SUBSIDENCE BRECCIAS IN KIMBERLITE PIPES – AN APPLICATION OF FRACTAL ANALYSIS

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INTRODUCTION

Volcanic breccias form in a variety of ways and the study of such breccias offers insight into the dynamic processes that can characterise a volcanic event. The description, characterisation and interpretation of volcanic breccias related to kimberlite pipes is a fundamental aspect of current kimberlite emplacement models. The breccias found in kimberlite pipes show a wide spectrum of highly variable rock types, from the 100% fragmental kimberlite breccia to the country rock breccia with greater than 90% xenoliths. More often found near the external kimberlite contacts, these country rock breccias may be bedded or massive, mono- or heterolithic, and the clasts may vary from angular to well-rounded.

This study describes a particular variety of country rock breccia; a contact breccia without any juvenile kimberlite component that has been observed by the author at Venetia, The Oaks, River Ranch, and Wimbledon kimberlite pipes. The breccias are likely to have a complex history depending on the complexity and nature of the volcanism, but the question is asked whether the primary brecciation mechanism is by volcanic explosion, hydraulic implosion or subsidence wear abrasion. The clast size distributions and clast shapes can be compared to that from mine-blasted muckpiles using industrial explosives, and from open pit slope talus caused by gravity induced rockmass failure.

In the blasting sciences and particularly in the metallurgy industry particle size distributions are normally compared with empirical distributions such as the Rosin-Rammler and Weibull distributions. Brown and Wohlertz (1995) have shown that the Weibull distribution can be calculated from physical principals, and that the Rosin-Rammler is a derivative of the Weibull function. They also establish mathematically the association of the Weibull distribution to the more fundamental fractal dimension (Ds) that governs the scale-independent growth of cracks during fragmentation. The fractal dimension may therefore be indicative of the fragmentation mechanism in breccias.

Fractals are being used ever more extensively in geology (e.g. Yielding, et al., 1992) and volcanology specifically (e.g. Dellino and Liotino, 2002). One form of the fractal equation is $N(r) = k\ r^{D}$, where r is the radius of the particle, k is a constant, N(r) is the number of particles of radius greater than r, and D is the fractal dimension. On a log-log plot of cumulative particle frequency versus particle radius, a fractal distribution appears as a straight line with a slope of -D. A fractal

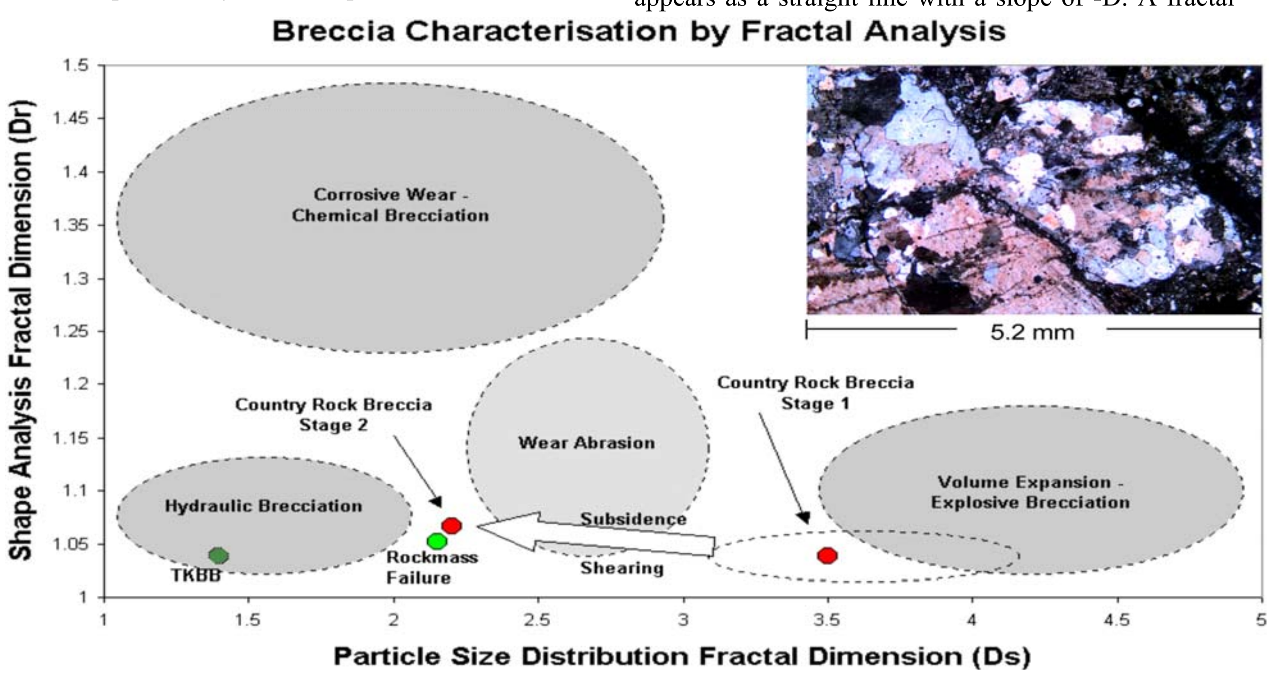

Figure 1: Modified after Jébrak (1997). Typical Ds and Dr values for some breccias types are shown as a guideline. Averaged results from this study are plotted, showing how subsidence of breccias reduce the Ds value. The inset photo is from a thin section (from drill hole HDH2) showing re-fragmented breccia clasts.

distribution has no mean value, the calculated mean depends on the scale of the measurement (Jébrak, 1997).

Similarly, fractals are used to describe the complexity of a particle shape. Simplistically, if the particles edge (analysed as a line) appears self-similar (looks the same at any scale), the boundary can be defined as fractal. In reality geological particles are never true fractals, but show only fractal behaviour over a finite scale. Bérubé and Jébrak (1999) discuss and compare the various techniques used for boundary fractal analysis. The shape analysis technique used in this study was that of box-counting (Roach and Fowler, 1993). The author used the FracLacCirc plug-in, written by A. Karperien for the freeware program ImageJ (derived from the NIH imaging software). Box-counting is considered slower and less accurate than other methods, particularly since it underestimates the fractal dimension at higher fractal values (Bérubé and Jébrak, 1999). However, the results for this study show low fractal values and the average of 30 runs was taken per outline, each run with a different box/grid starting position in order to remove sampling inaccuracies.

Jébrak (1997) classify breccias based on properties that include the size distribution fractal dimension (Ds), the shape fractal dimension (Dr), the roundness (perimeter^2/area), circularity (4π*area/perimeter^2), dilation and fabric (figure 1). This paper attempts to similarly classify the country rock breccias in the study area from photographs and drill core logs.

Sheared Country Rock Breccias

Figure 2 show the locations of the samples taken around the Venetia kimberlite cluster. Samples taken in the open pit are scaled photographs on which each visible clast has been manually outlined. A massive county rock breccia, at least 150m wide, was identified by the author on the western side of the River Ranch open pit in Zimbabwe. The analyses of photographs of the River Ranch breccia are included in this section.

The breccias photographed in the pit face are clast-supported and have angular fragments, as well as a penetrative shear-fabric that dips towards the main kimberlite body. This is seen at Venetia (Kurszlaukis and Barnett, 2003) and at River Ranch where a strong fabric dips towards the kimberlite pipe (N81^{o}E) at 32^o, very close to the friction angle of the rocks. The author considers this shear fabric to be distinctive of this type of breccia and is often enhanced by preferred clast orientations parallel to the fabric. The larger clasts are typically joint bounded, with one flat, joint-controlled side lying on or parallel to the shear planes. The larger clasts also show signs of shearing apart. In this latter case dilation between the clasts is very low, but in general the clasts cannot be pieced together and dilation (in the absolute sense) must be high. However, clasts are tightly packed together with no siliceous or carbonate cement. Drill core samples of the same breccia (drill core HDH2) often show clasts with a sandy, medium-grained matrix and secondary carbonate veining. The source of the carbonate is most likely the kimberlite itself, and was introduced by carbonated aqueous solutions after brecciation.

The clasts are monolithic in the sense that they derive from the local country rock, which is itself a heterogeneous mix of feldsphathic and biotite gneisses, biotite schists and amphibolite that is typical of the Limpopo Metamorphic Belt. The clasts are well mixed, but do not contain the shale clasts that are so abundant in the heterolithic kimberlite breccia facies filling the

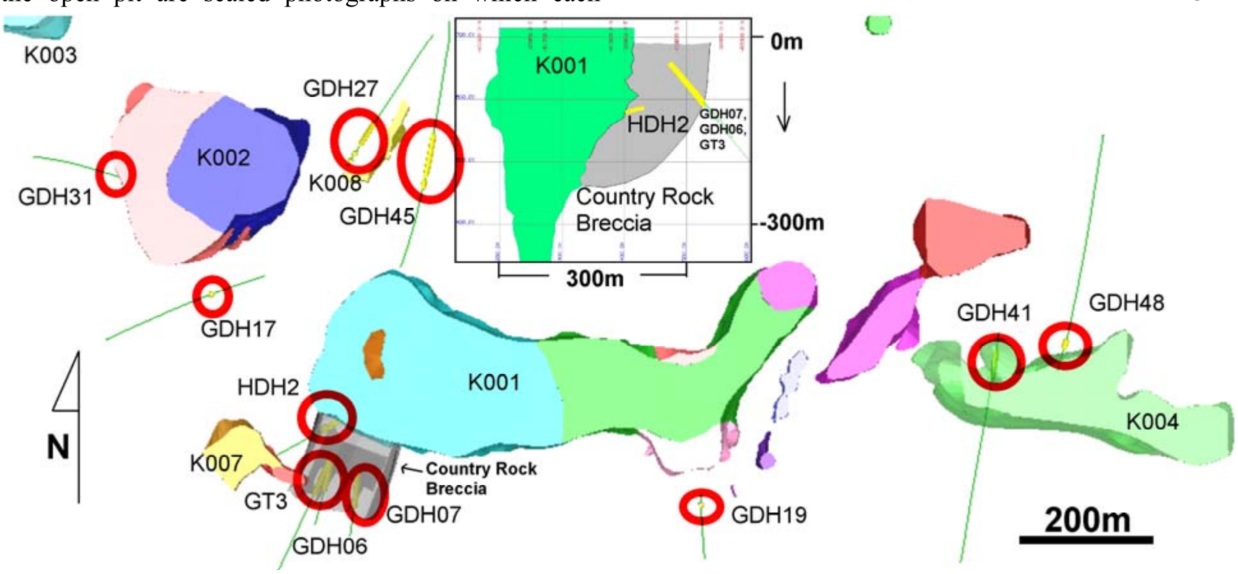

Figure 2: The figure shows the location (red circles) of the drillhole samples taken around the Venetia pipes for this study. Photographs taken in the pit were from same areas as those marked GDH41 and GT3. The inset is a vertical section through the country rock breccia as modeled prior to this study.

adjacent pipe - that are most likely derived from an overlying Soutpansberg Group. This implies that the breccia clasts may have been transported (by some means) from their source more than a few tens of metres, but no more than a few hundreds of metres.

The sheared country rock breccia south of the Venetia K1 pipe (figure 2) was sampled in the open pit at the contact with the country rock and about 50m from the contact. The breccia body also sampled by four drill core samples. It is approximately 135m wide and has been exposed in the pit and by drilling to 120m in depth, but is likely to extend to a depth of at least 230m. The inset in figure 2 shows the most recent geological interpretation of the breccia body – the contact has been inferred to shallow out towards the "base" of the K1 pipe in section. The east and west sides of the breccia are sharp, vertical planes that have been interpreted as fault planes. The southern edge of the breccia is a fault along which a pegmatite dyke intrudes in places, and along which the K007 and K012 pipes were emplaced (Kurszlaukis and Barnett, 2003).

Figure 3 shows the fractal plot of all country rock breccias (Venetia and River Ranch) sampled by photograph during this study. The results of individual photographs are affected strongly by lack of resolution and measurement of smaller particles. This effect is seen in the fractal graphs by a shallowing tail. However, in figure 3 the data from photographs with scales varying over ten orders of magnitude are combined and define a convincing linear trend of Ds = 2.32 for particles larger than 3cm, and Ds = 1.67 for particles smaller than 3cm. Such fractal trends with more the one linear segment are termed multifractal (Roach and Fowler, 1993). The smallest scale data comes from photographs of two thin sections of drill core (HDH2). In thin-section, two stages of brecciation are evident (inset in figure 1). The second stage consists of angular clasts in a microcrystalline matrix, with single-grain deformation. The first stage is remnant within the clasts, which comprise microcline (and occasional biotite) particles that have partly annealed together. Ds from the second stage is plotted in figure 3, whereas the first stage has a much higher value, Ds = 3.0.

The Wimbledon pipe (near Kimberley) includes a massive breccia in which a shear fabric is developed that dips towards the pipe and steepens from 14^{o} at the country rock contact to 41^{o} at the kimberlite contact.

Country Rock Breccia Variations

The drillcore samples produced much more variable results. They are clearly multifractal in nature (see inset log-log graphs in figure 4). The drill core samples were undertaken by measuring the length of each clast intersected along the centre line of the drill core. They are therefore one-dimensional samples. The Ds determined from the face photographs (which are two-dimensional "area" samples) should be equal to 1 + Ds from the drill core (Yielding, et al., 1992), and is reported as such in this paper for comparative purposes. The drill core data shows two end-member types of size distributions, (A) breccia that has a high initial Ds = 3 to 6 (see GDH45 in figure 4), and (B) breccia that conforms closely to the results from the photograph analysis (e.g. HDH2 in figure 4). Re-examination of the core shows that the latter breccia includes the sandy matrix between the larger fragments, whereas the former does not. Some of the drill core results do not fall consistently into either of these two trends, and so an analysis was done to determine spatial variation in Ds through a number of the boreholes. The preliminary results are presented in figure 4. GDH06 shows consistently high Ds values. HDH2 shows consistently

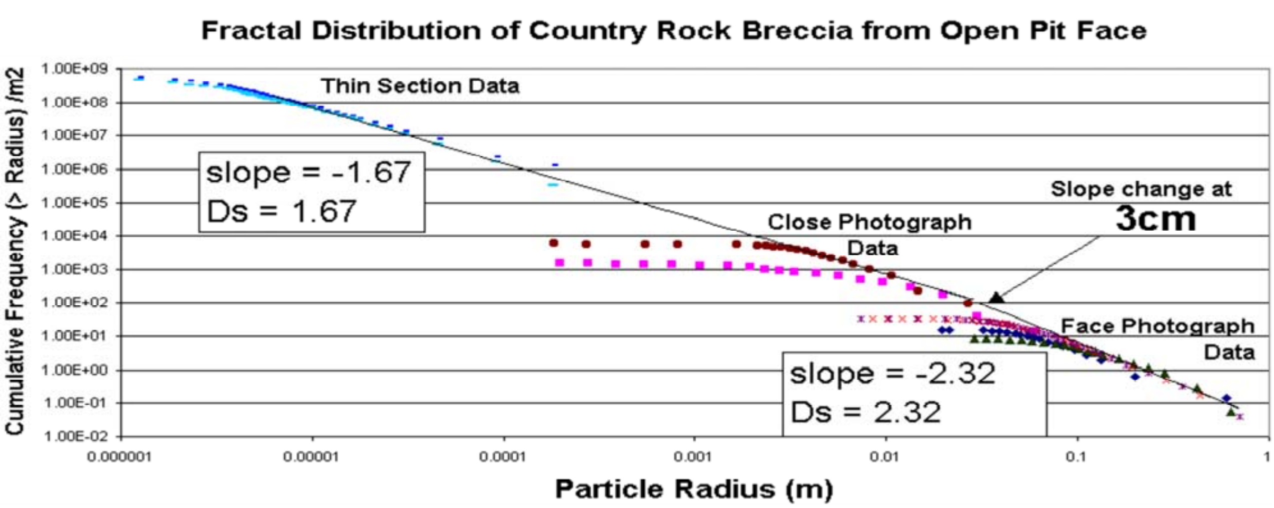

Figure 3: The amalgamation of analyses of all sheared breccia data from Venetia and River Ranch define the multifractal trend over 10 orders of magnitude. Clasts smaller 3cm may be partly buffered from brecciation.

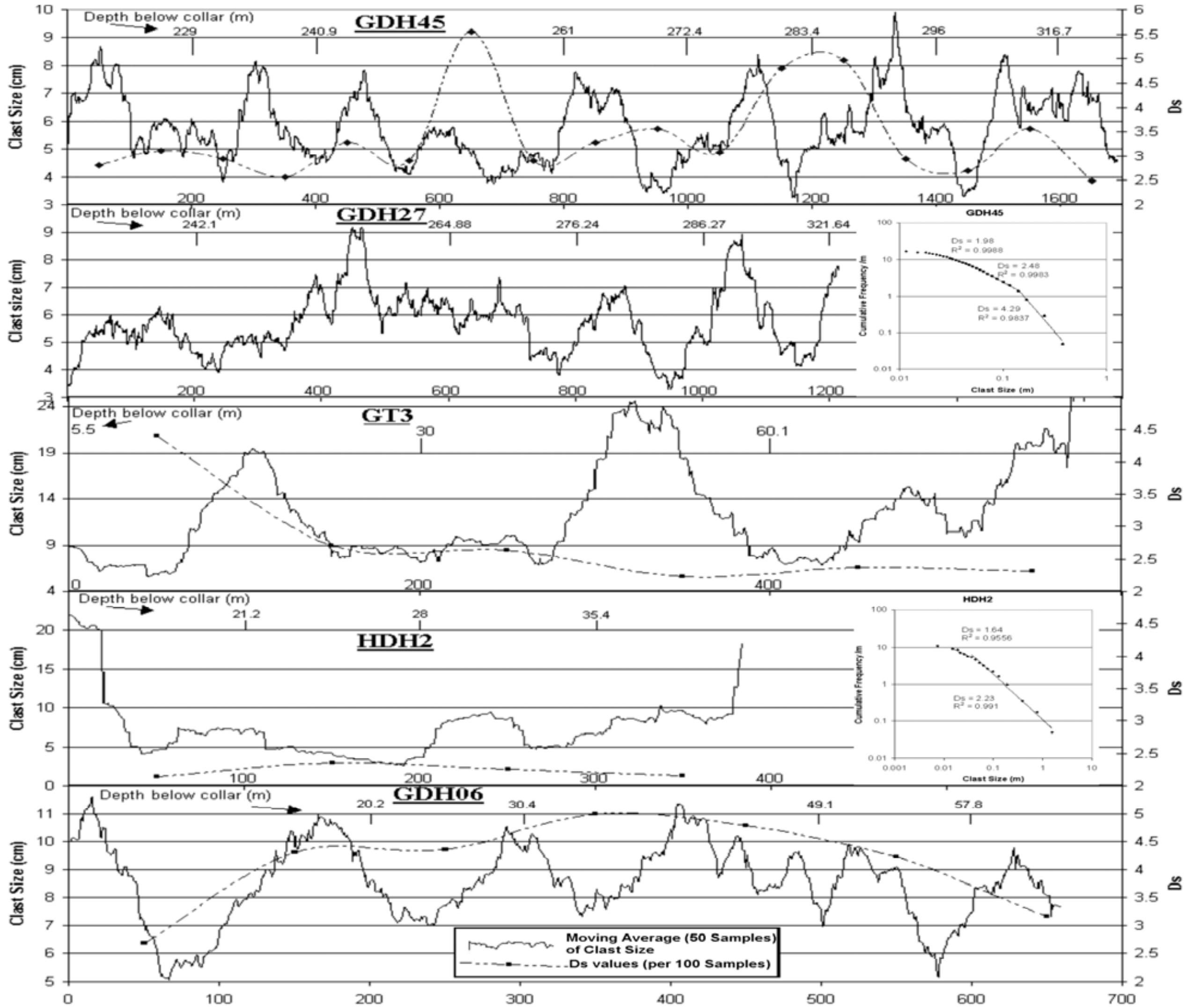

Figure 4: This figures shows the detailed variation in particles sizes down the drill holes (the solid line indicates moving average values) and the variation in Ds values (broken line). The x-axis is the sequential particle number. The two inset log-log plots show typical multifractal results from the two main breccia varieties.

low Ds values that are identical to the photographed breccias with a fabric. GT3 shows a fairly uniform drop from the high end-member to the low end-member. GDH45 shows a complex variation from very high Ds values to low values that approach the lower end-member. Note the cyclic nature of the peaks on the moving-average size variation curves, strongly suggesting the presence of massive layers 10 to 15m in thickness. Also note the close correspondence between the position of some of the peaks in GHD45 and GDH27, suggesting some type of lateral continuity.

Boundary Fractal Analysis (Dm)

The dimensionality of a straight line or a line outlining a Euclidean shape is 1. A complex "rugged" line is filling a two dimensional plane and the Dr value determined from fractal analysis of such a line must therefore lie between 1 and 2. The Dr value of geological particles typically range between 1 and 1.36, but in magmatic ash particles it may reach as high as 1.57 (Dellino and Liotino, 2002). Figure 5 shows the results of the boundary fractal analysis on country rock breccia clasts, blasted particles (using industrial explosives), pit slope rock failure particles and clasts from a heterolithic kimberlite pipe breccia (with greater the 75% xenoliths) adjacent a country rock breccia. All show very low Dm and the average for the country rock breccia is 1.07±0.02. The breccia is closest to rock failure particles in roundness, circularity and Dr (1.05±0.02). Note that the country rock breccia that has been incorporated into the pipe breccia have undergone additional rounding.

CONCLUSIONS

The Ds value determined from two rock failures in the open pit slope is 2.15 (figure 1). The sheared breccias have a very similar fractal dimension (2.3) in core and in the pit. Data obtained from two underground mining block caves have Ds values of 1.2 to 1.6. The Ds values from three collapsed underground nuclear blast cavities (Boardman, 1970) range from 1.4 to 1.6. On the other hand, pure explosive breccias are known to have very high Ds values (figure 1; Jébrak, 1997). It is therefore concluded that the breccias seen in drill core form a range from pure explosive breccias through reworked breccias that have undergone abrasion and shearing (figure 1) to develop the prominent fabric seen in the pit. The amount of re-fragmentation would be reflected by the drop in the Ds value. Further reworking into the kimberlite diatreme causes a further drop in Ds to around 1.3 (measured for pipe breccia; figure 1). Based on the development of the observed layering (figure 4) and shear fabric that dips towards to kimberlite diatreme, it is further concluded that the breccia has undergone substantial gravity-induced subsidence (slumping) into the diatreme. The volcanological process must produce a large volume deficit at depth that allows the breccias to subside. In the same way remnant clasts of explosive breccia are seen in thin section, similar much larger clasts, zones and layers within the country rock breccia will still preserve the high Ds values and not be sheared (observed by Kurszlaukis and Barnett, 2003). The technique described in this paper will allow the detailed structure and history of country rock breccias around pipes to be clearly mapped out. The clear understanding of the brecciation mechanism is leading towards much more accurate modelling of the kimberlite pipe morphology and volcanology.

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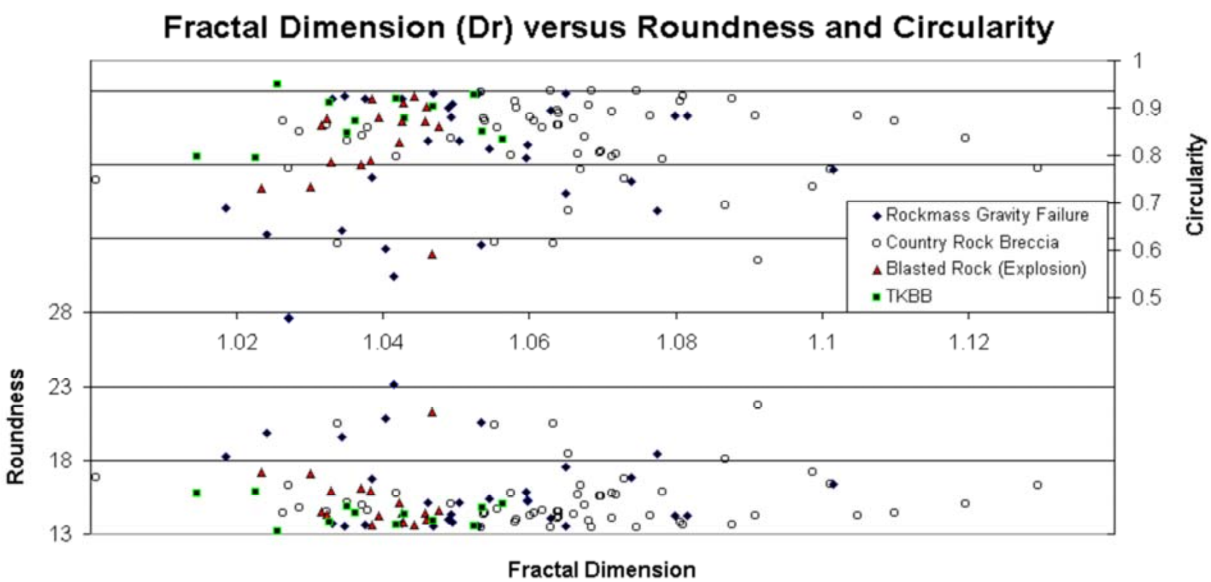

Figure 5: The plot summarizes all the data from the boundary fractal analysis.