channel and deposition area.

Shortly after the described event, a fully automated monitoring system, developed in cooperation with the United States Geological Survey (Cascades Volcano Observatory), was installed at Acquabona debris flow site. The system consists of three on-site stations measuring pore-water pressure and rainfall in the initiation area, flow velocity, depth, total and fluid pressure along the channel. Three cameras should provide video recording of event initiation and surface velocity profiles. The analysis of the data collected will provide a better understanding of debris flow initiation and behaviour in Acquabona catchment.

Acknowledgements

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References

Cannon, S.H., Ellen, S.D., 1988. Rainfall that resulted in abundant debris-flow activity during the storm. USGS Prof. Paper 1434, 27–33.

Cojean, R., Staub, I., 1998. Mécanismes d'initiation des laves torrentielles dans les Alpes françaises. 8e Congrès de l'AIGI, Vancouver, 8 pp.

Iverson, R.M., 1997. The physics of debris flows. Reviews of Geophysics 35 (3), 245–296.

Iverson, R.M., LaHusen, R., Major, J.J., Zimmerman, C.L., 1994. Debris flow against obstacles and bends: dynamics and deposits. EOS, Trans. Am. Geophys. Union 75, 274.

Iverson, R.M., Reid, M.E., LaHusen, R.G., 1997. Debris-flow mobilization from landslides. Annual Review of Earth and Planetary Sciences 25, 85–138.

Jakob, M., Hungr, O., Thomson, B., 1997. In: Two debris flows with anomalously high magnitude. Proc. of 1st Int. Conf. on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment. ASCE, San Francisco, California, pp. 382–394.

Johnson, A.M., 1984. Debris flow. In: Brundsen, D., Prior, D.B. (Eds.), Slope Instability. Wiley, pp. 257–355.

Marchi, L., Tecca, P.R., 1992. Int. Symp. INTERPRAEVENT. Garmisch, Austria. Hill slope debris flows in the Dolomites: characteristics and associated risk 3, 83–92.

Takahashi, T., 1991. Debris flows, IAHR Monograph. A.A. Balkema, Rotterdam, 165 pp.

Tropeano, D., Casagrande, A., Luino, F., Cescon, F., 1996. Processi di mud-debris flow in Val Cenischia (Alpi Graie)—Osservazioni nel bacino del T. Marderello. Quaderni di studi e documentazione dell'Associazione Georisorse a Ambiente 20, 5–31, in Italian.

VanDine, D.F., 1985. Debris flows and debris torrents in the Southern Canadian Cordillera. Can. Geotech. J. 22, 44–68.

Whipple, K.X., 1997. Open-channel flow of Bingham fluids: applications in debris flow research. Journal of Geology 105, 243–262.

Wilson, R.C., Wieczorek, G.F., 1995. Rainfall thresholds for the initiation of debris flows at La Honda, California. Environ. Eng. Geoscience 1 (1), 11–27.