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THE GRAIN SIZE DISTRIBUTION OF ROCK-AVALANCHE DEPOSITS IN VALLEY-CONFINED SETTINGS

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INTRODUCTION

Detailed sedimentological data for rock-avalanche deposits are sparse in the current literature. A review yields the following common results based on both observation and direct measurement:

i. highly fragmented but undisaggregated clasts (MCSAVENEY, in press);
ii. preservation of original stratigraphy (STROM, 1999);
iii. crude inverse grading (CRUDEN & HUNGR, 1986).

Recent work has attempted to better quantify the sedimentology of rock-avalanche deposits using either a facies approach (SCHNEIDER et alii, 1999, WASSMER *et alii*, 2004) or direct measurement (HEWITT, 1999; CASAGLI & ERMINI, 2003). Direct measurement of rock-avalanche deposits has been hindered by both natural impediments such as internal exposure availability and accessibility and, crucially, sampling methodology. Previous sedimentological data has been collected as part of other rock avalanche research and so have often, necessarily, been limited to single small samples (MCSAVENEY, in press; HEWITT, 1999) from the main body of deposits without detailed study of the surrounding exposure to set the sample in a structural context. Research into the internal structure of landslide dams in the Apennines (CASAGLI & ERMINI, 2003) used far larger samples and a combination of methods, but again little account has been taken of the detailed internal structure of the deposits. This results in a single large measured section either representative of one facies / lithological band, or mixtures of several facies / lithological bands when considering that rock avalanche deposits often show stratification (Figs. 1, 2).

AIMS

The focus of this research has been to better characterize the sedimentology of rock-avalanche deposits in valley confined settings - deposits that are amongst the most common to form natural dams (COSTA & SCHUSTER, 1988). The stability of such landslide dams is of critical importance, if such a dam fails, 50 % fail within 10 days and the material characteristics of the blockage are a crucial factor in determining the time of this failure and size of the flood generated (COSTA & SCHUSTER, 1988; CASAGLI & ERMINI, 2003). Of the currently available techniques for predicting the timing of failure breach development and flood magnitude (see MANVILLE, 2001 for a comprehensive review), only one allows even crude input of sedimentological properties of the landslide dam, Boss BREACH^{TM}, a modified version of BREACH (FREAD, 1987). The data collected for this research is directly applicable to this physically based model of dam breach-development.

METHODS

Five rock-avalanche deposits, chosen for their large internal natural exposures are used in this research; Falling Mountain (Figs. 1, 2), Acheron, Round Top, and Poerua in New Zealand, and the Flims rock-avalanche in Switzerland. All are valley confined deposits, either Type II or III in the scheme of COSTA & SCHUSTER (1988), or down valley directed, varying in volume from 6 x10^6 m^3 to 10^{10} m^3.

Direct sampling of the rock-avalanche deposits was carried out using a field and laboratory sieve method combined with laser granulometry for minimal error (WEN *et alii*, 2002) to determine grain size distributions (GSD). Individual samples were in the order of 15 kg and the size range measured, determined from the maximum internal clast sizes, is 256 mm to 0.002 mm (- 8 Phi to + 9 Phi). All clast sizes sieved in the field have been corrected for moisture content to laboratory conditions using a derived relationship for each deposit (DUNNING, unpublished). Sampling at each deposit was biased through examination of internal structure, in particular preserved stratigraphy (Figures 1, 2). Samples were taken in preserved lithological bands to assess the variation in GSD with lithological variations and relative height in section, or height above base where observable.

The GSD data obtained have been analysed using GRADISTAT (BLOTT *et alii*, 2001) to yield descriptive statistics and undergone model fitting for evaluation of transport processes using the Weibull distribution (WEIBULL, 1951), with a least squares method, and also the method of HOOKE and IVERSON (1995) to obtain the fractal dimension, (d), for each sample where applicable.

Figure 1 - Internal structure of the Falling Mountain rock-avalanche deposit of 1929(New Zealand) as evidenced by bands of fragmented argillite and greywacke clasts. The field of view is 5 m for scale

Figure 2 - Close up view of a highly fragmented but undisaggregated greywacke clast from the interior of the Falling Mountain deposit. The fractures appear to radiate from a single point in this example

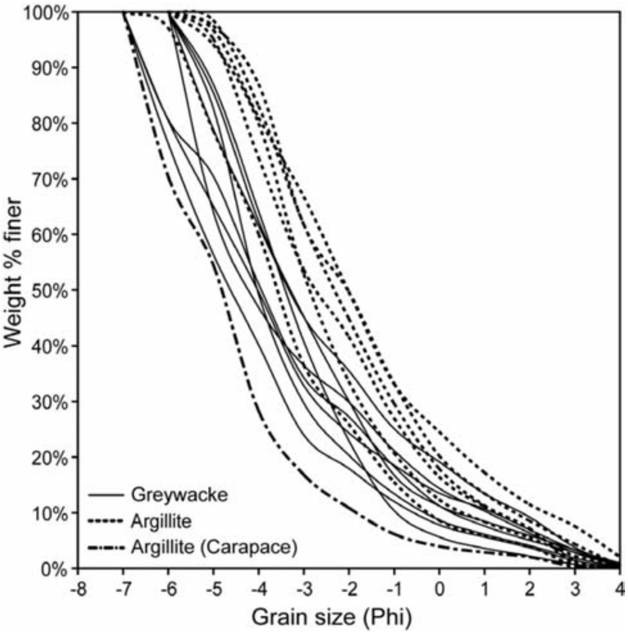

Figure 3 - GSD data from a near full internal exposure of the Falling Mountain deposit around 3 km from the source. The data segregate based upon preserved lithology rather than height above basal contact. Note the anomalously coarse argillite GSD from a sample in the surface and near surface carapace

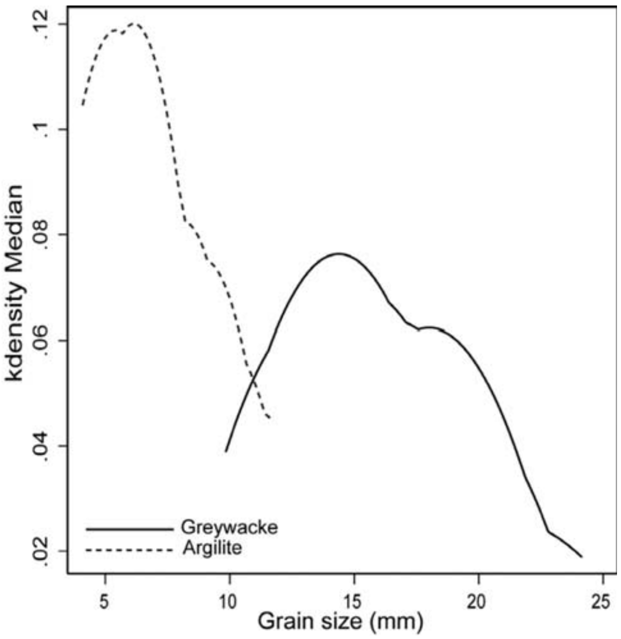

Figure 4 - Kernel density estimate of the median grain size based on the Falling Mountain GSD data shown in Fig. 3. Although the variation due to lithology is clear it would appear that the greywacke GSD contains two sub-sets and the argillite data distribution is cut short at the fine grade - probably due to mineralogy

RESULTS

INDIVIDUAL DEPOSITS

Results suggest that the original source stratigraphy and lithology exert a fundamental control on final deposit GSD in internal exposures of the deposits studied. Individual deposits studied have each contained two distinct preserved lithologies (band types) in the source or are considered mono-lithological in the case of Poerua and Round Top - schistose equivalents of inter-bedded greywacke and argillite. Where two lithological types are present, the GSD segregates based upon the preserved lithological band type in the final deposit, regardless of other variables (Figures 3, 4).

The Flims rock-avalanche, containing two distinct limestone band types unusually shows three distinctive final GSD forms. One of these GSD forms is characteristic of samples taken near the external margins and surface of the deposit where mixing is interpreted to have occurred (SCHNEIDER *et alii*, 1999) and appears unrelated to either of the two limestone source units and can be attributed to process overprinting on the unconfined margins.

In addition, samples taken in sub-vertical sections of the horizontally banded Flims and Falling Mountain deposits show the vertical variations in grain size for band types. Inverse grading is not observed, variations in grain size are entirely dependent upon band type except within thicker preserved bands where normal grading can be observed -this may be attributed to original source rock properties rather than transport process overprinting. There is, however, a coarse carapace facies (DUNNING, 2005) forming the upper portion of mature rock-avalanches that may be mistaken for a crude form of grading (Figures 5, 6).

ALL DEPOSITS

An analysis of the full data set allows a number of sedimentological properties for rock-avalanche deposits to be described (Table 1). These data show that the rock-avalanche deposits studied are finely skewed, poorly to very poorly sorted and that transport processes generate negligible silt grade material or finer. The fitting of GSD models has revealed that although the GSD's are Weibull like in nature, and have been reported as following a Weibull distribution, they are better represented as following a self-similar distribution (MCSAVENEY, 2002). The mean fractal dimension obtained after fitting a self-similar distribution is 2.44 (Table 1). This is below the 2.58 of SAMMIS *et alii* (1987) that equals a geometry where particles of all sizes are interpreted to be as likely to fracture and spacing between same size clasts is maximised.

Variable	N	Minimum	Maximum	Mean	Standard Deviation
Mean (Phi)	89	-.13	-5.69	-2.63	1.31
Median (Phi)	89	-.82	-6.19	-3.24	1.36
Sorting (Phi)	89	1.46	3.69	2.60	0.48
Gravel (Wt %)	89	46.97	98.65	75.85	12.08
Fractal (d)	89	1.95	3.04	2.44	0.20

Table 1 - Sedimentological properties of rock avalanches based on 5 deposits

Table 2 shows some of the significant relationships calculated for descriptive statistics based on the deposits sampled. The weight percent gravel (clast > 2 mm) in a sample has proved to be a key variable in the descriptive statistics. It is easily measurable in the field with minimal equipment and is significantly related to all variables apart than sorting that is considered fixed at poor to very poor. It is possible using just simple measure of weight percent gravel to calculate approximate values for all descriptive statistics and reconstruct a most probable GSD. The fractal dimension of samples increases with decreasing grain size towards values well in excess of 2.58, up to a maximum of 3.04 (Table 1), approaching values achieved in natural and simulated gouge (SAMMIS *et alii*, 1987) and considered to represent an excess of fine clast generation.

	Mean (Phi)	Median (Phi)	Sorting (Phi)	Gravel (Wt. %)	Fractal (d)	Altitude (m)
Mean (Phi)	X	.988**	.369**	-.958**	.529**	-.118
Median (Phi)	.988**	X	.310**	-.939**	.506**	-.081
Sorting (Phi)	.369**	.310**	X	-.547**	.280**	-.392**
Gravel (Wt %)	-.958**	-.939**	-.547**	X	-.612**	.225
Fractal (d)	.529**	.506**	.280**	-.612**	X	.018
Altitude (m)	-.118	-.081	-.392**	.225	.018	X

Table 2 - Speamans Rho correlation tests N=89, from 5 deposits, for altitude N=65 from 2 deposits. Results significant at the 0.1 level are starred twice, those significant at the 0.5 level are starred once

Figure 5 - View over the Tsatichhu rock-avalanche deposit, Bhutan (580 m wide) showing the coarse carapace and the finer interior where the overtopping water has cut through proximal to the source region. The dam failed through seepage and face failure in 2004, 10 months after formation

Figure 6 - View over the carapace of the Tsatichhu rock-avalanche deposit to the dam crest (the deposit was around 110 m deep) with seepage evident. The carapace and upper interior properties contrast are interpreted to have played a key role in the dam failure

DISCUSSION

The results indicate that the common observation of rock-avalanche deposits having crude inverse grading (CRUDEN & HUNGR, 1986) is often a misconception. In a mature rock avalanche deposit, beneath a relatively thin, boulder rich carapace, internal grading is purely a function of preserved stratigraphy. This has an important implication for rock avalanche transport processes; it suggests that the same mechanism of fragmentation is active at all levels in the moving mass below a zone of near passive transport of poorly broken up rock. The mean fractal dimension, below the ideal value specified by SAMMIS *et alii* (1987), suggests that the deposits tested had not reached a position in which all particle sizes are as likely to fragment. Examinations of the GSD's and descriptive statistics in combination with the fractal dimension indicate that there is an excess of coarse clasts and preferential fracture of these clasts over finer grades. The maximal fractal dimensions are achieved in the finest and weakest bands tested (Figures 3, 4) and may represent fragmentation and shear concentration in these weaker lithological units.

The results show that weight percent gravel is a key variable for field testing of deposits. An estimation or sieve measure of a suitably sized sample of rock avalanche debris can be compared to a plot (Figure 7) to provide values for sorting, mean and median grain size as well as the fractal dimension. This plot should form a vital part in a pro-forma approach to rock avalanche study, a standardized method of recording the sedimentological and geomorphological characteristics of rock-avalanche deposits so that deposits can be compared like for like. A standard pro-forma would also enable a database of deposits to be collected and so refine the sedimentological relationships described in this research.

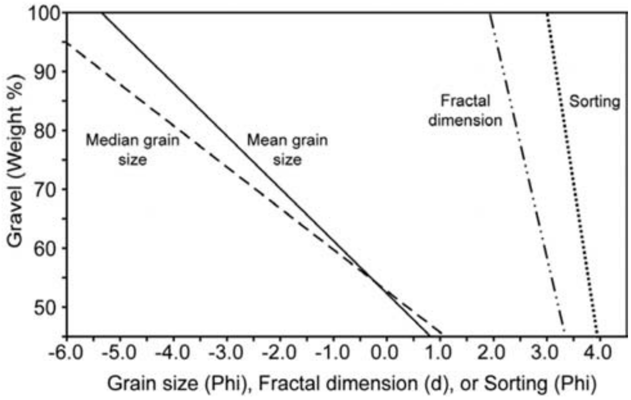

Figure 7 - Pro-forma developed based on the sample GSD data to allow calculation of the key descriptive statistics based on a measure of gravel only. The relationships identified are applicable to all of the sample data regardless of morphological and lithological variations

APPLICATION TO ROCK AVALANCHE DAMS

Previous research has illustrated the importance of the material properties of a natural dam to its stability (COSTA & SCHUSTER, 1988, CASAGLI & ERMINI, 2003). The data presented has provided a greater understanding of the internal structure, sedimentology and material properties of rock avalanches, a common natural-dam forming mass movement.

The failure of such dams is reported to commonly occur via overtopping rather than seepage or piping (COSTA & SCHUSTER, 1988) and so the development of a dam-crest breach is critical to predicting failure and subsequent downstream flood events. The software package Boss BREACH^{TM} models the development of a breach and the outflow hydrograph and peak discharge, the model outputs can be then used as an input for Boss DAMBRKTM a package used for flood routing (MANVILLE, 2001). Boss BREACH^{TM} is the only available model that utilizes the dam material characteristics. The results provided above for a number of deposits in varied geomorphological settings, lithologies, and of varied volumes is a dataset able to be directly used for Boss BREACH^{TM} to analyze breach-development in rock-avalanche dams.

The data do, however, raise interesting questions. Currently Boss BREACH^{TM} can only model a two layer natural dam, the data show that rock avalanches are multilayered by preserved stratigraphic units, with each layer having material properties relating to the source lithology. If rock-avalanche dams fail primarily through overtopping, it is the band type that forms the crest of the dam and the coarse openwork carapace facies (DUNNING *et alii*, 2005) that is of critical importance for breach development and flood modeling.

Although interpreted to occur less frequently, landslide dams do fail through seepage and dam-face failure (DUNNING *et alii*, in press). In such cases the internal sedimentological structure, in particular the GSD's formed by varied lithologies, and the lithology / joint spacing of the carapace play a far more important role. Preliminary modelling using a finite-element continuum code (Flac 5.0, HC ITASCA, 2005) has shown that the rock-avalanche dam failure style is strongly dependent upon internal structural variations. The original source rock lithology, as it controls final deposit GSD, also controls the permeability of the resulting deposit and its resistance to erosion. Modelling under lake filling conditions, based upon the Tsatichhu / Ladrong rock avalanche dam failure (DUNNING *et alii*, in press) resulted in rapid, large scale, catastrophic failure under realistic sedimentology with phreatic tonguing through the carapace. Under test conditions using sedimentologies often inferred in the literature, dam failure did not occur, allowing lake full levels to be reached and a probable overtopping breach.

CONCLUSIONS

Results from the detailed investigation of rock-avalanche deposit sedimentology have been presented. The internal GSD's of the deposits have been shown to be controlled by source lithological variation rather than transport mechanism. Below a coarse carapace that shows what are interpreted to be simple collapse structures along pre-existing discontinuities, the same process appears active at levels in the deposits. The process serves to leave a highly fragmented mass with GSD's that follow a self-similar (fractal) distribution with a value suggesting an excess of coarse clasts, and so preferential fragmentation of these coarse clasts. Although fitting of a Weibull distribution (WEIBULL, 1951) yields values that lead to process interpretations of multiple comminution, as would be expected, the model fit deviates from the data in most cases to an unacceptable level and must be rejected.

Further work is required to establish the role of the internal structure of rock avalanche deposits on the dam breach formation and failure mechanisms. In particular the time in motion required to generate the mature rock avalanche sedimentology described above is unclear. In settings where the runout is low from the valley wall into the final valley blocking position it is possible that the internal structure will not be fully developed. In such cases the resultant deposit sedimentology, as well as providing a snapshot of early transport processes, may undergo failure preferentially through overtopping. Such immature sedimentology, if present, would partially explain the number of overtopping failures observed over those through seepage and dam-face failure. Further research into the sedimentology will continue to yield results applicable to the study of the formation and failure of rock-avalanche dams.

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