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ASSESSMENT OF THE FRAGMENTATION ENERGY IN ROCK AVALANCHES

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ABSTRACT
Fragmentation is one of the mechanisms involved in rock avalanches. Quantifying the energy transfer during a rock avalanche can help to assess the influence of fragmentation on mobility. In this paper, two methods are examined to assess fragmentation energy. One is based on the comminution theory and the other on the blasting energy used in mining industry to predict fragmentation of jointed rock masses. These two methods are applied to seven well-documented rock avalanches for which the in-situ block size distributions of the intact rock mass and of the debris deposits are known. Fragmentation seems to increase with the travel distance, and scatter in data reflect the type of material.

RÉSUMÉ
La fragmentation est un des mécanismes impliqués lors d'avalanche rocheuse. La quantification de l'énergie de fragmentation permet d'apprécier l'importance de cette dernière sur la mobilité d'une masse de débris en regard de l'énergie potentielle disponible. Dans cet article, deux méthodes sont examinées pour apprécier l'énergie de fragmentation. L'une est basée sur les théories de comminution et l'autre sur les énergies de sautage utilisées dans le domaine minier pour prédire la fragmentation des massifs rocheux fissurés. Ces deux méthodes sont appliquées à sept sites bien documentés d'avalanches rocheuses pour lesquels la blocométrie du massif intact et des débris est connue. La fragmentation des matériaux d'avalanche rocheuse augmente avec la distance de parcours. La dispersion des résultats semble refléter les différences entre les matériaux.

1. INTRODUCTION

Large rock avalanches are amongst the most spectacular and catastrophic natural events. Unfortunately, they cause loss of human lives and infrastructure as well as environmental damages in all mountainous area around the World. The study of parameters and phenomena involved in such events are very important for both landslide risk assessment and geomechanical characterisation of mass movements. An important stage of such phenomena is the post-failure mass movement, which is generally the most destructive phase in a rock avalanche. One of the key factors in this process is the mass mobility or runout distance. This is controlled by several factors such as: initial potential energy, materials characteristics, slope failure mechanisms, and environmental settings. Considering the non-channelized runout of a debris mass, without any obstacle, the following equation summarizes energy balance during a rock avalanche (modified from Müller, in Heim 1932):

$$\Delta E_T(t) = \Delta E_P(t) + \Delta E_K(t) + \Delta E_F(t) + \Delta E_{IF}(t) + \Delta E_D(t) = 0 \qquad [1]$$

where E_T, E_P, E_K, E_F, E_{IF} and E_D are respectively the total energy, the potential energy, the kinetic energy, the friction energy along sliding plane, the internal friction energy and the disintegration energy (e.g.: fragmentation) at time *t*. Although ground and air vibration energies produced by the moving mass are not negligible (Melosh 1979), these were not taken into account herein.

Following Eq. 1, energy consumed by the disintegration of the debris mass, such as fragmentation processes, reduces its kinetic energy. The grain size diminution between the starting area and the deposit area of a rock avalanche should give an indication of the relative influence of fragmentation on the mass mobility.

Some authors claim that fragmentation influences the behavior or runout distance of rock avalanche (De Matos 1988; Strom 1994; Campbell et al. 1995; Kilburn and Sorensen 1998; Schneider et al. 1999; Davies and McSaveney 1999; Davies et al. 1999; Erismann and Abele 2001; Davies and McSaveney 2002). To date, none of them has quantitatively measured the particle size reduction and assessed the related energy consumption for rock avalanches.

Following this idea, the aim of this work is to assess the fragmentation energy as a function of the mean particle size reduction, from the starting zone to the deposition zone, at the scale of a rock avalanche, following calculation techniques used in the mining industry.

The next sections present the theories on industrial fragmentation, theories on rock avalanche fragmentation, the methodology adopted to assess the fragmentation energy of rock avalanche, and finally the description and the fragmentation energy calculated for seven rockslide avalanche sites, three in the French Alps and four in the Canadian Rockies.

2. THEORIES ON FRAGMENTATION

2.1. Blasting

Most of the time, mining engineers follow rules of thumb to adjust the quantity of explosive energy needed to blast a certain volume of rock materials. This has led to the development of many empirical relations over the years. As early as 1725, Belidor showed that charge weight (i.e. energy) is proportional both to the volume excavated and to the surface area of that volume (Persson et al. 1993).

Since this time, many parameters were shown to influence the efficiency of the blast. After Gama (1995, 1996), they can be divided in three groups: 1- explosive parameters, which depend on the type of explosive: detonation pressure, available energy, gas volume, and density; 2- charge loading parameters: charge dimension, type and point of initiation steaming, and decoupling; and 3- rock mass properties such as: cohesion, density, dynamic compressive strength, dynamic tensile strength, and structure.

One of the simplest approaches to assess the blasting energy is the use of the rock constant "c" (Langefors and Kihlström 1963). This is an empirical measure of the amount of explosive (in kg) needed for loosening 1 m^3 of rock (Persson et al. 1993). After blast tests in Swedish rocks, it was found that the values of c vary between 0.2 kg/m^3 in brittle crystalline granite to 1 kg/m^3 in rock showing strata perpendicular to the blast direction. A "c" value of 0,4 kg/m^3 can be used for fissured rock materials. The problem with this method is that it doesn't take into account the particle size before and after the blast. Also, to transform the constant "c" into energy we have to multiply it by the explosion energy (Q_v) released by a type of explosive. For example, Q_v for TNT is 5,1 MJ / kg (Persson et al. 1993).

Another way to evaluate the equivalent blast energy is to use the concept of rock mass fragmentability, which is termed "*K*" by Gama (1995, 1996). Gama (1995) defined the fragmentability (*K*) as "the threshold of specific energy of the explosive that may break the rock mass in order to just separate blocks along their weakest links, and inducing no further fragmentation". Using the concept of fragmentability, Gama (1995) mathematically defined the explosive energy required for block size reduction by blasting in jointed rock mass as:

$$W_B = K(S_b / S_a)^{1/2} \qquad [2]$$

where W_B is the explosive energy consumed in kWh / ton of rock and S_a and S_b are respectively the size of block after and before the blast. Then, following Eq. 2, for a certain volume of rock, if $W_B < K$ there is no fragmentation, if $W_B = K$, it means that $S_a = S_b$, then explosive energy work is used only to separates block along their discontinuities. After Gama (1995), average values of *K* for three rock types are 0.128 for basalt, 0.112 for granite and 0.092 for limestone (in kWh / ton of rock).

2.2. Crushing

Fragmentation by crushing, also called comminution in literature, has been studied since the end of the 19th century. The "first theory of comminution" was elaborated by Rittinger (1867). He postulated that the work needed to fragment a solid by crushing or grinding is proportional to the area of the new surfaces created and hence inversely proportional to the produced diameter. Kick (1885) proposed the "second theory of comminution" in which the fragmentation work is considered proportional to the reduction in volume of the crushed material.

Bond (1952), observed that crushing and grinding are concerned both with surface and volume and proposed the "third theory of comminution". This theory is a unification of the two first theories. He considered that work needed to break particles of a certain size is initially proportional to its volume but becomes proportional to the area as new surfaces areas are created. He stated that the energy spent to fragment rock varies with the crack length formed, or as one-half of the square root of the new surface area produced.

Bond (1955) defined rock breakage as this:

> "Rock breakage is produced by deforming the rock, commonly under pressure, until the resulting stress locally exceeds the breaking strength and crack tips forms, usually on the surface. The surrounding strain energy then flows to the new crack, which is thereby extended to split the rock. When the rock breaks, or the strain is otherwise released, the mechanical energy input is transformed into heat."

For practical use in fragmentation by crusher or grinding machine, Bond (1952) established that the energy (*W*) required for fragmentation by the crusher is:

$$W_C = 10 W_i (d_{80}^{-1/2} - D_{80}^{-1/2}) \qquad [3]$$

where W_C is the work, in kWh/short ton, to crush material from an initial diameter, D_{80} (in micrometer), to a smaller diameter, d_{80}. W_i is the Bond's work index, which depends on the type of material (Table 1). Values in Table 1, were determined empirically from laboratory impact crushing tests, and plant and pilot mill tests on the same materials (Bond 1952).

2.3. Fragmentation in rock avalanche

Observations of cuts in several rock avalanche debris deposits, such as the Frank slide (Fig. 1), confirm that fragmentation is a significant mechanism in long runout rock avalanches (Cruden and Hungr 1986; De Matos 1988; Strom 1994; Schneider et al. 1999; Davies et al. 1999; Davies and McSaveney 2002).

Table 1: Average work index values for various materials (modified after Bond 1955)

Material	**W_i** (kWh/short ton)
Clay	6.3
Limestone	12.5
Quartz	13.6
Granite	15.1
Oil shale	15.8
Flint	26

Davies et al. (1999) defined the fragmentation scenario in a rock avalanche as this:

> “a rock avalanche begins as the detachment of a relatively coherent rock mass from a mountain side; the mass immediately begins to collapse into successively smaller and more numerous joint-determined fragments as it moves down the mountain side … field evidence suggests strongly that the fragmentation process continues throughout the whole runout”.

One can add to this definition that joint-determined collapse is true at the beginning, when particles are coarser, but after a certain degree of crushing, material becomes finer and breakage along joints gives place to breakage along mineralogical imperfections and micro-heterogeneities within the material. That is the reason why the finer the material, the more energy is needed to achieve fragmentation (Fig. 2).

De Matos (1988) based on industrial comminution process concluded that in rock avalanches, natural comminution should be influenced by:

- the depth of the debris mass (i.e. stress produced by its own weight);
- the duration of the event ;
- the mineralogical composition of rock ;
- the discontinuities and defects within the rock mass (joint, flaws, weak minerals, etc.) and;
- the presence of water.

In the case of the presence of water, according to rock composition, Tourenq (1970) showed that if there is presence of water, wearing of the rock material increase whilst in fragmentation process, water seems to play a secondary role, only when swelling minerals are present within the material. Bond (1955) also stated that dry grinding requires about 33% more energy then wet grinding.

Figure 1: Road cut through the debris of Frank slide. Height of the cut is about 15 m. Electrical post gives an idea of the scale (photography by J. Locat).

2.4. Limits of the theories on artificial fragmentation

Before using Eqs. 2 and 3 for evaluating fragmentation energies in rock avalanche, some limitations have to be pointed out. Both methods use average values. Since Bond’s work index for Eq. 3 and fragmentability (*K*) for Eq. 2, are determined from experimental test results, inherent experimental errors are involved.

For example, Bond’s work index (*Wi*) was determined with different crusher machines, where a part of energy is lost in machine wearing and deformation. In the case of Eq. 2, fragmentability (*K*) was determined from blasts in different masses of rock. Blast depends on the type of rock and on the degree of its fracturing but also on type of explosive and geometry of the blast pattern in regard to geological structures.

Nevertheless, natural fragmentation observed in rock avalanche is comparable to artificial fragmentation used in industrial processes, and both deal with the same material: jointed rock masses.

This led to the hypothesis that the amount of energy required to achieve fragmentation should be approximately of the same order. In this paper, rock avalanche is then taken as a giant natural blast or crusher machine.

Numerical analysis of Eqs. 2 and 3 (Fig. 2) shows the energy input necessary to break one ton of limestone, from initial particle size (D_{50}) of 10 m, 5 m and 1 m to smaller particle size (d_{50}). These D_{50} were selected to cover the range of initial sizes from avalanches listed in Table 2. The analysis shows two main points:

- Both methods are in the same range of energy, but blast energy is slightly higher for initial block sizes larger than 1 m, as can be seen for *D_{50}* of 5 m and 10 m.;
- To cause fragmentation finer than 0.1 m by crushing, influence of the initial block size on the energy required for fragmentation become negligible.

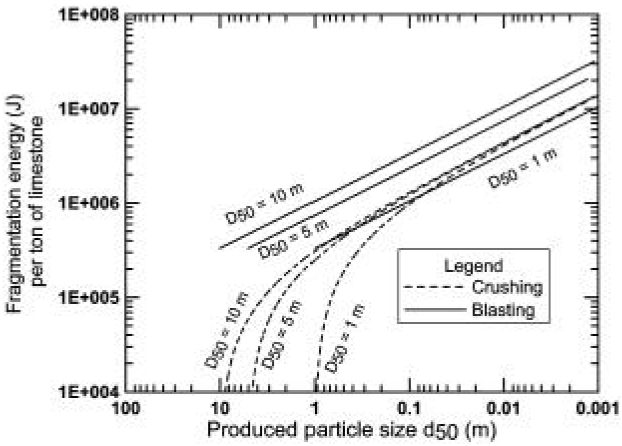

Figure 2: Graphical representation of Eq. 2 and 3 for initial block sizes (D_{50}) of 10, 5 and 1 m.

Also, the percent passing size has been fixed to 50 % instead of the 80 % proposed in Eq. 3. It is valid only if the passing block size distribution curves of the initial and final material are parallel, i.e. if the reduction ratio (*Rr = D/d*), remains constant for all sizes, which is assumed for all the avalanches studied here.

3. METHODOLOGY

3.1. Rock avalanche characterisation

With respect to the geotechnical characterisation analysis framework (Leroueil et al. 1996), rock avalanches data used hereafter were collected by Couture (1998) and Locat (2001) following the methodology detailed in Couture et al. (1999). In summary, this methodology can be divided in four major steps which includes: (1) gathering documentation, (2) field work including field testing, (3) laboratory testing and specific interpretation and; (4) analysis related to stability, mobility at the post failure stage, and energy balance. The originality of this methodology is both the application of geomechanical methods and the evaluation of the block size distribution in the detachment zone to compare the size distribution of debris in order to evaluate fragmentation energy in rock avalanches.

3.2. Energy calculation

3.2.1. Potential energy

Potential energy is the available thermo-mechanical energy of a body that depends on its mass, the gravitational acceleration, and the elevation drop of its centre of gravity from a higher starting point to a lower ending point. For rock avalanche, it can be expressed as this:

$$E_P = H_G \, r V g \qquad [4]$$

Where E_P is the total potential energy of a landslide, H_G is the vertical distance between the centers of gravity (CoG) of the mass (Fig. 3), ρ is the density of the mass, *g* the gravitational acceleration (9.81 m/s^2 on Earth), and *V* the volume of the failed mass.

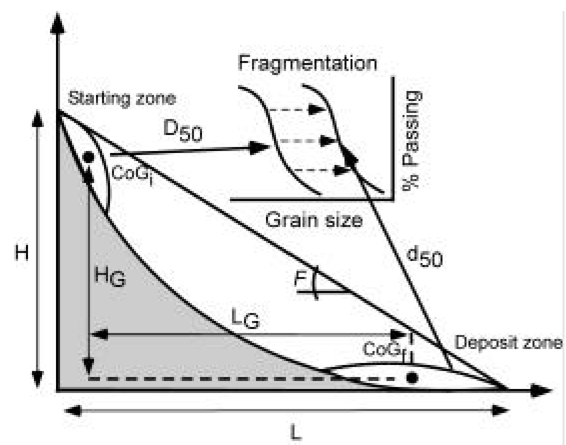

Figure 3: Definition of the geometrical parameters used in the text. H_G and L_G are respectively the vertical and the horizontal distances between the initial position (CoG_i) and the final position (CoG_f) of the centre of gravity.

3.2.2. Fragmentation energy

As previously indicated, assessment of the artificial fragmentation efficiency in regard of the consumed energy is directly linked to comparison between the particle size of original materials and the final dimension of the produced material.

Techniques developed in the mining industry (Doucet and Lizotte 1992; Kemeny 1994; Hadjigeorgiou et al. 1995) were adapted to assess the fragmentation efficiency in rock avalanche (Couture et al. 1996; Hadjigeorgiou et al., 1996). Therefore, one can consider that in-situ block size distribution of the intact rock mass is the initial block size of the material and the grain size distribution of the debris is the final grain size of the process.

To assess the mean block size of the intact rock mass, a structural mapping survey in the detachment zone is performed. This consists of scan lines surveys, where dip direction, trace length and position of all joints and discontinuities encountered along a line into an observation window are measured (Hadjigeorgiou et al. 1995). Ideally, it should be done in three orthogonal directions at sites where the fracturing characteristics of the entire rock mass are well exposed. In laboratory, scan lines data are analysed with a three-dimensional joint set model, e.g. STEREOBLOCK, to evaluate block size distribution based on Beacher stereological principles and on statistical analysis of joint sets (Hadjigeorgiou et al., 1995) .

For the debris mass, photograph-sampling technique uses a graduated frame or a known size element, such as a ball, as scale when photographs are taken. At the laboratory, each photo is analysed using image analysis technique. Block contouring is performed for each scanned photo and images are transferred onto a numerical form. Then, the image analysis system can measure the numerical diameter of each block using the scale as a calibration of the pixels. Statistical analyses are carried out to provide grain size distribution of the rock avalanche debris.

With the particle size distribution of the mass before and after the rock avalanche, one can use the Eqs. 2 and 3 to assess the fragmentation energy per ton of material. To obtain the total fragmentation energy, the energy is multiplied by the tonnage of the failed mass. This methodology is applied for the 7 rock avalanches presented hereafter.

4. ROCK AVALANCHE DESCRIPTIONS AND RESULTS

Description of rock avalanches studied in this paper were previously presented in the literature, therefore, the following descriptions summarise the general informations and the reader must refer to papers cited in the text for a more detailed description. Relevant details and energy calculations for each rock avalanche are listed in Table 2.

Table 2: Energy calculations and characteristics of four Canadian (Fr, SM, QE and JCN) and three French (CL, LM and Ch) rock avalanches considered in the study.

Parameter	Fr	SM	QE	JCN	CL	LM	Ch
Detached volume (x 10^6 m^3)	30	13	45	2.37	2	90	0.13
Deposit area (x 10^6 m^2)	2.4	1.3	0.9	1.2	0.4	2.1	
Mean thickness of the source (m)	55	65	50	15	10	160	8
Mean thickness of the deposit (m)	15	25	60	4	15	60	50
Horizontal travel distance – *L* (m)	3500	1650	2645	2800	800	4500	600
Vertical travel distance – *H* (m)	760	420	950	860	370	1250	520
Vertical travel distance of the CoG – H_G (m)	506	275	480	550	165	1040	415
Fahrböschung – *F* (slope angle in º)	12.3	14	20.3	17.1	24.8	15.5	40.9
Equivalent coefficient of friction – *f*	0.22	0.25	0.37	0.31	0.46	0.28	0.87
Excessive travel distance – *Le* (m)	2284	978	1125	1424	208	2500	0
Length deposit – *Ld* (m)	2300	1130	1800	1880	425	500	400
Run-up (m)	120	120	190	10	30	130	n/a
Type of rock	Lim.	Lim.	Lim.	Quart.	Lim.	Sch.	Amph.
RQD	97	95	95	94	100	97	79
RMR	71	78	78	80	91	64	65
Q	6	11	11	10	13	1	2
Basic friction angle (ϕ_b)	38	36	36	32	42	35	35
Mean block size distribution (m):							
Detachment zone D_{50}	2.25	8.58	8.58	0.65	5.85	2.00	0.98
Deposition zone d_{50}	0.36	1.20	0.68	0.53	4.90	0.14	0.23
Reduction ratio ($Rr = D_{50}/d_{50}$)	6.3	7.2	12.6	1.2	1.2	14.5	4.3
Ep (x10^{14} J)	3.872	0.912	5.509	0.334	0.084	23.874	0.014
W_B (x10^{14} J)	0.6458	0.2993	1.3744	0.0277	0.0188	2.9504	0.0023
W_C (x10^{14} J)	0.3869	0.0958	0.5047	0.0045	0.0010	2.9126	0.0018
W_B in % of Ep	17%	33%	25%	8%	22%	12%	17%
W_C in % of Ep	10%	11%	9%	1%	1%	12%	13%

4.1. Rock avalanches in Canadian Rockies

4.1.1. Frank

Frank rockslide avalanche (Fr) occurred on April 29th, 1903, and killed more than 70 people. It is located at 49° 36'N, 114° 25' 43''W, in the southeastern part of the Rocky Mountains in Alberta. The failure surface mainly followed the bedding planes of the eastern flank of the Turtle Mountain anticline (Benko & Stead 1998). It involved more than 30M m^3 of Paleozoic limestone. The deposit architecture presents an inverse grading over the 14 m of the mass depth (Fig. 1) and shows mean grain size varying between 0.035 m at the base to 0.3 m under a top layer of large boulders averaging 2 m (Cruden and Hungr 1985; Couture 1998).

4.1.2. Slide Mountain

Slide Mountain rockslide avalanche (SM) is situated on the eastern border of Jasper National Park at 53° 5' 50''N, 117° 38' 24''W, about 40 km northeast of the town of Jasper, Alberta. The failure surface essentially followed the bedding plane, which is a curved dip slope (Evans et al., 1997). About 13M m^3 of limestone (Palliser Formation) avalanched from the southwest slope of the mountain and filled the Fiddle River valley. Fiddle River has cut through the debris forming a steep sided gorge 20-40 m deep.

4.1.3. Queen Elizabeth

The Queen Elizabeth rockslide avalanche (QE) is situated on the southwest side of the sharp crested Queen Elizabeth Ranges at 52° 52' 36''N, 117° 42'W, 4 km east of Medecine Lake in the Jasper National Park (Evans et al, 1997). A special failure mode across bedding was identified there and termed "break-out" by Evans et al. (1997). Palaeozoic limestone ran down and created a landslide dammed lake in the main valley, which has since been infilled with sediment.

4.1.4. Jonas Creek

This place is characterised by two well defined rockslide-avalanches, namely the North and South Rockslides, that lie on the west side of the Jonas Ridge Mountain at 52° 26'N, 117° 24' 30''W, along the Highway 93, in the Jasper National Park (Locat 2001). In this paper, only the North slide (JCN) is selected for calculation. About 2.1M m^3 of quartzite from the Gog Group, collapsed along the bedding planes, which dip directly into the valley, and ran down the valley of the Sunwapta River. In the starting zone, the bedding and the two orthogonal joint sets, which have a mean spacing of 0.65 m, control the dimension of the initial block size (Bruce and Cruden, 1980). Very few fine materials were observed.

4.2. Rock avalanches in the French Alps

4.2.1. Clap de Luc, Drôme

The rockslide of Clap du Luc (CL) is situated about 1.5 km upstream of the village of Luc-en-Diois at 45° 14' 36''N, 5° 27' 29''E, along the la Drôme River (Couture et al., 1997). Approximately in the year 1442 A.D., about 2M m^3 of massive bedded limestone detached and slid along the stratification, fragmenting in metric blocks which spread in two arms on both sides of a rock spur.

4.2.2. La Madeleine, Savoie

The La Madeleine rock avalanche (LM) is situated near the Italian border in the Maurienne Valley at 45° 17' 41''N, 6° 57' 52''E, halfway between the hamlets of Lanslevillard and Bessans (Couture et al. 1997; Couture et al. 1999). About 90M m^3 of schist collapsed by sliding along the schistosity. Deep gorges were carved in the debris by the Arc River. Internal structure of the deposit, such as inverse grading, can be observed (Couture 1998).

4.2.3. Charmonetier, Isère

The rockslide of Charmonetier (Ch) is located about 150 km south-east of the city of Lyon at 45° 01' 50''N, 6° 02' 08''E, on the north-eastern flank of the Massif de Taillefer, accessible by the road N91 between the cities of Grenoble and Briançon (Couture et al. 1997). The 24th of August 1987, after heavy rainstorms, a rock mass, constituted of amphibolites, averaging 0.13M m^3, detached and traveled down in the ravine of Charmonetier, eroding a blanket of loose materials about 1.5 m deep.

5. DISCUSSION

Limits of the method proposed herein for rock avalanches are:

- Block size distribution of the intact material is determined from material near the failure zone, which is not the material directly involved in the avalanche;
- Quality of the intact block size distribution computed is linked to the number and the representativity of outcrops on which the scan lines are carried out;
- Photo sampling technique used in rock avalanche analysis covers a wide area, sometimes over 1 km^2; it involves a lot of photo samples to be representative;
- Photo sampling on the surface of a debris mass in large rock avalanche underestimates the degree of fragmentation due to inverse grading as in Frank or La Madeleine.

Nevertheless, data comparison and energy calculations based on rock avalanches characteristics presented in Table 2 show that for the studied cases:

- In Table 2, fragmentation energy varies between 1 and 13 % of *Ep* when using crushing formula (Eq. 3) and between 8 and 33% when using blasting formula (Eq. 2);
- Finer is the size of the debris higher is the excessive travel distance (*Le* on Fig. 4);

- Reduction ratio (*Rr*) or degree of fragmentation seems to increase with the volume of the failed mass (Fig. 5);
- Massive and hard materials (CL and JCN on Fig. 5), with higher RMR values, are less fragmented than the others;
- Channelization and incorporation of loose material during mass movement induce scatter in data, especially for small volume rock avalanches as in the case of Charmonetier.

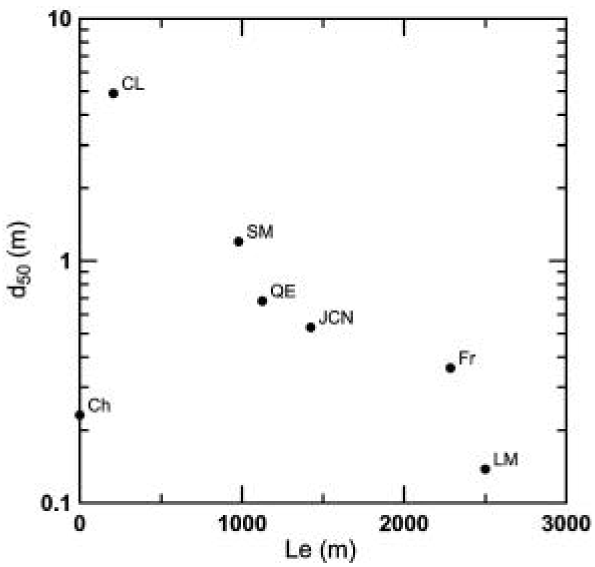

Figure 4: Relation between the excessive travel distance (*Le*) as defined by Hsü (1975) and the mean size of the debris.

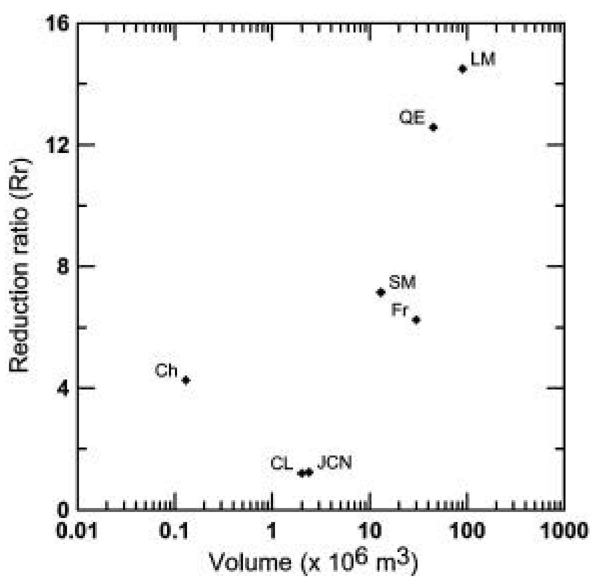

Figure 5: Relation between the reduction ratio (*Rr*) and the volume of the failed mass.

6. CONCLUSION

An approach to evaluate the degree of fragmentation and the energy related is proposed in this paper. It shows that fragmentation energy varies between 1 and 33 % of the potential energy of a rock avalanche. Analysis of seven rock avalanches showed that the degree of fragmentation increases with the volume of the failed mass and with the travel distance. Also, different types of materials seem to have different fragmentation behaviour. More data are needed, especially from rock avalanche deposits exposing the internal architecture of the debris, to better understand the fragmentation processes in rock avalanche.

7. ACKNOWLEDGEMENTS

The authors would like to thank the FCAR (Fonds pour la Formation de Chercheurs et l'Aide à la Recherche), NSERC (Natural Sciences and Engineering Research Council of Canada) and Geological Survey of Canada for their financial support. Special thanks to Ms. Christiane Levesque for help in correcting the text.

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