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The significance of geology for the morphology of potentially unstable rocks

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Abstract

From a consideration of the concepts of geological weathering and structure, it can be expected that rockfall hazards should be characteristically different in different geological environments. This paper tests this idea by looking at the geometric characteristics of rock fragments formed on natural slopes in four different geological environments in Eastern Australia, where rockfall phenomena are often characterised by rolling of pre-detached debris. By measuring the three principle dimensions and making a systematic assessment of the shape characteristics of samples of rock debris in significant geological environments, it is found that the distributions of size and shape for the surface debris are statistically different. From the results, it is shown that the size and shape of debris is directly controlled by the rock type, its weathering characteristics and the structure of the parent rock mass. The severity of rockfall hazards is shown to be relatively lower in areas of Tertiary basalt, as the size of rolling fragments is limited by closely spaced fracturing inherited from its formation and the tendency to deteriorate further as it weathers deeply and rapidly. It is also lower in areas of Palaeozoic volcanics, since these tend to produce relatively angular fragments with higher proportions of fragments that are inherently more resistant to rolling. By contrast, thickly bedded sandstones form larger blocks with a larger proportion of shapes that are more prone to rolling. The size distribution of fragments is shown to be well approximated by a lognormal statistical distribution, and using the data provided in this study, it is possible to generate the size and shape data needed to undertake a stochastic assessment of rockfall trajectories in different geological environments.

Keywords

rockfall hazard; rock fragment; block; size; shape; geology

1 Introduction

Hazards posed by falling rocks are an important issue to be addressed by engineers and managers in many parts of the world. Not surprisingly, the motion and fate of falling rocks have been the subjects of many studies throughout the applied geosciences literature (eg. Broili, 1973; Budetta and Santo, 1994; Guzzetti et al, 2003; Agliardi and Crosta, 2003; Giani et al, 2004).

Much attention to date has focussed on rockfall environments where the hazards are severe such as in alpine areas, where large blocks of rocks, or sections of rock mass can detach from high cliffs in steep, topographically-immature valleys (Azzoni et al, 1995). In such environments Paronuzzi (2009) observes that “most single blocks move downslope by parabolic rebounds in the air”. However, the significance of rockfall extends well beyond this, to the widespread occurrence of undulating/rolling topography, where already-detached rocks on more moderate slopes can pose a potential hazard through motions dominated by “rolling”.

The particular characteristics of motion of a “falling” rock depend strongly upon the steepness of the slope (Ritchie, 1963; Dorren, 2003). However, whether a rock can fall (fall, bounce and/or roll) in a sustainable way, and its resultant trajectory, depends on many factors. These include characteristics of the slope (roughness, steepness, material) and characteristics of the block (shape, size, substance (strength, resilience)) (Ritchie, 1963; Pfeiffer and Bowen, 1989; Giani, 1992; Azzoni et al, 1995; Agliardi and Crosta, 2003). This paper considers the relationship between geological origin and the size and shape of rocks that present as hazards on slopes in regions of moderate topographic expression.

2 Size and shape of rock fragments

2.1 The significance of size and shape

Whilst slope morphology and steepness exert major controls over whether motions are dominated by bouncing or rolling (Ritchie, 1963), the size and shape of blocks significantly affect the precise trajectories (Pfeiffer and Bowen, 1989), and the severity of associated risks to life and property. It is readily apparent that larger rocks pose greater hazards, all other things being equal. The size of a mobilised rock, or more precisely, the size of the rock relative to the slope surface roughness (Pfeiffer and Bowen, 1989) also controls the likelihood that its motion will or will not be sustained (Dorren, 2003). Also, as larger rocks have greater physical size and greater momentum, they are less likely to lodge amongst irregularities on a slope of given roughness (Ritchie, 1963).

The shape of blocks has a significant effect on the ease with which motion can be initiated: in the context of pre-detached debris on slopes, more-angular blocks with a smaller number of flat faces are inherently more stable than rounded blocks. The shape of blocks also affects the extent to which rolling will be sustained, and the randomness of the motions generated during impact (Kobayashi et al. 1990). In particular, as the angularity of blocks increases, the tendency for transitions between translational and rotational motions increases (Pfeiffer and Bowen, 1989).

Information on the size and shape of falling rocks is important for most methods of rockfall motion prediction, to greater or lesser extents. Azzoni et al (1995) observes that to carry out correct analysis of in situ tests, it is crucial to determine, as carefully as possible, the geological and geomechanical characteristics of the falling blocks and the slope, and that the characteristics of motion after impact are heavily conditioned by the block's shape. Bourrier (2009) considers that trajectographic modelling remains highly speculative since the information available on the mechanical and geometrical properties of the soil is not sufficient. Dorren (2006) concludes that for further

improvement of rock fall simulation on different slope types, more quantitative data is required on rock shape as well as the rock size.

Advances in computer hardware and software now make it possible to perform complex dynamic analyses taking actual block shape into account (Maeda 2009; Lisjak and Grasselli, 2010). Agliardi and Crosta (2003) considers that the accuracy and precision in the description of the block shape and mechanical properties is usually so low that complete dynamic analysis is prone to sum up an unacceptable amount of error. This clearly points to a need to improve our understanding of rock shape in rockfall environments.

2.2 Our understanding of size and shape.

There is surprisingly little in the scientific literature to assist our understanding of the likely size and shape of potentially falling rocks in different geomorphic environments. It has been recognised that the outcomes of fragmentation processes are often populations of fragments with log-normal size distribution, but these are not contextually specific (Turcotte, 1997). For rocks that might detach from exposed rock masses, there are texts on structural geology that present general information on rock mass structure, with reference to different geological settings (eg. Suppe, 1985), and works on rock mass structure characterisation (eg. Kalenchuk et al., 2006). There are also papers, which for a variety of purposes, describe case studies which report site specific data that relates fragment size to rock mass structure (Agliardi and Crosta, 2003; Latham et al., 2006; Topal et al., 2007; Sturzenegger et al., 2011), but whilst they might describe the hazard of rocks that might detach from cliffs, these are not directly applicable to the characteristics of detached rock debris on hill slopes.

For rocks that occur as pre-detached fragments in geological environments, existing information on size and shape is rare. Some consideration has been given to the size and shape of fragments in natural sedimentary environments such as rivers and beaches (Sneed and Folk, 1958; Dobkins and Folk, 1970; Miura et al 1998) but its relevance to the rockfall problem is small. Some consideration has been given also to rock fragments that are occurring as residuum or debris in soils, from agricultural and landform evolution (soil loss) perspectives (Flint and Childs, 1984; Le Roux and Vrahimis, 1987; Parsons and Abrahams, 1987; Poesen and Lavee, 1994a, 1994b; Simanton and Toy, 1994; Ugolini et al., 1996; Poesen et al., 1998) but its relevance is also limited.

2.3 Basis and approach for this study

The shape and size of rock debris is a function of the rock type and the processes that have caused it to become a fragment in its current situation. More specifically, the morphology of rock fragments is determined by the rock material and its fabric, the primary structures imparted to it during its formation, the additional structures imparted to by subsequent tectonic processes (the so-called “tectonic imprint”; Coe and Harp, 2007), the processes responsible for its detachment from the rock mass and the weathering environments it has been exposed to (Lindholm, 1987).

The first four of these factors collectively determine the rock mass structure. They are related through the geological setting (past and present) in which the rocks occur, and they are largely independent of where in the world the rocks occur. For example, undeformed sedimentary basins typically exhibit a fundamental jointing system (Mandl, 2005) comprising systematic tension jointing which is perpendicular to bedding (Hobbs, 1967; Narr and Suppe, 1991). These commonly comprise 2 sets of orthogonal joints (Mandl, 2005) with a spacing which is similar to the thickness of the bed they are developed in (Narr and Suppe, 1991). As a consequence, beds of sandstone and conglomerate in undeformed sedimentary basins tend to comprise relatively equi-dimensional orthogonal (cubic) prisms in the rock mass.

By contrast, mildly deformed sedimentary basins (fold belts) exhibit additional tectonic joint sets (eg, Coe and Harp, 2007). These include cross joints (Bai et al. 2002), strike joints (Engelder and Geiser,

1980) and oblique joints (Price, 1959). As many as 5 or 6 joint sets may coexist. Sedimentary beds in these environments, which are usually inclined, tend to comprise more rectangular and/or rhombohedral and triangular prisms in the rock mass than their un-deformed counterparts.

Volcanic and ignimbritic units have a fundamental jointing system of cooling/shrinkage joints, which are generally oriented perpendicular to the bed surfaces and which may display a columnar arrangement, developed to greater or lesser extents (Suppe, 1985; Spry, 1961; Fityus et al, 2010). Undeformed volcanic units (eg, Tertiary flood basalts) typically comprise polygonal prismatic blocks in the rock mass. Volcanic units in deformed environments (eg, within folded fore-arc basin sequences) may be overprinted by tectonic joints, making the blocks within the rock mass smaller, less prismatic, and consequently, more irregular.

The processes which produce large debris from an intact rock mass are mostly environmentally controlled. They include detachment, weathering and possibly erosion processes, though not necessarily in this order. The variety of specific processes within these general categories varies greatly from alpine to tropical environments (Robinson and Williams, 1994). Invariably, water, temperature and salts play important roles, but to differing extents (Hall, 1999; Evans, 1970; Doornkamp and Ibrahim, 1990). A common factor, however, is the occurrence of these processes in the ground/soil and, to some extent conditions in the ground are less variable than on the surface.

It is the premise of this work that the morphological characteristics of blocks formed from similar basic geologies, in similar physical environments, will have similar and characteristic size and shape distributions. Hence, it is possible to characterise the size and shape distributions of potentially unstable debris for general geological settings, and to use this information in any region where similar geological and environmental conditions prevail.

This premise is tested here in the context of rock fragments derived from a variety of common geological settings, encountered in the physical environment of New South Wales (NSW) in eastern Australia, where the management of hazards posed by detached rock debris on slopes is a significant and resource-intensive issue. To test the premise, we have surveyed populations of loose rocks, occurring naturally on “undisturbed” slopes in geologically different regions, to determine their shape, dimensions and basic morphology. The statistics derived from the survey data are compared to determine if there is a characteristic difference between the rocks that would pose hazards in different geological environments.

3 The geological environments of New South Wales, Australia

The rockfall hazard of New South Wales is mostly confined to its eastern margin (Leventhal and Kotze, 2008), where topographic expressions associated with the Great Dividing Range and the Great Escarpment (Ollier, 1982) are sufficiently great to accommodate rockfall phenomena. The geology of this area, shown in Figure 1, is largely made up of a number of identifiable regions of differing type and origin, mostly of Palaeozoic age, or younger (Branagan and Packham, 1967). The primary geological environments comprise Palaeozoic fold belts, granites, undeformed Permo-Mesozoic sedimentary basins Tertiary flood basalts. The units relevant to the present study are contextualised in the following:

The Lachlan and New England Fold Belts: While the Lachlan (older, more southerly) and New England (younger, more northerly) fold belts are clearly differentiated in space and time, their geological characteristics have much in common, and so can be considered collectively for the purposes of this study. These comprise sequences of marine and terrestrial sediments with interbedded volcanics and tuffs, deposited in a variety of settings including deep water (turbidite), island-arc fore-arc and back-arc (Fergusson, 1991; Fergusson and Coney 1992). These sedimentary

and volcanic rocks were accreted onto the continental margin by a series of subduction zones that stepped progressively eastward throughout the Palaeozoic (Cawood and Leitch, 1985; Gray 1997), and display additional tectonically-derived structural features, accordingly.

In general, those lithologies more directly associated with accretion and subduction are more heavily structured and metamorphosed. As a consequence, the units that would produce potentially unstable rock debris are:

- sandstones and conglomerates of the fore-arc basin, which occur as moderately to steeply dipping beds which display between three and six well-developed sets of joints. These range from lithic in nature to quartzose, and commonly they contain a significant reworked volcanogenic content (Roberts et al. 1991). Their lithification mostly confined to the diagenetic (zeolite) zones, and though they may be slightly metamorphosed (Offler, 2005) they do not display significant foliations.
- Volcanics (lavas and ignimbrites) mostly of acid and intermediate varieties, which occur as moderately to steeply dipping beds and which display well-developed jointing, including roughly polygonal cooling joints and subsequent tectonically-induced joints.
- Metamorphosed sediments from accretionary wedges comprising quartzites, slates and phyllites. They display tectonically-induced joints and foliations that are commonly sub-vertical. (Offler, 2005; Philips et al 2010)

Permo-Mesozoic Sediments: these mostly include the Permian Sydney basin (Herbert and Helby, 1980) and its Gunnedah basin extensions. They occur as relatively flat-lying, undeformed sedimentary sequences that display typical sedimentary structures and fabrics and usually only primary, non-diastrorphic jointing. Because of the strong pelitic and lutitic character of the coal measures sequences, these are not usually associated with strong topographic expression and are not recognised as significant sources of rockfall hazard. By contrast, the Narrabeen group and Hawkesbury sandstones of the Triassic are typified by resistant quartz arenites that form steep topography that is littered with debris. These are differentiated in Figure 1.

Basalts: The basalts of NSW occur mostly along the Great Dividing Range, as a consequence of the widespread intraplate volcanism that coincided with the uplift of the eastern Australian highlands during the late Mesozoic and early Tertiary (Johnson et al. 1989). Wellman and McDougall (1974) suggest that the majority of basalts are the result of either central volcanoes (large volcanic complexes) or lava fields (fissure-swarm eruptions). Johnson et al. (1989) report that mafic rocks in NSW comprise mainly alkali basalts, hawaiites and tholeiitic basalts, but they are more commonly of undersaturated or near-undersaturated varieties. The fundamental structure of basalt rocks is columnar jointing (Suppe, 1985; Spry, 1961), generally at relatively close spacing (Fityus et al 2010), Pyroxenite xenoliths are a common feature and venticulated horizons are common. Tectonic fractures are mostly absent.

Anecdotally, the rock fragment debris from each of these environments in eastern Australia has its own characteristic distribution of sizes and shapes. Until the present study, these characteristic differences have neither been confirmed nor quantified. This study has focussed on surveys carried out in four of the primary geological environments identified above. These are

- Bedded lithic sandstones from the folded and faulted Palaeozoic rocks of southern New England Fold Belt
- Bedded felsic and intermediate volcanics and ignimbrites from the folded and faulted Palaeozoic rocks of southern New England Fold Belt
- Thickly bedded quartzose sandstones from the near-horizontally bedded Triassic Narrabeen group of the Sydney Basin
- Tertiary basalts.

Figure 1. Major geological subdivisions of New South Wales, Australia. (note: where regions are undefined, they comprise Quaternary sediment or in-substantial outcrop; the white line indicates approximate axis of the Great Dividing Range and the yellow line, the Great Escarpment)

4 Methods

4.1 Surveys

For each of the studied geological environments, surveys of between 130 to 200 fragments were made at sites where debris was littered on steep slopes. For each environment, surveys involved sampling 30 to 50 fragments at each of 3 to 5 different sites, chosen so that they included a variety of typical geomorphic environments such as on the outcrop/subcrop and at the base of the slope. The survey sites were all within a 200km radius of the city of Newcastle, as shown in Figure 1.

Surveys comprised assessments of the basic geometric form of each fragment, the number of flat and curved bounding surfaces, the presence of flaws that might cause it to fragment, and measurements of its three principal dimensions. Since the underlying purpose of this study is to understand rockfall hazard characteristics, the minimum size of blocks surveyed was 20cm since it is considered that blocks smaller than this, that find their way onto transportation infrastructure, do not pose a significant hazard to the majority of moving vehicles (Austroads, 2003).

4.2 Assessment of size

The three principal dimensions (d_{max} , d_{mid} , d_{min}) of each block were measured with a retractable measuring tape. The maximum dimension, d_{max} , was taken to be the longest dimension of the block. The minimum dimension, d_{min} , was the smallest dimension measured in a direction perpendicular to d_{max} . The intermediate dimension, d_{mid} , is measured perpendicular to both d_{max} and d_{min} . This process was relatively straight forward, except for larger blocks that were partially embedded in the slope. Where smaller blocks were partially embedded, efforts were made to extract them to accommodate accurate measurement of all dimensions. For larger blocks that could not be extracted (relatively few: <5%) the full set of dimensions could only be estimated on the basis of judgement.

4.3 Assessment of basic form

Assessment of shape is not a simple task, since there are an infinite number of possible fragment shapes, and transitional shapes between basic forms. Sedimentologists have defined a number of classifications, some related to quantifiable or semi-quantifiable indices, to define particle shape (Waddell, 1935; Lindholm, 1987; Reinech and Singh, 1975). These include sphericity, roundness and form. There is considerable disagreement, however, how these should be defined (Sneed and Folk, 1958) and how they should be determined objectively (Blatt et al. 1980).

Since the purpose of the study was to explore the relationship between block geometry and geology in the context of the rockfall problems, the characterisation of shape used is related to the significance of shape in regard to the inherent tendency of a block to roll and to sustain a rolling motion. To this end, we defined a series of basic forms that can be generally grouped into 5 shape families, characterised by particular rolling behaviours and based on our experiences of in situ rock rolling studies (Spadari et al, 2012). The basic forms are shown in Figure 2 and defined as:

Figure 2. Basic forms for the classification of block shape.

Ball forms. These are generally defined by geometries where $d_{max} \approx d_{mid} \approx d_{min}$. They are generally made up of many surfaces (>5) and their rockfall motion on relatively flatter slopes is characterised by steady rolling in a consistent direction. They include spheres, cubes, and octahedra.

Cylinder forms. These are generally defined by geometries where $d_{max} > (d_{mid} \approx d_{min})$. They generally have a relatively uniform cross section along their length and their rockfall motion is characterised by steady rolling in a consistent direction, with their longest axis approximately normal to the slope direction, but they are sensitive to obstructions and may arrest suddenly if their axis is caused to align in the direction of the slope. They include cylinders, prisms and elongated rhombohedra.

Disc forms. These are generally defined by geometries where $(d_{max} \approx d_{mid}) > d_{min}$. They are generally made up of 2 principal surfaces (parallel and separated by d_{min}) and once initiated, their rockfall motion is characterised by fast rolling and bouncing (like a wheel) in a consistent direction. However, motion is difficult to initiate, requiring the plane of the disc to be perpendicular to the ground surface and parallel to the slope direction, and it will arrest suddenly if the face of the disc becomes parallel to the slope surface. They include discs, square and polygonal tablets and hemispheres.

Cone forms: These are generally defined by conical or pyramidal forms dominated by a single large face (base) and a sectional area that reduces toward an apex with perpendicular distance away from the face (usually $d_{max} > (d_{mid}, d_{min})$). These forms are inherently resistive to sustained rolling, tending to roll around the apex until they come to rest pointing up the slope. They include pyramids and cones.

Acute forms: These have few common characteristics other than that they typically have a relatively small number of faces and mostly acute angles. They exhibit relatively little tendency to initiate or sustain motion. They include wedges, tetrahedrons, slabs and disphenoids.

Examples of these are shown in Figure 3

Figure 3. Examples of measured samples with a variety of basic forms.

The examples in Figure 3 show blocks that closely conform to the precise geometric form assigned to them. More commonly, natural blocks are not so easily assigned a form. In situations of irregular blocks where a precise geometric form is not clearly apparent, the assigned form was assigned the additional term “irregular”. In deciding on which form should be assigned in such cases, consideration was given to how the block would roll: that is, would its motion be more like that of a ball, or a cylinder, or a disc etc. Clearly, this is a subjective process, requiring judgements to be exercised. In the present study, the observations were made by three field workers. To reduce the potential for bias in the result, each of the three field workers was involved in surveying blocks in the different geological environments, and checks were made to ensure that they were making consistent shape determinations for the same blocks.

4.4 Other observations

An evaluation was also made of the “roundness” of the blocks, in terms of how many flat and curved surfaces it displayed. Ideally, a cube would have six flat surfaces and a sphere would have a single curved surface. However, an irregular sphere (or a block with the basic rolling characteristics of a sphere) might actually be made up of several flat and/or curved surfaces. Curved surfaces refer exclusively to convex surfaces: concave surfaces were classified as flat since they have a similar influence on the rolling motion as do flat surfaces. The interpretation of the distribution of faces on a block is also subjective, in that blocks are often found to have increasing numbers of faces of decreasing size, if the detail of the examination is increased. Again, the implications for rolling motions were used to determine what constitutes a “face”. As a rule, if a face was considered big enough to individually affect the motion of block, it was counted in the survey. Another aspect prone to subjectivity was that of flat faces and curved faces, as a series of flat faces with obtuse internal angles tends to behave as a single curved surface. Also, curved surfaces can be compound (ie. made up of curves of differing radii). Checks were again made to ensure consistency of judgement between researchers.

The final observation for each block was whether it had apparent features/ flaws that might increase its likelihood of fragmentation should it roll or for. This was generally easily determined.

5 Results

The summary statistics of the sizes and shapes of measured blocks for the four different geologies is shown in Table 1.

parameter	Palaeozoic volcanics	Tertiary basalts	Palaeozoic sandstones	Narrabeen sandstones
# samples	141	197	149	137
$d_{\max}$ (cm) [min-max (average)]	12-234 (58)	15-62 (33)	20-310 (66)	20-370 (224)
$d_{\min}$ (cm) [min-max (average)]	4-94 (26)	7-45 (19)	4-160 (33)	10-200 (53)
d_{mid} (cm) [min-max (average)]	8-150 (40)	12-52 (25)	15-200 (49)	18-230 (81)
d_{average} (cm) [min-max (average)]	8-130 (41)	13-53 (25)	13-220 (49)	18-260 (83)
total # faces (average)	5.07	6.00	5.42	5.26
# flat faces (average)	4.27	4.84	4.35	4.35
# curved faces (average)	0.80	1.16	1.07	0.91
% defected blocks	39	76	31	44

Table 1 Summary statistics for the surveyed blocks.

It is apparent from Table 1 that blocks from the different geological environments are similar in some aspects and different in others.

5.1 Size

The most obvious difference in the debris from the different geological environments is in the size of the blocks that occur. Narrabeen sandstones have significantly greater average block sizes, whilst the basalts have significantly smaller sizes. This is illustrated in greater detail in Figure 4, which shows the frequency distribution of the average block size for each geological environment, superimposed on the same figure. It is clear that the mean size of basalt fragments is predominantly between 10 and 50cm, and does not exceed 70cm, whereas the Narrabeen sandstone blocks in the survey are predominantly between 20 and 100cm, but are present in small but consistent numbers up to a maximum of 270cm. The Palaeozoic sandstones and volcanics are most similar, with relatively similar mean dimensions, but a greater range of larger fragments amongst the sandstones.

The size characteristics of the different geologies can be quantified by describing their statistical distributions using familiar statistical functions. It is apparent from Figure 4 that the distribution of mean particle sizes in each case is asymmetric, being skewed toward the smaller sizes. Such a distribution lends itself to approximation by a log-normal distribution (Turcotte, 1997; Sturzenegger et al., 2011). A parameter (such as the mean block size) is log-normally distributed if the log of the parameter is normally distributed (Aitchison and Brown, 1957; Crow, and Shimizu, 1988).

In Figure 5, the fragment size distributions for each rock type are plotted together with log-normal approximations, generated using the mean and variance values derived from the measured population of fragments. The parameters used to generate the log-normal distribution are presented in Table 2.

Figure 4. Block size frequency distributions for the four different geological environments.

Figure 5. Block size frequency distributions with corresponding log-normal approximations for the four lithologies studied.

It is apparent from Figure 5 that the particles in each case are generally well approximated by a log normal distribution, although there does appear to be a small but systematic underestimation of the cumulative frequency for any particular sized fragment. This is possibly the result of limiting the size of the smallest fragment measured to about 0.2m, as was noted by Sturzenegger et al. (2011).

It is interesting to note from the data in table 1 that the mean of the average block size ($d_{average}$) in each case closely matches the mean of the intermediate block size, d_{mid} .

parameter	Palaeozoic volcanics	Tertiary basalts	Palaeozoic sandstones	Narrabeen sandstones
# samples	141	197	149	137
mean of $d_{average}$ (cm)	42.3	25.3	49.2	84.8
variance of $d_{average}$ (cm)	685.2	56.38	960.7	3373
mean of $\ln(d_{average})$	3.56	3.19	3.76	4.23
variance of $\ln(d_{average})$	0.320	0.078	0.252	0.382

Table 2 Statistical parameters for the measured populations used to generate the log-normal distributions in Figure 5.

5.2 Shape

The data in table 1 suggests that there are some small but distinct differences in the shape characteristics of fragments produced in the different geological environments. The Tertiary basalts generally exhibit a greater number of both flat and curved faces. Conversely, Paleozoic volcanics generally exhibit a smaller number of both flat and curved faces. Despite their genetic differences the two sandstones are relatively more similar in shape, although the more structurally deformed Palaeozoic sandstones show a tendency to a slightly greater number of faces.

Figure 6 compares the relative distribution of basic forms within the different geological environments. In general, fragments from the different geological origins have their own particular distribution of basic forms, and although the differences are significant, all results generally follow a trend of cylinder and/or disc form being dominant (around 60% in total) with ball, cone and irregular forms being relatively less frequent. Some specific observations include:

Figure 6 Frequency distribution of basic forms according to geological environment.

- The Palaeozoic volcanics generate a significantly greater proportion of cone forms, a relatively large proportion of acute forms and relatively smaller proportions of ball, cylinder and disc forms.
- The Tertiary basalts generate relatively larger proportions of acute and cylinder forms and relatively fewer ball and disc forms.
- The Palaeozoic and Narrabeen sandstone fragment shapes are the most similar, with relatively fewer acute forms, but with Narrabeen tending to more cylinder forms, and the Palaeozoic sandstones tending to more balls and discs.

Figure 7 presents more detailed data on the specific forms within each of the samples fragment populations. From Figure 7, the following additional observations can be made:

- The Palaeozoic volcanics generate a significant number of pyramids, hemispheres and discs.
- The Tertiary basalts generate relatively significant proportion irregular discs, prisms and wedges.
- Although the Palaeozoic and Narrabeen sandstone fragment shapes are most similar, considered in terms of basic forms, their distributions of specific shapes have less in common. The Narrabeen tends to have a somewhat limited distribution of shapes, dominated by discs, hemispheres and prisms, whereas the Palaeozoic sandstones tend to display more variety with a better distribution of shapes among the ball and disc forms.

6 Discussion.

6.1 Geological Considerations

The results confirm that the size and shape characteristics of naturally occurring rock fragments are specific to the geological origin. They suggest that both size and shape are controlled by geological environment, although the significance for size is greater.

These outcomes are consistent with what might be suspected on the basis of geological principles. The typically smaller size distribution of basalt fragments is consistent with what would be expected from a mafic volcanic parent rock that is already affected by closely-spaced, cooling-induced columnar fracturing (Fityus et al, 2010). The closely-spaced fractures, in combination with its strongly mafic character (silica undersaturated), and the presence of feldspathoid minerals, ultramafic xenoliths and vesicles, make this rock highly susceptible to in situ weathering in low outcrops and in subcrop (Siegesmund and Török, 2011). The net result of these factors is that the already fractured rock mass becomes further deteriorated during the process of becoming exposed, and those fragments that survive to pose a rockfall hazard are relatively small and frequently flawed, as indicated by the data in Table 1.

It is interesting to note that there is some inconsistency between the shape data in Figures 6 and 7 and the shapes that might be inferred from the data on the number of faces in Table 1. Basalt debris was found to have the greatest average number of faces, which would suggest that it is prone to occur in rounder forms. However, the shape data shows that basalt has the greatest proportion of acute and relatively fewer ball forms. This inconsistency can be reconciled by observing that, although basalt fragments tend to become rounded during weathering, their propensity to be flawed and prone to planar fracture means that they are continually producing polygonal fragments of increasing geometric complexity as they undergo size reductions.

Figure 7 Frequency distribution of shapes according to geological environment.

The results for the Palaeozoic volcanics are consistent with both expectation and anecdotal experience, in that felsic volcanics commonly tend to produce more angular surface detritus than do other rock types. Like the basalts, the felsic and intermediate volcanics of the Palaeozoic occur as heavily columnar-jointed rock masses, although at typically wider spacing. However, unlike the basalts, they are pervaded by additional sets of tectonically-induced fractures from their subduction zone setting. As a result, the fragment size of Palaeozoic volcanic is greater than that of the basalts, though not substantially so. More significantly, the Palaeozoic volcanic are more siliceous, and so, weather more slowly, are more resistant to becoming rounded and produce much thinner soils. Accordingly, the measured data records that they present the greatest number of angular/acute forms and the smallest degree of rounding.

The results for the Narrabeen and Palaeozoic sandstones are most similar, as might be expected from their common origin as thickly bedded units. Their systematic differences are, however, also consistent with expectation. The mean size of Narrabeen blocks is larger, reflecting the thicker beds typically encountered in the Narrabeen (up to 8m) and the absence of jointing except for the primary non-diastrorphic joints inherited from their formation in a sedimentary basin. As these typically comprise two orthogonal sets that are perpendicular to the sedimentary beds, they tend to define prismatic blocks in subcrop, with a tendency to produce large debris with ball and prismatic forms. The additional tectonically-induced joints in the Palaeozoic sandstones contribute to a reduction of block size and an increase in the diversity of geometric form produced. Whilst this generally accords with the measured data, the Palaeozoic sandstones do produce the greatest proportion of ball forms. This is probably because they are more prone to become rounded through weathering than the quartzose, Narrabeen sandstones, which produce the smallest average number of curved surfaces.

It is significant that the four geological environments studied do not present any significantly foliated rocks. This makes the characteristic distributions of size and shape noted above more significant in that they are developed in what are geomaterials without strongly developed fabric anisotropy. It would be expected that in foliated rocks, the tendency to produce disc and acute forms would be substantially greater (Lindholm, 1987).

6.2 Significance for rockfall engineering.

The data presented in this work suggests that the severity of the rockfall hazard from detached debris encountered in different geological settings is systematically and predictably different.

Whilst these results were specifically derived for sites in eastern Australia, they are potentially applicable to analogous geological settings anywhere around the world. Results for the Narrabeen sandstone, for example, will have relevance for any other undeformed sedimentary sequence such as Paraná basin on the South American Platform, the Ordos basin in China, the Taoudeni, Chad and Bida basins of West Africa and sequences within Basin and Range Province of the south west USA. Similarly, the data for Palaeozoic fold belt sandstones is significant for areas within (but not exclusive to) the Cape Fold Belt in South Africa, parts of the Valley and Ridge Province of the Appalachians in the USA, and the Ventana mountains of Argentina. Data for the Tertiary flood basalts, which are widespread worldwide, will be applicable to areas on nearly every continent including Paraná traps in South America, the Deccan Traps of India and the Karoo region in Africa.

The data presented in this paper is useful in the rigorous quantitative determination of design parameters for rockfall protection measures in the different geological environments. The size distribution data, described by a log normal distribution, could be used in conjunction with the shape distribution data, to undertake a stochastic modelling of rockfalls in these environments to estimate likely rockfall trajectories at the base of natural slopes.

For the geological settings studied, the basalt areas pose relatively the smallest hazard, since the mean block size is around 0.25m, with mean maximum block dimensions of around 0.5m and these are commonly deriving from deep soil profiles. Modelling of basalt slope rockfalls should assume that around one third of all fragments are likely to adopt the rolling motion of a cylinder, whilst only around 15% of fragments are likely to roll as balls. Hence, rockfall interception structures need only be designed for relatively low energy impacts: for a likely rolling speed of 10m/s, the energy of the largest block is unlikely to exceed 10kJ.

Although the mean size of Palaeozoic volcanic fragments is somewhat larger than those of basalt (0.42m) and considerably larger maximum dimensions are possible (in excess of 2m), these geological environments produce a significantly greater proportion of relatively stable (cone and acute) forms, and so, all other things being equal, blocks in these environments have relatively less chance of initiating and sustaining a rolling motion. Also, their tendency to produce angular debris within thin soils makes them more prone to evolve rougher slopes that further impede rolling motions. Again, relatively low energy barriers are likely to be appropriate, although their more angular nature gives them a greater tendency to acquire higher energy rotations, and so, some design consideration should be given to accommodating this.

In both sandstone environments studied (tectonically deformed and undeformed), the debris is dominated by cylinder and disc forms (around one third of each) and with significant ball forms (around 20%). This greater proportion of potentially more unstable shapes, together with considerably greater mean and maximum block sizes, makes it more likely that larger rolling blocks will be encountered in such environments.

7 Conclusions

The results of this study confirm that the geometric characteristics of rock debris, which are significant for the assessment of rockfall hazards on rock-littered slopes, are systematically characteristic of the particular geological environment in which they occur. The rock type, the structure of the parent rock mass and the processes of producing detached debris, all combine to control the size and shape of the blocks that are formed. For the limited variety of geological settings considered here, it is generally observed that volcanic parent rocks produce a greater proportion of more stable (less inclined to roll), angular forms, whereas sandstones tend to produce larger debris with a greater proportion of geometric forms that more prone to roll.

The ongoing development of new and improved methods of rockfall analysis has seen strong emphasis directed at simulating the mechanistic processes, with relatively little attention paid to the associated geological phenomena. This paper refocusses some of the rockfall research attention back onto the significance of geology in rockfall phenomena. With the availability of quality data on the size and shape of potentially unstable rocks, there is renewed opportunity to reconsider the methods of analysis currently employed to make rockfall assessments. The data suggest that block shape varies widely and characteristically with geology, to an extent beyond that which can be readily accommodated by existing rockfall codes. The results of this work will be useful as the application of DEM to rockfall analysis (Bourrier et al., 2011) continues to gain popularity, making the inclusion of specific block shapes more tractable.

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