Available online at www.sciencedirect.com
ScienceDirect
Journal of Volcanology and Geothermal Research xx (2008) xxx–xxx
Journal of volcanology and geothermal research
www.elsevier.com/locate/jvolgeores

Research paper

The rock mechanics of kimberlite volcanic pipe excavation

Wayne Peter Barnett *

Mineral Resource Management, De Beers Group Services (Pty) Ltd, P.O. Box 82232, Southdale 2135, South Africa

Accepted 11 December 2007

Abstract

The rock mechanics theory for deformation of open pit and underground mining excavations can be used to better understand aspects of the growth and geometry of kimberlite volcanic pipes. Large scale rock mass behaviour around an excavation, such as a volcanic pipe, is dependent on the rock mass strength, the in-situ rock stress conditions and the excavation geometry. Rock mass strength is empirically derived from the intact rock strength and quantification of the shear strength, frequency and orientation of rock discontinuities. Tensile slope or sidewall failure typically occurs in shallow level (~0–1000 m) conditions in which pre-existing structures shear due to gravity-driven forces. The orientation of the pre-existing structures provides an important control on the size, shape and position of the rock mass failure. Slope failures are shown to influence the development of many kimberlite volcanic craters and the distribution of layered volcaniclastic facies in the crater. Explosions or removal of key-blocks in a pipe sidewall can cause undercutting and collapse of the sidewall, with the rock unravelling along pre-existing structures towards surface. Many lithic-rich breccias commonly found on the margins of kimberlite pipes are interpreted to form in this way. At intermediate (>1000 m) to deep (>2500 m) depths, the increasing compressive stress can cause fractures to develop around an excavation. Stress-induced fractures should cause scaling of a volcanic pipe's sidewalls and expansion perpendicular to the maximum component of compressive stress. A larger horizontal tectonic stress ratio and a lower internal pipe pressure will promote pipe sidewall fracturing. Volcanic pipe expansion will also be increased in rate by (i) mechanical sidewall erosion by flowing magma and/or pyroclasts, (ii) by failure on large intersecting fault or dyke structures, and (iii) by reduction in the country rock mass strength by volcanic explosions. The final pipe shape and distribution of some internal facies is therefore a consequence of the dominant rock mechanical failure processes in the pipe sidewalls. The type of failure is dependant on the rock mass strength, geological structures, stress and depth below surface.

Keywords: structure; stress; diatreme; breccia; dilution

1. Introduction

Volcanic pipes preserve the remnant textures and fabrics of a complex interplay between upward-progressing processes (such as explosions and volatile streaming) and downward-progressing processes (collapse, resedimentation and subsidence; Laznicka, 1988). The downward-progressing processes are typically gravity-driven. The pipe is a natural excavation filled by volcaniclastic and coherent magmatic material, and is created by rock fragmentation. Brittle rock fragmentation requires the application of differential stress on the rock mass. Similarly, in mining the rock around an excavation fragments under the application of stress and is transported downwards into the excavation by gravitational forces. Aspects of the outward growth or expansion of a volcanic pipe can be compared to the expansion of an unsupported collapsing mining excavation. To understand rock behaviour in both scenarios the science of mining rock mechanics should be considered carefully.

The purpose of this paper is to discuss mechanical processes in the rock mass around a kimberlite volcanic excavation that occur as the rock responds to formation of the excavation. Some basic principals of quantifying rock strength and predicting rock behaviour are introduced before discussing types of rock failure or fracturing processes in mining excavations. Such processes

* Corresponding author. Fax: +27 11 374 5032.
E-mail address: Wayne.Barnett@debeersgroup.com.

0377-0273/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2007.12.021

are related to volcanic systems using kimberlite pipe examples. The dominant pipe growth process will differ depending on the type of volcanism, nature of the country rock mass and depth in the pipe (Fig. 1). It should be remembered that during eruptions the interplay of forces in a volcanic system is far more dynamic and complex than in a mining excavation. No attempt is made in this paper to explain or simulate the volcano dynamics. Rather, just the expected, fundamental rock mechanical processes are discussed.

2. Jointed rock behaviour

To predict when a rock will fail it is necessary to select and apply a failure criterion. These criteria typically predict the stress at which an intact rock fails/fractures or a discontinuity slips. There has been a number of failure criteria developed. The simplest example is the Mohr-Coulomb criterion (Coulomb, 1773) which is often referred to in rock mechanics and structural geology (e.g. Hobbs et al., 1976; Price and Cosgrove, 1990). The Barton and Bandis empirical equation (Barton and Bandis, 1990) is a modified version of the Mohr-Coulomb equation that has been modified to predict the failure of real pre-existing discontinuity surfaces that contain variations in roughness and rock weathering:

$$\tau = \sigma_n \mathrm{Tan}[\phi_r + \mathrm{JRC}\log_{10}(\mathrm{JCS}/\sigma_n)] + C_0 \quad (1)$$

where τ is the shear stress at failure, σ_n is the stress normal to the failure plane, C_o is the cohesion and the term in square brackets is the effective friction angle. The effective friction angle is defined by $\o_r$ the base/residual friction angle, JRC the Joint Roughness Coefficient, and JCS the Joint Compressive Strength. The base friction angle is the friction angle for the joint if all asperities creating roughness on the joint plane were removed and the plane becomes smooth and planar (typically done in a laboratory). The JRC is a value between 0 and 20 that is visually estimated from a calibrated diagram and rates rougher planes with higher coefficients. The JCS is an estimate of the uniaxial compressive strength in megapascals (MPa) of the intact rock defining the walls of the joint plane, that may be weakened by hydrothermal alteration or weathering.

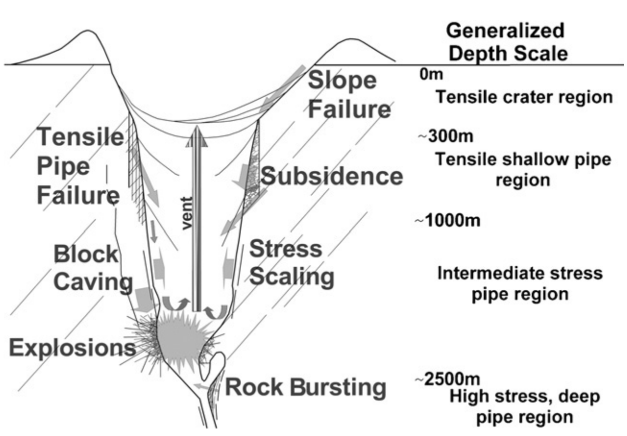

Fig. 1. Generalized illustration of the volcanic pipe excavation processes discussed in this paper. An indication is given of the expected depths or regions at which the processes may be found. These generalized depths are based on known rock behaviour in typical mining environments experienced in the mining industry (COMRO, 1988). The overall dynamics of the volcano are explosive upward ejection of volcaniclastics from the pipe through a vent, followed by downward subsidence of the country rock and volcaniclastics towards the mass deficit created by the explosive process.

One of the most important concepts in rock mechanics is the difference between intact rock strength and rock mass strength. The strength of an intact rock sample without fractures as measured in a laboratory is greater than a rock sample that contains discontinuities. Discontinuities are usually more easily sheared than intact rock and therefore cause the overall rock mass containing such discontinuities to strain more easily under applied stress. The Hoek-Brown failure criterion (Hoek and Brown, 1980a,b; Hoek et al., 2002) is one of the most commonly used criteria in rock mechanics used to predict the strength of a typical rock mass containing structures.

The spacing of the discontinuities and the scale of the rock mechanics problem being addressed determines how the problem is dealt with. On a very small scale the rock is unlikely to contain discontinuities and the behaviour of the rock is simply predictable by using an intact rock failure criterion (e.g. Mohr-Coulomb). On a slightly larger scale, depending on the discontinuity spacing, the rock might contain one discontinuity. In such a case the discontinuity will dominate the behaviour of the rock and a "simple" calculation of shear on the discontinuity (e.g. using Barton and Bandis Eq. (1) above) could be adequate to resolve the rock behaviour. On an even larger scale the rock will contain multiple discontinuity planes and in certain circumstances it may be possible to calculate geometrically how the forces distribute on the planes and determine the conditions under which the rock mass will fail.

However, if more than three to five discontinuities are present in the rock then a deterministic geometric analysis becomes difficult. In such cases an empirical criterion, such as the Hoek-Brown criterion, is used, often involving a qualitative or at best semi-quantitative assessment of the impact of the jointing density on the rock mass strength. The empirical approach to quantifying rock mass (i.e. on a large scale) strength has been developed extensively and successfully in rock mechanics through the use of rock mass classifications. Classifications try to cater for all the rock characteristics that can potentially reduce the strength of the rock mass from the initial intact rock strength. These characteristics can include:

1. The frequency/spacing, roughness, infill strength, and alteration of joints.
2. The influence of rock microfracturing.
3. The orientation of joints relative to the excavation geometry.
4. Groundwater flow rate or pressure.
5. Explosion damage.
6. In-situ stress conditions.
7. Weathering, that is often time dependant.

There are many tailor-made rock mass classification systems for many different rock environments, but the most globally used examples include the Geomechanics Classification System

Please cite this article as: Wayne Peter, B., The rock mechanics of kimberlite volcanic pipe excavation, Journal of Volcanology and Geothermal Research (2008), doi:10.1016/j.jvolgeores.2007.12.021

(Beniawski, 1973, 1978) and its modified versions (Laubscher and Taylor, 1976; Laubscher, 1990; Laubscher and Jakubec, 2000), Geological Strength Index (Hoek, 1994), as well as the Q system (Barton et al., 1974) and the Rockwall Condition Factor (COMRO, 1988). These systems use combinations of the above strength reducing characteristics to produce a classification value that represents the "strength" of the rock mass. This value can be used to design rock support and estimate rock behaviour in the mining environment (Fig. 2). The different rating systems have been developed and calibrated in different mining environments and might be more applicable for some specific mining problems than others. These systems could potentially also be used in the volcanic pipe environment.

3. Tensile slope failure in the mining open pit or volcanic crater environment

The crater environment of a kimberlite pipe comprises layered pyroclastic and/or resedimented volcanoclastic rock (Sparks et al., 2006). A common component of the volcaniclastic rock are layered volcaniclastic breccias (e.g. Field and Scott Smith, 1999; Kurszlaukis and Barnett, 2003; Stiefenhofer and Farrow, 2004; Sparks et al., 2006), where the accidental lithic clast component is predominantly derived from failure of the crater slopes.

Rock failures in an open pit are often classified into four basic failure types (Hoek and Bray, 1981; Fig. 3). Sliding failure (Fig. 1 and Fig. 3a) is characterised by slip on a pre-existing near-planar surface that dips towards the pit. Depending on the excavation geometry there might be releasing planes on either side of the failure and a tension joint behind the failure. The pre-existing structure on which sliding occurs might be a fault plane, a fracture or joint set, but is very often layering-parallel (sedimentary or metamorphic) jointing/partings that dip into the excavation at angles greater than the friction angle of the rock. The Barton and Bandis equation shown above Eq. (1) is a useful way to assess the likelihood that such a plane would undergo sliding. It is quite common in open pits for the layering on one side of the pit to be unfavourably orientated and to create sliding-type slope stability problems on just that side of the pit.

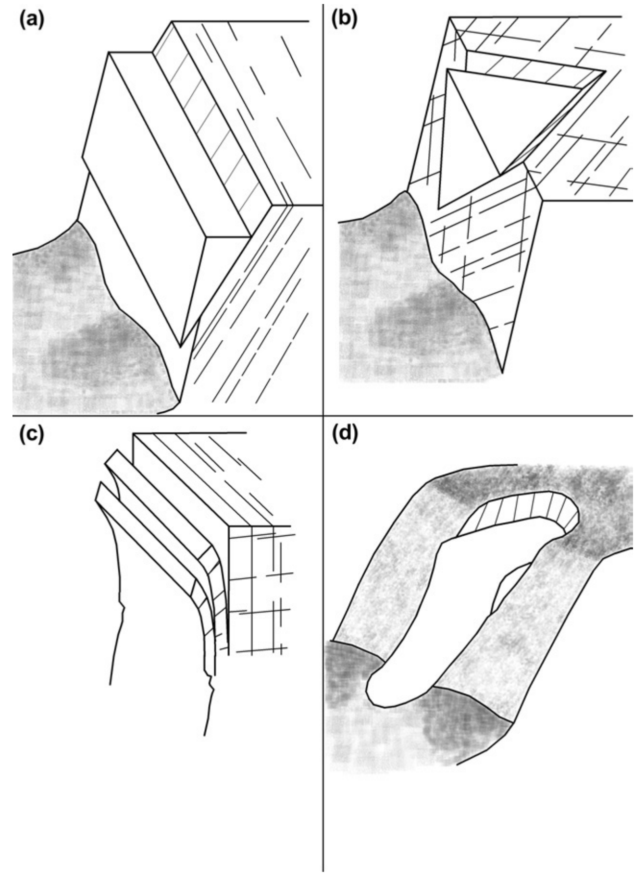

Fig. 3. Schematic illustration of the most elementary gravitationally-induced, tensile slope failure geometries. Modified after Hoek and Bray (1981). (a) Sliding/planar failure. (b) Wedge failure, (c) Toppling failure, and (d) Circular failure.

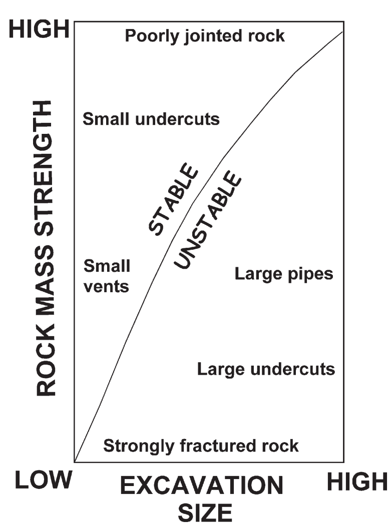

Fig. 2. Schematic diagram illustrating the basic rock mechanics principal of how the rock mass rating (or strength) governs the maximum size that an excavation can be made before it becomes unstable and will gravitationally collapse. Modified after Laubscher (1990). The inset text represents hypothetical examples to help explain the concept illustrated by the diagram.

In the Venetia kimberlite cluster (Limpopo Belt, South Africa) the K02 pipe is a good example of a volcanic excavation in which the internal facies has been strongly influenced by sliding failure of the excavation walls (Kurszlaukis and Barnett, 2003). The southern slope of the open pit contains the southern limb of an east–west trending synform structure in which the rock layering dips north to northeast at circa 40^{o} (Barnett, 2003). The unfavourable orientation causes severe stability problems by sliding failure in the southern pit slope. The same explanation of rock mass failure can be used to explain the presence of talus fans of lithic-rich volcaniclastic breccias prograding northeast to east from the southern contact of the K02 pipe (Fig. 4; Kurszlaukis and Barnett, 2003). Brown et al. (2006b) show that the entire package of interlayered breccias and pyroclastic rocks in the K02 pipe fills at least 50% of the pipe (Fig. 4 inset) to depths of at least 700 m below the present-day surface, which is interpreted as evidence of extensive spalling and collapse of the pipe sidewall.

Please cite this article as: Wayne Peter, B., The rock mechanics of kimberlite volcanic pipe excavation, Journal of Volcanology and Geothermal Research (2008), doi:10.1016/j.jvolgeores.2007.12.021

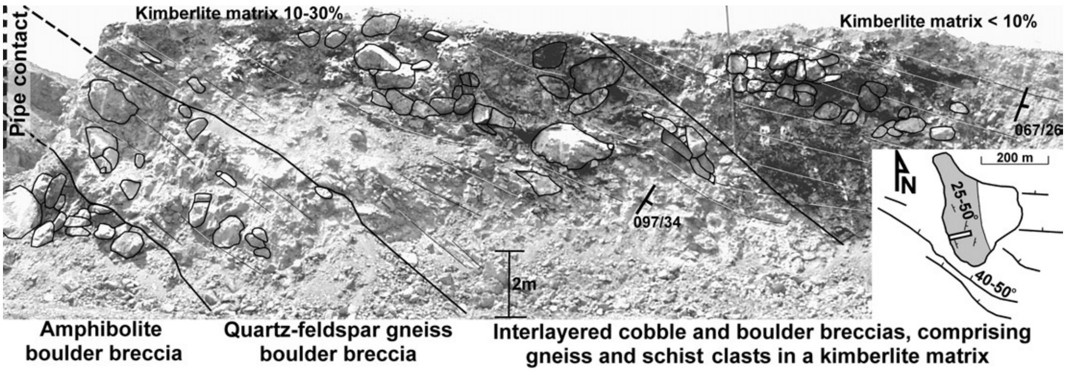

Fig. 4. Crater facies talus fans prograding from the geologically unstable southern pipe contact into the Venetia K02 pipe. Modified from Kurszlaukis and Barnett (2003). The view is northwards. Four individual fans (or facies) are shown separated by thick black lines, each with a distinctive breccia clast type or kimberlite matrix component. Some distinctive, large boulders are outlined to illustrate crude layering defined by clast size variations and elongations. The layering is also highlighted by thin black and white lines, and two measurements are shown (azimuth/dip). The inset figure shows K02 in plan view with the position of the figure marked with a rectangle. The strike and dip of the country rock is illustrated, as well as the dip of the breccia layers (Brown et al., 2006b). The extent of the layered breccia facies is shaded grey.

Wedge failure (Fig. 3b) is characterized by slip of a wedge shaped block of rock along the intersection line of two discontinuity planes, in which case the intersection line plunges into the pit at an angle that is steeper than friction angle of the rock (Hoek and Bray, 1981). This is a very common failure type that can utilize combinations of pre-existing planar structures, including large fracture or fault planes to potentially cause failure on the scale of an entire slope. The likelihood of wedge failures can be calculated by using applied geometry to determine the normal and shear stress vectors on each contributing failure plane, and the Barton and Bandis equation Eq. (1) to get the peak shear strength on each of those planes.

Toppling type failure (Fig. 3c) is less common, and often formed by a sub-vertical and dense fracture cleavage or overturned layering with well developed jointing, in which tabular blocks are found with the long axis of the blocks orientated in a sub-vertical position and the blocks balancing on a relatively small basal area. Toppling of such a block occurs when it is tilted such that the centre of gravity of the block lies outside the basal area (Hoek and Bray, 1981). Within a volcanic environment toppling is likely to occur when explosive volcanism undercuts part of a slope causing rotation (i.e. tilting) and slumping of the slope. Small-scale examples of lithic blocks introduced into the pipe by toppling can occasionally be observed along the margins of kimberlite pipes. One example is a 5 m high and 0.5 m wide amphibolite megablock supported in a poorly sorted tuff that was observed detached by 1 m from the eastern margin of the Venetia cluster K04 pipe.

Circular or rock mass failure is the most common large scale failure mechanism, where structures combine to form a single failure surface that is circular or curved when viewed on a vertical section—steep at the top and shallowing with depth towards the toe of the failure (Fig. 3d). The weaker the rock mass (e.g. highly jointed or strongly weathered) the more likely such failure can occur, and at smaller scales. There is a limit to the height at which a slope that is steeper than the internal angle of friction can remain stable. The higher and steeper the slope the greater the stresses that form at the toe of the slope, and the more likely that pre-existing discontinuities will fail and propagate. The propagating fractures connect forming a single circular failure plane (Hoek and Bray, 1981). Slumping in partially consolidated or unconsolidated tuff in volcanic craters and cones are circular-type failures. The crater of the Orapa kimberlite pipe (Botswana) has a country rock contact that dips at a different angle through each rock type in the stratigraphy. Those angles are equal to the internal angle of friction for each rock type (Jakubec et al., 1996, 2001; Field and Scott Smith, 1999), and this implies that the final crater shape was achieved after the country rock mass failed back to its natural angle of repose.

The crater facies of the Mwadui pipe (Tanzania) is described by Stiefenhofer and Farrow (2004). Layers of granite breccia lie directly on top of the main eruptive pyroclastic rock of the pipe. This breccia is interpreted to be a result of failure of the granite basement comprising the wall rock of the pipe crater. As a typically very competent rock, the granite must have been strongly fractured (possibly by volcanic explosions) and then undergone circular-type failure. Layers above the basal breccia comprise decreasing quantities of granite clasts and increasing resedimented volcaniclastic kimberlite, presumably from an undercut tuff ring (Stiefenhofer and Farrow, 2004). Similar granite breccias are described from the Koala pipe in the Lac de Gras Field, North Western Territories, Canada (Nowicki et al., 2004; Crawford et al., 2006).

Field and Scott Smith (1999) suggest that many of the Lac de Gras kimberlite pipes have been filled by resedimented volcaniclastics and sediments, including locally derived shale blocks up to 20 m in size. The Diavik cluster of pipes, within the Lac de Gras Field, are observed by Graham et al. (1998) to contain crater-wall derived mud-fragment rich talus beds (deposited during dry conditions) and mudflows and debris flows (wet conditions) interbedded with pyroclastic rocks. The Aries kimberlite (Kimberley Basin, Australia) contains an upper pipe filled with bedded, sediment-rich gravity deposits (Downes et al., 2007). Field et al. (1997) describe talus fans of dolerite breccias in the crater facies of the Orapa pipe southern

Please cite this article as: Wayne Peter, B., The rock mechanics of kimberlite volcanic pipe excavation, Journal of Volcanology and Geothermal Research (2008), doi:10.1016/j.jvolgeores.2007.12.021

lobe. The Victor Northwest pipe (Attawapiskat cluster in Ontario, Canada) has layered volcaniclastic rocks containing horizons of lithic breccias, and are capped by a country rock breccia up to 35 m thick that is interpreted to be a result of pipe wall collapse and avalanching (Webb et al., 2004; Van Straaten et al., 2006).

All the above examples show how important the behaviour of the country rock mass in which the volcanic crater is situated can be on the final crater geometry and on the nature and distribution of the facies within the crater. The physical properties of each country rock type locally influences the crater slope angles (e.g. Orapa) and the abundances of lithic fragments within the pipe. The location and flow direction of avalanche and debris flow breccias within the crater can be influenced by the position and specific orientation of geological structures within the country rock that allow slope failure to occur.

4. Tensile rock unravelling in shallow mining conditions or upper volcanic pipe

4.1. Mine excavation behaviour

The low compressive stress in shallow mining levels can contribute to the most extreme cases of excavation failure and expansion. Tensile environments allow the unravelling of well-jointed rocks, typically by tensile collapse of the hangingwall in mines (COMRO, 1988). The most common examples are within the upper 1000 m from the surface (tensile shallow pipe region in Fig. 1). At deeper mining levels the compressive stress provides confinement preventing tensile failure, except in situations where specific mining geometries locally induce tensile stress.

The best example of controlled tensile failure in shallow level mining is the block caving mining method where the rock is induced to collapse under its own gravity, providing an inexpensive method of rock fragmentation. Once an adequately sized excavation is created/mined, the hangingwall above the excavation collapses by tensile failure and slip on joints. The critical width of the undercutting excavation that is required to initiate such collapse is dependant on the density of jointing and ultimately on the overall rock mass strength. Rock mass classification systems, particularly Laubscher's Mining Rock Mass Rating system (Laubscher, 1990), can be used to predict the critical width of the undercut (following the principal illustrated in Fig. 2). Collapsed rock subsides towards mining extraction points (drawpoints) and further fragments by comminution and abrasion. This block caving process has obvious similarities to the volcanic excavation process illustrated by Lorenz and Kurszlaukis (2007). The volcanic explosion is deemed to create a mass deficit at depth (i.e. an undercut; Fig. 1) by ejecting pyroclastic rock and country rock clasts through a central vent conduit (akin to a drawpoint). The undercut pyroclastic pipe infill and undercut country rock may then cave or subside towards the mass deficit. Collapsing and subsiding clasts will fragment by impact, comminution and abrasion.

Sub-vertical pipe-like excavations in mining are called passes or shafts depending on their function. The shafts or passes are typically circular in cross-sectional shape. Such excavations have the tendency to become unstable in weak rock mass conditions and if inadequately supported they unravel creating much larger excavations that are extremely hazardous to access and re-support. The sidewall fails in tension by structure-controlled wedge or circular failure. The failed rock leaves a small undercut that makes it easier for more failures to occur and an out-of-control collapse process begins (Stacy, 2004; Stacy et al., 2004). Shallow (<800 m deep) level rock passes designed at 4 m in diameter at Cullinan Mine (Premier kimberlite pipe near Pretoria, South Africa) are observed to collapse to over 10 m in diameter. Menzies (2004) and Joughin and Stacy (2004) document 2–3 m wide passes that grow to widths as large as 30 m in shallow level and deep level mining. Some such run-away excavations encroach on nearby mining operations endangering the lives of those working there. Rock mass classification systems for vertical passes that follow the principal illustrated in Fig. 2, show that even a vertical excavation of relatively small diameter (down to circa 1 m) can collapse in strongly fractured, hard rock conditions (McCracken and Stacy, 1989).

4.2. Kimberlite pipe behaviour

In the same way a mining shaft fails, the expansion of the upper volcanic pipe will depend strongly on the country rock mass quality and the internal pressure generated by the magma in liquid, fluidized or pyroclastic form. An internal restraining pressure from the kimberlite will inhibit widening of the pipe, but partially consolidated pyroclasts that subside down the pipe after an explosion will create ample opportunity for pipe sidewalls to fail in tension. Kimberlite pipes often consist of contact breccias around the outer edge of the pipes (Clement, 1982; Hetman, 2006). In some cases these breccias, that comprise local wall rock types, reach several hundred metres in width, breadth and depth. Two basic breccia textures are common (Barnett, 2004). Non-sheared contact breccias have no clast alignment or fabric, with angular, partially dilated to tightly packed clasts (Clement, 1982). There is usually a carbonate cement or just voids between the clasts. Sheared breccias have a weak to strong clast alignment and penetrative shear fabric (dipping 30 ± 15^{o} towards the volcanic centre), with tightly packed, angular to subrounded clasts in a rock-flour and/or carbonate cement.

It is suggested by Barnett (2004) that the sheared variety of country rock breccias formed around kimberlite pipes undergo fragmentation in a similar manner to the particles in a block cave, by subsidence, comminution and abrasion. These contact breccia bodies are likely to grow by means of an upward caving process (Fig. 1) and subside downwards into the volcanic pipe as room is made by the explosive expulsion of pyroclast pipe infill. The caving process in the country rock along side of the volcanic pipe might be initiated by undercutting by a volcanic explosion, by small scale sidewall failure and unravelling (like a mining pass), or by rock mass circular-type failure as described above.

An example of undercutting and collapse is provided by the Koffiefontein pipe. Observations presented by Naidoo et al.

(2004) suggest that the weaker mudstones in the pipe walls were removed during eruptions and incorporated into kimberlite volcaniclastic layers dipping into the pipe. More competent sandstone and dolerite from the undercut, overlying stratigraphy then collapsed during periods of quiescence, forming epiclastic debris flows above syn-eruptive volcaniclastics (Naidoo et al., 2004). The Venetia K02 pipe has a protrusion (Kurszlaukis and Barnett, 2003; protrusion in Fig. 4 inset) that does not open to surface, but is preserved in the final stages of upward caving as the overhanging country rock collapsed and filled the protrusion cavity. The southwest corner of the Venetia K01 pipe contains a breccia body that is about 135 m in north–south extent, 140 m in east–west extent and over 200 m deep (Kurszlaukis and Barnett, 2003; Tait et al., 2006). Preliminary models of this breccia body suggest a circular cross-sectional shape typical of the failure mechanism illustrated in Fig. 3d. The breccia textures and statistical analyses of the particle size distribution suggest that the breccia underwent subsidence towards the centre of the K01 pipe (Barnett, 2004). Subsided country rock breccia bodies of similar scale are exposed at the River Ranch pipe (Zimbabwe), Wimbledon pipe (near Kimberley, South Africa) and The Oaks pipe (Limpopo Belt, South Africa).

Verichev et al. (2003) interpret the xenolith content of Vladimir Grib kimberlite pipe (Arkhangelsk Kimberlite Province in Russia) to be due to a stage of pipe side wall collapse. The southern margin of the northern lobe of the Jericho pipe (Northwest Territories, Canada) contains a coarse breccia with clasts exceeding 3 m in size (Cookenboo, 1999). The north, central and southern lobes of the Aries kimberlite comprise predominantly of lithic-rich (>60%) kimberlite breccias with angular to subrounded clasts (Downes et al., 2007). The local sandstones are interpreted to be fractured by phreatomagmatic explosions, and the fracture-weakened rock mass was able to collapse into the pipe, leaving local overhanging sidewalls. The Fox kimberlite (Lac de Gras) has cobble to boulder sized breccias interpreted to be the result of pipe wall collapse (Porrit et al., 2006). The Jwaneng Mine Central Pipe (Botswana) contains clast-supported shale breccias in discontinuous lenses around the pipe margin (Brown et al., 2006a). Significantly, the thickest zone of shale breccias (10–15 m wide) occurs along the south-eastern margin where the shale country rock that dips north-westwards at 30–45° creates slope stability problems in the mining open pit (sliding failure as represented in Fig. 1 and Fig. 3a). Many more kimberlite pipes, if not the majority of kimberlite pipes, are likely to have similar breccias bodies, but of variable size and state of preservation.

Not all failed country rock disintegrates into numerous smaller breccia fragments. Large structure-bounded blocks can topple or slide still partially intact into the pipe, and when preserved in kimberlite pipes these blocks have previously been termed “floating reefs” (Clement, 1982). Drilling and modelling of the Centre Pipe at Jwaneng Mine has shown a fractured but partially intact country rock block at least 520 m in height and 70 m wide that has subsided about 50 m into the pipe (R. Price, pers.comm.). Brown et al. (2006a) describe megablocks 5 to 100 m in size from the same Jwaneng pipe. The large (circa 150 m long) detached section of the northern edge of the K04 pipe in the Venetia cluster would seem to have subsided and rotated into the pipe (Kurszlaukis and Barnett, 2003). Lithic blocks and megablocks in the Aries kimberlite include a basalt megaclast 57.5 m in size (Downes et al., 2007).

The above described lithic breccias and megabreccia clasts are common in kimberlite pipes and can have a serious negative effect on ore body diamond grade. Laznicka (1988) describes the above discussed breccia forming processes as an extremely common part of maar-diatreme volcanic systems in general. Perhaps the best evidence for tensile collapse processes in the sidewalls of kimberlite pipes are the fact that many preserved pipe shapes have sidewalls or protrusions parallel to the local country rock joints and structures, and not just parallel to the feeder dyke. Published examples of such pipes include the Venetia cluster (Kurszlaukis and Barnett, 2003), Aries pipe (Downes et al., 2007), Ekati cluster in Lac de Gras (Nowicki et al., 2004; Crawford et al., 2006; McElroy et al., 2006) and Kimberley cluster (South Africa; Clement, 1982). There are many unpublished examples.

5. Increasing depth and compressive stress

5.1. High stress mining principals and examples

The vertical component of compressive stress (σ_v), due to the overburden weight, increases as depth increases. The horizontal components of stress increase proportionally to σ_v and as a function of Poisson’s Ratio (ν; e.g. Ryder and Malan, 2002). As a result, the normal component of stress (σ_n) on joint or fracture planes (see Eq. (1)) also increases with depth, which prevents the discontinuities from shearing. Therefore, higher compressive stress makes excavations more stable. The depth at which this effect becomes apparent depends on the geometry of the joints and excavation face, the in-situ horizontal stress conditions and the cohesive condition of the joints, but typically starts to become obvious at depths greater than 1000 m. Higher differential stresses then become necessary to cause rock mass failure by overcoming the increased shear strength of the joints or the compressive strength of the rock.

The equations used to describe the stress state around an idealized circular excavation (long in relation to its diameter) analyzed in 2D cross-section parallel to its diameter, subjected to a biaxial field stress with principal stress vectors $q_{\min}$ and $q_{\max}$ in that 2D plane, are known as the Kirsch equations (e.g. Ryder and Malan, 2002; Budavari, 1983). On the tunnel boundary, where radial stress and shear stress is zero, the maximum (σ_{Max}) tangential stress value is:

$$S_{\mathrm{Max}} = 3q_{\max} - q_{\min} - p \qquad (2)$$

where p is any internal pressure and σ_{Max} is at a position on tunnel boundary perpendicular to $q_{\max}$.

It is generally regarded in the South African hard-rock mining industry that a stress of two-thirds the laboratory derived Unconfined (uniaxial) Compressive Strength (UCS) is sufficient to cause fracturing and damage of hard poorly-jointed rock around an unsupported excavation (see also Mandl, 2005). This

Please cite this article as: Wayne Peter, B., The rock mechanics of kimberlite volcanic pipe excavation, Journal of Volcanology and Geothermal Research (2008), doi:10.1016/j.jvolgeores.2007.12.021

rule-of-thumb is used in this document, but it should noted that shaft failure can occur at lower stresses than even half the UCS (Durrheim and Sellers, 2004) if major geological structures interfere.

Therefore, once the maximum tunnel boundary stress Eq. (2) reaches around two-thirds of the UCS strength, then rock fracture propagation and scaling at the sides of the tunnel or volcanic pipe can be expected, as well as compressive shear failure of a well-jointed rock mass (Fig. 1 intermediate to high stress pipe regions). "Scaling" is the name of the process whereby slivers of fractured rock break off the sides of tunnels. The scaling effect creates a geometry known as dog-earing (identical to borehole breakout) such that the scaled "ears" occur on the sides of the shaft or pass perpendicular to the most compressive horizontal stress (position of maximum stress in Eq. (2). The shape of the final shaft or pass is therefore elongated perpendicular to the most compressive horizontal principal stress.

According to Dukes et al. (2004), Tau Lekoa Mine (South Africa) has high horizontal stress of about 30 MPa in the N–S direction, and a low stress around 5 MPa in the E–W direction. Scaling occurred in rock passes deeper than 1050 m, with the longest axis orientated perpendicular to the maximum horizontal stress. The quartzite between 1050 m and 1200 m has a UCS of 335 MPa and scaled 2 to 3 m in the E–W direction. The quartzite below 1200 m has an average UCS of 230 MPa and the extent of scaling ranges from 3 m at 1200 m to 27.5 m at 1734 m. At low horizontal stress ratios it can be considerably more difficult for rock to fail. At Kloof Gold Mine (South Africa), there is a measured N–S horizontal stress component of 75.5 MPa and an E–W component of 71.6 MPa (Durrheim and Sellers, 2004). No.3 shaft only starts to show signs of scaling at a depth below 2.5 km, particularly where large geological features intersect the shaft, such as dolerite dykes (Hart, 2004).

Given the complexities in quantifying the precise location, orientation and strength of all weaknesses in a rock mass, it is not possible to accurately predict the growth size and geometry of a failing or unravelling vertical excavation. Stacy et al. (2004) present an interesting analysis showing how the final area extent of a vertical ore-pass would be expected to increase in size with increase in original diameter, increasing depth and decreasing angle to intersecting strata. They admit that the magnitudes given become irrelevant when considering the effects of ongoing in-pass erosion (from tipping rock) in combination with scaling and changing stress conditions, and progressive block failure as the pass expands. Likewise, the process of pipe sidewall erosion must be considered as a contributing factor to pipe growth in an active volcanic system.

Deep level mining environments (typically below 2.5 km) are also known for rockbursts (Fig. 1). A rockburst is an explosive release of potential strain energy where the rock is fragmented and ejected at high velocity. A rockburst occurs for the same reasons stress-induced scaling occurs, but in a situation where the stored strain energy in the rock mass loading system is more than the rock mass is capable of dissipating during failure (Gill et al., 1993). A violent unstable energy release occurs. Stiffer rock properties (i.e. higher Young's modulus), higher applied stress magnitudes, and more complex excavation geometries promote rockburst conditions. Rockbursts should occur in a volcanic system, particularly deep in the system where the pipe or feeder dyke has an irregular geometry.

5.2. Theoretical application of high stress to kimberlite pipes

Using the simplified Kirsch Eq. (2), it is possible (assuming homogenous rock properties) to estimate the most likely maximum stress around a circular kimberlite pipe at various depths. In hydrostatic conditions the horizontal strain caused by the overburden stress (σ_v) must be balanced by a reactive horizontal stress. The horizontal stress is sometimes loosely estimated in the Witwatersrand goldfields in South Africa as 10 MPa, plus 10 MPa per 1 km depth (Durrheim and Sellers, 2004). It can also be more universally estimated by adding $\nu\sigma_v/(1\text{-}\nu)$ to the regional horizontal tectonic stress, which is the method used in Figs. 5 and 6. The lines in Fig. 5 illustrate how the magnitude and ratio of horizontal tectonic stress influences the stress concentration around the circular pipe with depth, assuming no internal pipe pressure (e.g. magma pressure). At a horizontal tectonic stress ratio of 2:1 MPa, compressive rock failure would only start at a depth below 3.5 km for a rock of strength 100 MPa (remember that effective strength = 2/3 * UCS = 67 MPa). At a tectonic stress ratio of 50:25 MPa (also 2:1 ratio) the peak pipe stress is around 130 MPa right near surface and compressive rock failure would occur near surface in a rock of UCS strength 195 MPa (effective strength = 130 MPa) and less. Increasing the tectonic stress ratio to 50:10 MPa further improves the range of conditions in which compressive rock failure can occur, such that at 1 km depth a rock with strength of 240 MPa would start compressive failure around the pipe.

Any internal pressure in the volcanic pipe reduces the likelihood for rock failure. In Fig. 6 the horizontal in-situ stress conditions (circa 14 MPa in both principal horizontal directions) currently measured around Cullinan Mine, near Pretoria, South Africa, has been used to show the effect of varying the internal magma pressure from 20 MPa to 0 MPa. In this case a shaft or pipe of 0 MPa internal pressure (14 MPa under pressure at surface) would start compressive failure of a rock (100 MPa UCS strength) at a depth of around 2 km (at circa 67 MPa maximum stress). However, at a 20 MPa internal pressure (6 MPa over-pressure at surface) the pipe would only start failing at around a 3.3 km depth. The conditions of low internal pressures inside a kimberlite pipe might be achieved by a fluidization process (Hawthorne, 1975; Clement, 1982; McCallum, 1987; Field and Scott Smith, 1999; Gernon et al., 2006; Sparks et al., 2006; Walters et al., 2006) or subsidence towards a mass deficit caused by a volcanic explosion (Lorenz et al., 1999; Lorenz and Kurszlaukis, 2007).

5.3. Supporting geological observations

Unfortunately, there are very few published examples to support the above inferred deep, high-stress processes in volcanic

Please cite this article as: Wayne Peter, B., The rock mechanics of kimberlite volcanic pipe excavation, Journal of Volcanology and Geothermal Research (2008), doi:10.1016/j.jvolgeores.2007.12.021

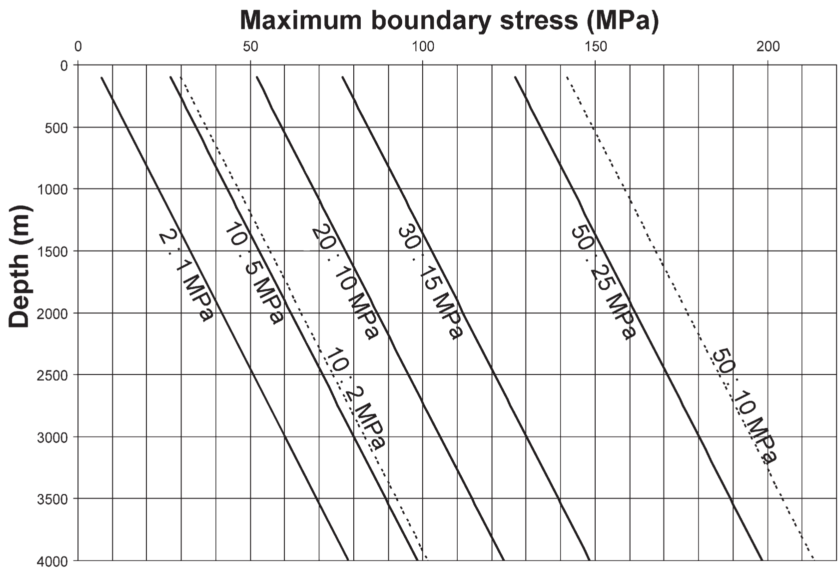

Fig. 5. A graphical plot of the maximum boundary stress versus depth below surface around a circular pipe in a horizontal biaxial stress field, with a negligible internal magma pressure (underpressure conditions). From Barnett and Lorig (2007). Each plotted line represents a specific stress ratio with the labels formatted as "$\sigma_H : \sigma_h$". The solid line plots have an effective stress ratio of 2:1, while the dashed line plots have an effective stress ratio of 5:1. Poisson's Ratio = 0.25, rock density 2800 kg/m^3 and magma pressure = 0 MPa.

systems. Elongations in the shapes of calderas of shield volcanoes in the Kenya Rift Valley are perpendicular to the maximum horizontal component of stress (σ_H), and are explained by Bosworth et al. (2000) to result from stress-induced scaling of the underlying magma chambers. Adamovič and Coubal (1999) note that the intrusive geometries of volcanic systems in the Bohemian massive are strongly elongated perpendicular to the σ_H component of the palaeostress.

Barnett and Lorig (2007) describe numerical modelling undertaken to simulate how a volcanic excavation might grow in the presence of joints through the process of stress-induced scaling or rather slabbing (when joint-bounded blocks detached from the tunnel or pipe sidewall). Case studies presented by Barnett and Lorig (2007) include (a) the Venetia cluster pipes and River Ranch pipe that are elongated WNW-ESE and perpendicular to the expected σ_H at the time of emplacement, (b) the Finsch pipe (South Africa) that develops a distinct elongation with depth that is perpendicular to earlier dykes and the expected σ_H, and (c) satellite carbonatite pipes in the Gross Brukkaros Volcanic Complex (Namibia) that show elongations perpendicular to the locally induced σ_H stress that is orientated radial to the Complex's centre point.

Note that the majority of observed pipe geometries should be elongated parallel to their feeder dykes and controlling

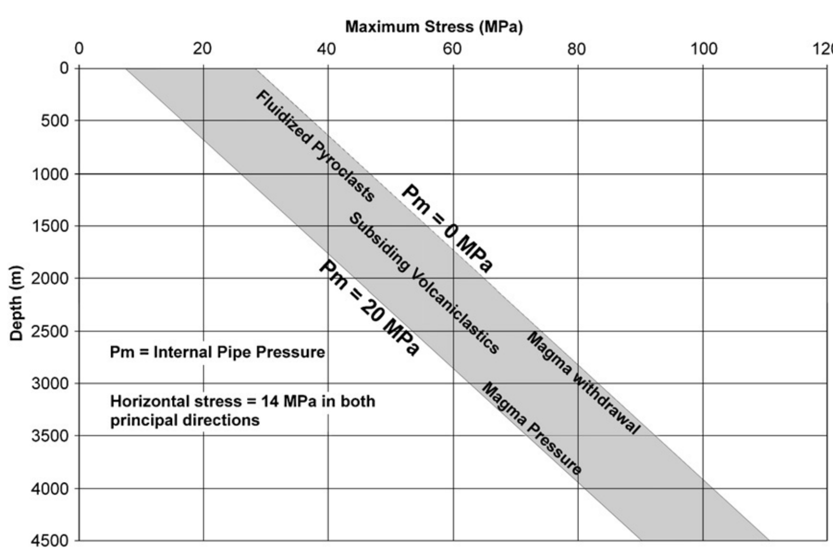

Fig. 6. Graphical representation of maximum stress around a circular pipe versus depth for a range in internal pipe pressures (Pm). Poisson's Ratio = 0.25, rock density = 2800 kg/m3 and $\sigma_H = \sigma_h = 14$ MPa. Some processes that may affect the pipe pressures are indicated.

Please cite this article as: Wayne Peter, B., The rock mechanics of kimberlite volcanic pipe excavation, Journal of Volcanology and Geothermal Research (2008), doi:10.1016/j.jvolgeores.2007.12.021

structures. Stress-induced geometries may only be observed if the intermediate stress region in Fig. 1 is exposed for observation.

6. Conclusions about volcanic pipes

Consider a shallow (<1 km), steep-sided volcanic crater or upper pipe that is partly empty or contains pyroclastic infill that is poorly consolidated or fluidized such that there is negligible internal wall pressure (Hawthorne, 1975; Clement, 1982; McCallum, 1987; Field and Scott Smith, 1999; Gernon et al., 2006; Sparks et al., 2006; Walters et al., 2006). If such a pipe is situated in an adequately jointed rock mass the rock will simply unravel in tension with the sidewalls collapsing into the pipe. Volcanic explosions can reduce the overall rock mass strength by the formation of blasting fractures and the destruction of cohesion on joints, making country rock instability more likely. Unless the horizontal tectonic stresses are very large (>circa 30 MPa), there will be no obvious stress control and the process will be completely dominated by the orientation of the existing structures (faults, joints and fractures). The break-back angle of a volcanic pipe will depend strongly on the rock mass quality. Additional volcanic explosions produce undercutting and a mass deficit at depth (at the site of the explosions) as pyroclastic material is ejected through a central vent (or feeder conduit, Lorenz, 1975; Lorenz et al., 1999; Lorenz and Kurszlaukis, 2007; Gernon et al., 2006; Walters et al., 2006). The surrounding pyroclastic material and country rock mass then gravitationally "block caves" and slumps towards the mass deficit causing the horizontal expansion of the pipe (Laznicka, 1988; Lorenz and Kurszlaukis, 2007). High horizontal tectonic stress and high stress ratios would greatly contribute to the rock mass failure process. Pipe-scale fault structures that intersect the volcanic pipe will create conditions where a large country rock block, potentially hundreds of metres in width, can slide into the pipe significantly increasing the size of the pipe.

High under-pressures in a volcanic pipe can be achieved at intermediate to deep depths (>1 km) within a volcanic pipe provided there is sufficient volatiles available to drive whole-pipe fluidization with the generation of low internal pressures (Gernon et al., 2006; Sparks et al., 2006; Walters et al., 2006) or if there is a drop in internal pipe pressure by magma withdrawal from the base of the pipe. Such under-pressures would aid stress-induced pipe growth processes. Horizontal tectonic stress greater than 20 MPa in magnitude in weak rock, or at least 30 MPa in combination with a high stress ratio (i.e. high differential stress) in true hard rock (UCS>200 MPa) would be required to start creating compressive rock failure in the pipe sidewalls at a depth of circa 1 km (Fig. 5). Sidewall failure by spalling or slabbing of the pipe (Barnett and Lorig, 2007) at lower tectonic stresses can occur at shallower depths in more jointed rock mass or in the presence of intersecting major structures. The pipe growth direction (elongation direction) would be nearly perpendicular to the principal horizontal component of stress. The growth of any volcanic pipe will be strongly aided by the erosive properties of flowing magma and/or pyroclasts through the pipe, as is the case for mining ore-passes (Stacy, 2004; Stacy et al., 2004).

At low horizontal tectonic stress magnitudes and low stress ratios, the magma supply conduit at intermediate depths (1–2.5 km) should remain more dyke-like, orientated parallel to the most compressive stress vector. The conduit would be prevented from expansion by tight stress confinement of the joints. The character of the pipe geometry changes with depth from a structurally and gravitational controlled pipe shape at shallow levels (<1 km) to a more stress controlled dyke-like or an ellipsoidal excavation shape at greater depths. Careful study of the pipe shapes and stratigraphy of a region could offer insight on the depth of erosion of the pipes and give an indication of the orientation and magnitude of tectonic stresses. Understanding the spatial distribution of the internal facies of a volcanic pipe is important for understanding volcanic processes in general, and for determining the distribution of diamonds within a kimberlite pipe ore body. The distribution and characteristics of the internal facies is often a result of rock mechanical behaviour of the pipe sidewall affecting the pipe geometry and integrating with internal pipe processes.

Acknowledgements

The author is grateful to Prof. Steve Sparks for encouraging this publication. De Beers is thanked for permission to publish. The paper benefited from reviews by J. Jakubec, M. Harder and J. Stiefenhofer.

References

Adamovič, J., Coubal, M., 1999. Intrusive geometries and Cenozoic stress history of the northern part of the Bohemian Massif. Geolines 9, 5–14.

Barnett, W.P., 2003. Geological control on slope failure mechanisms in the open pit at Venetia Mine. South African Journal of Geology 106 (2), 149–164.

Barnett, W.P., 2004. Subsidence breccias in kimberlite pipes—an application of fractal analysis. Lithos 76, 299–316.

Barnett, W.P., Lorig, L., 2007. A model for stress controlled pipe growth. Journal of Volcanology and Geothermal Research 159, 108–125.

Barton, N., Bandis, S., 1990. Review of predictive capabilities of JRC–JCS model in engineering practice. In: Barton, Stephansson (Eds.), Rock Joints. Balkema, Rotterdam, pp. 603–610.

Barton, N., Lien, R., Lunde, J., 1974. Engineering classification of jointed rock masses for the design of tunnel support. Rock Mechanics 6, 189–236.

Beniawski, Z.T., 1973. Engineering classification of rock masses. Transactions of the South African Institute of Civil Engineering 15, 335–344.

Beniawski, Z.T., 1978. Determining rock mass deformability: experience from case histories. International Journal of Rock Mechanics and Mining Science 15, 237–247.

Bosworth, W., Burke, K., Strecker, M., 2000. Magma chamber elongation as an indicator of intraplate stress field orientation: 'borehole breakout mechanism' and examples from the Late Pleistocene to recent Kenya Rift Valley. In: Jessel, M.W., Urai, J.L. (Eds.), Stress, Strain and Structure, A Volume in Honour of W.D. Means. Journal of Virtual Explorer, 2.

Brown, R.J., Gernon, T., Tshutlhedi, J., 2006a. Insights Into the Eruption of the Jwaneng Centre Lobe Kimberlite Pipe. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5 pp.

Brown, R.J., Tait, M., Field, M., Sparks, R.S.J., 2006b. Progressive Enlargement and Infill of a Kimberlite Pipe: K2 pipe, Venetia Kimberlite Field, Limpopo Province, South Africa. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5 pp.

Budavari, S., 1983. Response of the rock mass to excavations underground. In: Budavari, S. (Ed.), Rock Mechanics in Mining Practice. The South African Institute of Mining and Metallurgy Monograph Series M5, Chapter 3, pp. 55–76.

Clement, C.R., 1982. A comparative geological study of some major kimberlite pipes in the Northern Cape and Orange Free State. Unpublished PhD thesis, 2 Volumes, University of Cape Town, South Africa, pp. IXX + 432 + 406.

COMRO, 1988. An Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts. Chamber of Mines Research Organisation, Johannesburg, South Africa.

Cookenboo, H.O., 1999. History and process of emplacement of the Jericho (JD-1) kimberlite pipe, Northern Canada. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.G. (Eds.), Proceedings of the 7th International Kimberlite Conference. National Book Printers, Cape Town, South Africa, pp. 125–133.

Coulomb, C.A., 1773. Su rune application des règles de maximus et minimus a quelques problèmes de statique relatifs à l'architecture. Academy of Royal Sciences, Memoires de Mathematics et de Physique par divers savans 7, 343–382.

Crawford, B.B., Porrit, L., Nowicki, T., Carlson, J.A., 2006. Key Geological Characteristics of the Koala Kimberlite, Ekati Diamond Mine, Canada. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5 pp.

Dukes, G.B., van Oort, J., Van Heerden, F.D., 2004. Rockpass stability and rehabilitation at Anglogold Ashanti's Tau Lekoa Mine. Design, Development and Operation of Rockpasses, Colloquium. The South African Institute of Mining and Metallurgy, Saxonwold, Johannesburg. 13 pp.

Downes, P.J., Ferguson, D., Griffin, B.J., 2007. Volcanology of the Aries micaceous kimberlite, central Kimberley Basin, Western Australia. Journal of Volcanology and Geothermal Research 159, 85–107.

Durrheim, R.J., Sellers, E.J., 2004. Rockpasses at ultra deep level. Design, Development and Operation of Rockpasses, Colloquium. The South African Insitute of Mining and Metallurgy, Saxonwold, Johannesburg. 6p.

Field, M., Gibson, J.G., Wilkes, T.S., Gababotse, J., Khujwe, P., 1997. The geology of the Orapa A/K1 kimberlite, Botswana: further insight into the emplacement of kimberlite pipes. Russian Geology and Geophysics 38, 24–29.

Field, M., Scott Smith, B.H., 1999. Contrasting geology and near-surface emplacement of Kimberlite Pipes in Southern Africa and Canada. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.G. (Eds.), Proceedings of the 7th International Kimberlite Conference. National Book Printers, Cape Town, South Africa, pp. 214–237.

Gernon, T.M., Gilbertson, M.A., Sparks, R.S.J., Walters, A., Field, M., 2006. Gas–solid fluidization in an experimental tapered bed: insights into processes in diverging volcanic conduits. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5 pp.

Gill, D.E., Aubertin, M., Simon, R., 1993. A practical engineering approach to the evaluation of rockburst potential. In: Young, R.P. (Ed.), Rockburst and Seismicity in Mines.Balkema, Rotterdam, pp. 63–68.

Graham, I., Burgess, J.L., Bryan, D., Ravenscroft, P.J., Thomas, E., Doyle, B.J., Hopkins, R., Armstrong, K.A., 1998. Exploration history and geology of the Diavik kimberlites, Lac de Gras, Northwest Territories, Canada. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.G. (Eds.), Proceedings of the 7th International Kimberlite Conference. National Book Printers, Cape Town, South Africa, pp. 262–279.

Hart, R., 2004. Case study of Rock Pass System at Kloof No.3 Shaft. Design, Development and Operation of Rockpasses, Colloquium. The South African Insitute of Mining and Metallurgy, Saxonwold, Johannesburg. 5p.

Hawthorne, J.B., 1975. Model of a kimberlite pipe. Physics and Chemistry of the Earth 9, 1–15.

Hetman, C.M., 2006. Tuffisitic kimberlite: a Canadian perspective on a distinctive textural variety of kimberlite. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5p.

Hobbs, B.E., Means, W.D., Williams, P.F., 1976. An Outline of Structural Geology. John Wiley & Sons, Inc., Singapore. 571p.

Hoek, E., 1994. Strength of rock and rock masses. ISRM News Journal 2 (2), 4–16.

Hoek, E., Brown, E.T., 1980a. Empirical strength criterion for rock masses. Journal of the Geotechnical Engineering Division, ASCE 106 (GT9), 1013–1035.

Hoek, E., Brown, E.T., 1980b. Underground Excavations in Rock. ISRM, London. 527p.

Hoek, E., Bray, J.W., 1981. Rock Slope Engineering, Revised 3rd edition. The Institution of Mining and Metallurgy, London. 360p.

Hoek, E., Carranza-Torres, C., Corkum, B., 2002. Hoek-Brown Failure Criterion–2002. In: Hammah, R., et al. (Ed.), 5th North American Rock Mechanics Symposium and 17th Tunneling Association of Canada Conference: NARMS-TAC.Mining and Tunnelling Innovation and Opportunity, vol. 1. University of Toronto Press, Toronto, pp. 267–273.

Jakubec, J., Terbrugge, P.J., Guest, A.R., 1996. Pit slope design at Orapa Mine. Surface Mining Conference. South African Institute of Mining and Metallurgy, Johannesburg, South Africa, pp. 123–135.

Jakubec, J., Terbrugge, P.J., Guest, A.R., Ramsden, F., 2001. Pit slope design at Orapa Mine. In: Hustrulid, W.A., McCarter, M.K., Van Zyl, D.J.A. (Eds.), Slope Stability in Surface Mining. Society for Mining, Metallurgy and Exploration, Inc., pp. 227–238.

Joughin, W.C., Stacy, T.R., 2004. Risks associated with rock passes in deep level tabular mines based on historical pass performance. Design, Development and Operation of Rockpasses, Colloquium. The South African Insitute of Mining and Metallurgy, Saxonwold, Johannesburg. 15p.

Kurszlaukis, S., Barnett, W.P., 2003. Volcanological and structural aspects of the Venetia kimberlite cluster—a case study of South African kimberlite maar-diatreme volcanoes. South African Journal of Geology 106 (2), 165–192.

Laubscher, D.H., 1990. A geomechanics classification system for the rating of rock mass in mine design. South African Institute for Mining and Metallurgy 90 (10), 257–273.

Laubscher, D.H., Taylor, H.W., 1976. The Importance of Geomechanics Classification of Jointed Rock Masses in Mining Operations. Proceedings of the Symposium on Exploration for Rock Engineering, vol. 1. Johannesburg, South Africa.

Laubscher, D.H., Jakubec, J., 2000. The IRMR/MRMR Rock Mass Classification System for Jointed Rock Masses. SME Annual Meeting, Salt Lake City, Utah, pp. 475–481.

Laznicka, P., 1988. Breccias and coarse fragmentites.. Developments in Economic Geology, 25. Amsterdam, Elsevier. 832p.

Lorenz, V., 1975. Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to the formation of kimberlite diatremes. In: Ahrens, L.H., Dawson, J.B., Duncan, A.R., Erlank, A.J. (Eds.), Proceedings of the 1st International Kimberlite Conference, Cape Town, South Africa, 1973. Physics and Chemistry of the Earth, vol. 9, pp. 17–27.

Lorenz, V., Kurszlaukis, S., 2007. Root zone processes in the phreatomagmatic pipe emplacement model and consequences for the evolution of maar-diatreme volcanoes. Journal of Volcanology and Geothermal Research 159, 4–32.

Lorenz, V., Zimanowski, B., Büttner, R., Kurslaukis, S., 1999. Formation of kimberlite diatremes by explosive interaction of kimberlite magma with groundwater: field and experimental aspects. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.G. (Eds.), Proceedings of the 7th International Kimberlite Conference. National Book Printers, Cape Town, South Africa, vol. 2, pp. 522–528.

Mandl, G., 2005. Rock Joints: The Mechanical Genesis. Springer-Verlag, Berlin Heidelberg, Netherlands. 221 pp.

McCracken, A., Stacy, T.R., 1989. Geotechnical risk assessment for large-diameter raise-bored shafts. Transactions of I M M, Section A 98, A145–A150.

McCallum, M.E., 1987. Experimental evidence for fluidization processes in breccia pipe formation. Economic Geology 80, 1523–1543.

McElroy, R., Nowicki, T., Dyck, D., Carlson, J., Todd, J., Roebuck, S., Crawford, B., Harrison, S., 2006. The Geology of the Panda Kimberlite, Ekati Diamond Mine, Canada. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5 pp.

Menzies, I.D., 2004. Key note address: shaft Orepasses. Design, Development and Operation of Rockpasses, Colloquium. The South African Insitute of Mining and Metallurgy, Saxonwold, Johannesburg. 10 pp.

Naidoo, P., Stiefenhofer, J., Field, M., Dobbe, R., 2004. Recent advances in the geology of Koffiefontein Mine, Free State Province, South Africa. Lithos 76, 161–182.

Nowicki, T., Crawford, B., Dyck, D., Carlson, J., McElroy, R., Oshust, P., Helmstaedt, H., 2004. The geology of kimberlite pipes of the Ekati property, Northwest Territories, Canada. Lithos 76, 1–27.

Porrit, L.A., Cas, R.A.F., Crawford, B.B., 2006. The origin and implications of the TK-like infill of the fox kimberlite, Ekati Diamond Mine, NWT, Canada. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5p.

Please cite this article as: Wayne Peter, B., The rock mechanics of kimberlite volcanic pipe excavation, Journal of Volcanology and Geothermal Research (2008), doi:10.1016/j.jvolgeores.2007.12.021

Price, N.J., Cosgrove, J.W., 1990. Analysis of geological structures. Cambridge University Press, Cambridge, UK.

Ryder, J.A., Malan, D.F., 2002. Chapter 4: analytical elasticity and inelasticity. In: Ryder, J.A., Jager, A.J. (Eds.), Rock Mechanics for Tabular Hard Rock Mines. SIMRAC, Johannesburg, pp. 147–192.

Sparks, R.S.J., Baker, L., Brown, R., Field, M., Schumacher, J., Stripp, G., Walters, A.L., 2006. Dynamic constraints on kimberlite volcanism. Journal of Volcanology and Geothermal Research 155, 18–48.

Stacy, T.R., 2004. General guidlelines for the design of rock passes. Design, Development and Operation of Rockpasses, Colloquium. The South African Insitute of Mining and Metallurgy, Saxonwold, Johannesburg. 13p.

Stacy, T.R., Wesseloo, J., Bell, G., 2004. Predicting the stability of rock passes from the geological structure. Design, Development and Operation of Rockpasses, Colloquium. The South African Insitute of Mining and Metallurgy, Saxonwold, Johannesburg. 11p.

Stiefenhofer, J., Farrow, D.J., 2004. Geology of the Mwadui kimberlite, Shinyanga district, Tanzania. Lithos 76, 139–160.

Tait, M.A., Brown, R.J., Mnyama, A., 2006. Internal architecture of the Venetia K1 Kimberlite: a new geological model and implications for kimberlite emplacement processes, Venetia Mine, Limpopo RSA. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5 pp.

Van Straaten, B., Kopylova, M., Russel, K., Webb, K., Scott Smith, B., 2006. Victor Northwest Kimberlite Pipe, Ontario: alternating volcaniclastic and apparent coherent extrusive rocks. Long Abstracts of the 2006 Kimberlite Emplacement Workshop, Saskatoon, Canada. 5p.

Verichev, E.M., Garanin, V.K., Kudryavtseva, G.P., 2003. Geology, composition, conditions of formation, and technique of exploration of the Vladimir Grib Kimberlite Pipe, a new diamond deposit, Arkhangelsk Kimberlite Province. Geology of Ore Deposits 45 (5), 337–361.

Walters, A.L., Phillips, J.C., Brown, R.J., Field, M., Gernon, T., Stripp, G., Sparks, R.S.J., 2006. The role of fluidization in the formation of volcaniclastic kimberlite: grain size observations and experimental investigation. Journal of Volcanology and Geothermal Research 155, 119–137.

Webb, K.J., Scott Smith, B.H., Paul, J.L., Hetman, C.M., 2004. Geology of the Victor Kimberlite, Attawapiskat, Northern Ontario, Canada: cross-cutting and nested craters. Lithos 76, 29–50.

Please cite this article as: Wayne Peter, B., The rock mechanics of kimberlite volcanic pipe excavation, Journal of Volcanology and Geothermal Research (2008), doi:10.1016/j.jvolgeores.2007.12.021