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How Structure and Stress Influence the Location of Kimberlite

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INTRODUCTION

Kimberlite dykes and pipes are often observed to be located on brittle structures and clustered along linear trends parallel to known structural trends. Direct structural control by means of magma migration up through the crust along brittle structures is possible in some specific cases, but dykes are more often observed intruded into non-faulted rock. Combined field observations and numerical modeling provide further context for understanding the development of preferred pathways for kimberlite movement through the lithosphere.

Numerical stress modeling is a tool used to simulate coupled rock-fluid systems in two- and three-dimensions. We use two-dimensional numerical stress-strain models of simplified crustal fabric interpretations and the spatial distribution of known kimberlite occurrences to show that the distribution and orientation of kimberlites is influenced by structure and stress. We conclude that calibrated structure-stress-strain models can be used to understand the distribution and orientation of kimberlites and help exploration for primary diamond occurrences.

DYKE EMPLACEMENT THEORY

The least compressive component of stress is the most important stress component governing the (a) speed of propagation of a dyke fracture, or (b) the ability of the dyke to propagate (e.g. Pollard, 1973; Lister and Kerr, 1991; Anderson, 1979; Rubin, 1995; Gudmundsson, 2002), or (c) the infiltration of a pre-existing structure by a dyke (Delaney et al., 1986). An upward propagating dyke is thereby prevented from propagating by high confining stress. This suggests that the parts of the crust, in which the least compressive horizontal component of stress (σ_h) is lower in magnitude relative to other parts, should be more conducive to allowing kimberlite dykes to reach the surface.

Holyland and Ojala (1997) show that numerically modeled mean horizontal stress is important for gold mineralization. They suggest that hydrothermal fluids migrate towards areas in the crust of low mean stress during regional deformation (see also Feybesse et al., 2006). Sayers (1990) numerically models fluid permeability in fractured rock and concludes that increased compressive stress reduces the permeability of the rock in all directions, including that direction parallel to the σ_1. Permeability is reliant on the connectivity between structures in all directions, including the more tightly compressed structures perpendicular to σ_1. Therefore, low mean stress should improve permeability.

Since kimberlite magma can be considered to behave like a fluid in the crust, areas of low mean stress should be conducive to allowing kimberlites to reach the earth's surface. If a pre-existing structure is present in a suitable orientation, then the dyke will preferentially intrude the structure. Delaney et al. (1986) clearly set out the geometrical conditions governing when dykes will intrude structures. Higher magma pressures and relatively lower confining stresses allow the dykes to intrude structures orientated at a greater angle to the maximum horizontal component of stress.

Following the laws of hydraulic fracturing, dykes tend to propagate parallel to the direction of the greatest (compressive) principal component of stress (σ_1), and lie parallel to the plane defined by the greatest (σ_1) and intermediate (σ_2) principal stress components, and therefore perpendicular to the least compressive principal stress component (σ_3; Pollard, 1973; 1987; Nakamura, 1977). The kimberlite dykes and overall kimberlite occurrence trends are therefore most likely to be closest in orientation to the direction of the maximum horizontal component of stress.

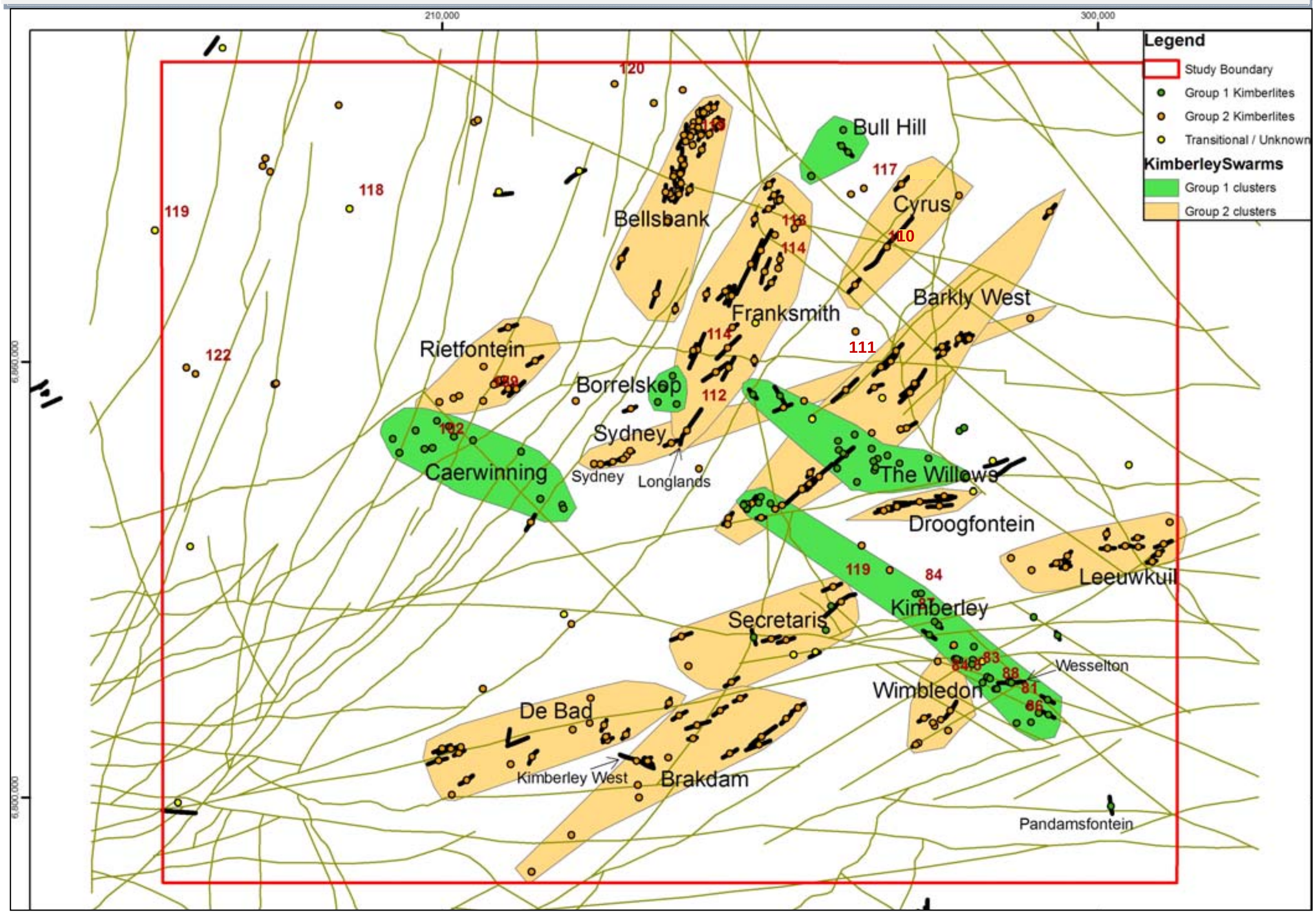

Figure 1: Map showing the Kimberley study area, the location of the two groups of kimberlites and the digitized crustal lineaments. Published radiometric ages are after Jelsma et al. (2009). The coordinates are in UTM 35S projection, on WGS84 datum.

KIMBERLEY STUDY AREA BACKGROUND

In order to investigate the possible relationship between stress, structure and kimberlites, the historically significant greater Kimberley area in South Africa was chosen since it contains over 304 known primary kimberlite occurrences that have been mapped and in many cases excavated since first discovery in 1870. The study area represents an area 110 x 140 km wide (Figure 1). The Kimberley area is also an area within which previous attempts to relate the kimberlite distribution with structural control has been unsuccessful.

The kimberlites were carefully divided into the two mineralogical groups (Group 1 and 2) based on available petrology records. In the Kimberley area the limited radiometric data suggests that the Group 1 occurrences intruded post 100 Ma, while the Group 2 occurrences intruded prior to about 113 Ma. For a compilation of available published geochronology, refer to Jelsma et al. (2009). Internal De Beers studies based on a database of dyke orientation and pipes shapes suggest that the trend of the Group 1 dykes in southern Africa are typically between N100°E and N160°E degrees, such as the well-known Lesotho trend (Jelsma et al., 2009). The trend of Group 2 dykes is typically between N040°E and N060°E degrees. The knowledge of these trends also helped classify the occurrences into the two defined Groups in cases where mineralogical reports were ambiguous or unavailable.

The primary data source for defining the broad structural fabric was a combination of the SANABOZI airborne magnetic data compilation of the entire southern Africa, and in-house De Beers surveys. The crustal fabric was defined by both fault disruptions in the magnetic signature and by mafic dyke intrusions that are regarded to intrude pre-existing major crustal discontinuities. Crustal fabric lineaments were digitized in ArcGIS (ESRI™). Note that the simplified interpretation process was rapid, in order to produce practical results with limited data, and not a full structural interpretation inclusive of kinematics and cross-cutting relationships.

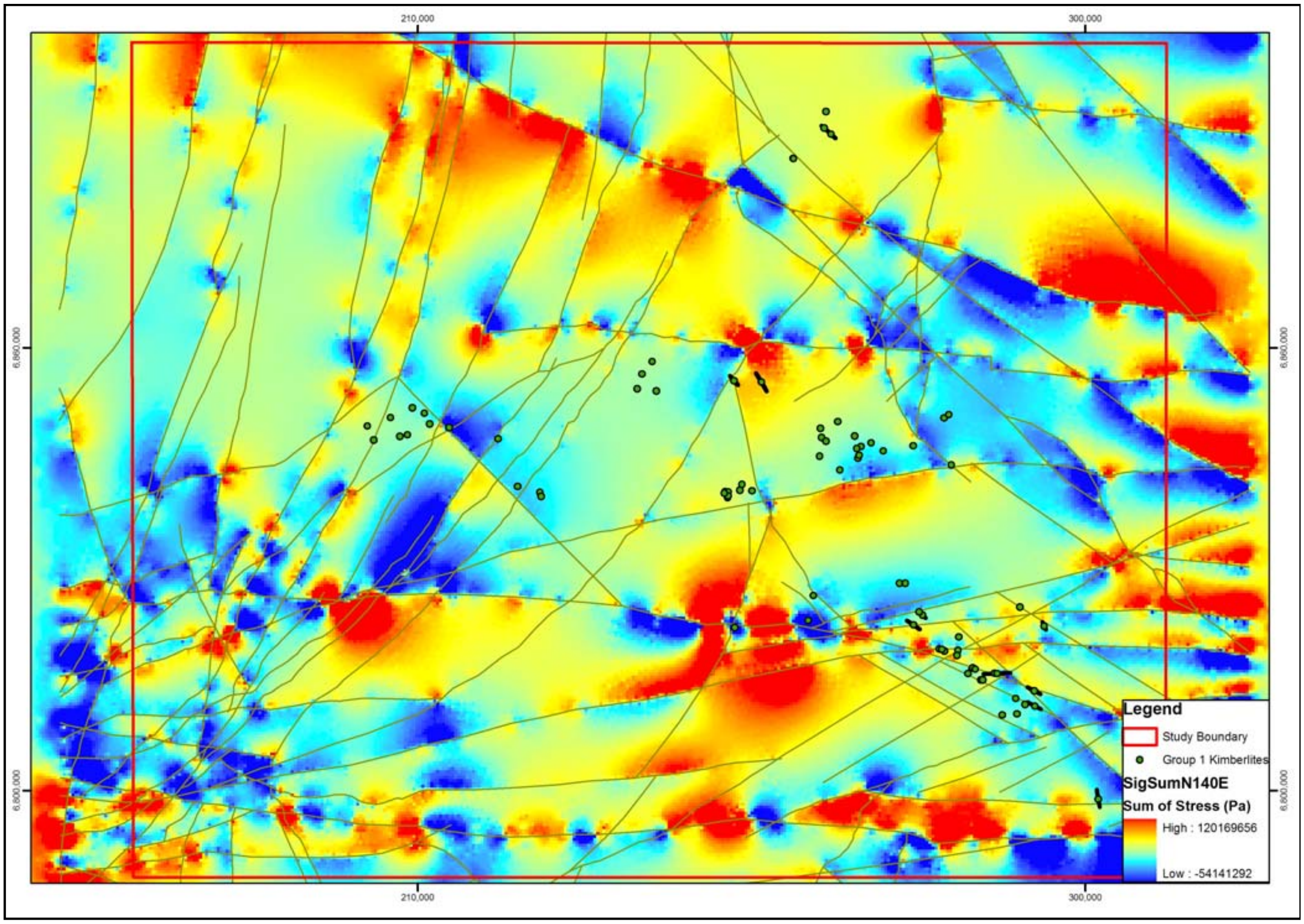

Figure 2: Mean stress (x2) model results for σ_H orientated N140°E. Group 1 kimberlites are preferentially located in lower mean stress areas, with 99% percent chance of being spatially influenced by the stress. The coordinates are in UTM 35S projection, on WGS84 datum.

NUMERICAL MODELING

Universal Distinct Element Code (or UDEC, a trade mark product of Itasca) is a discontinuum code that allows the simulation of discontinuous media like jointed or faulted rock. UDEC appears to have been first used for stress mapping by Holyland and Ojala (1997) who show that both two dimensional and three dimensional stress mapping produces excellent indications of structural control on gold mineralization for targeting purposes.

Scripts were used to export the lineaments from ArcGIS into UDEC. Once the structures are imported, a deformable finite-element mesh is generated within each structure-bounded block. The model was created with an edge rounding radius of 100 m and a mesh edge length of 2000 m. A minimum 10 km border zone acts as a buffer to the model and ensures that no point-loading stresses are applied to the structural model. Sensitivity analyzes have demonstrated that as long as the rock and structural properties are constant throughout the model, the final relative stress distribution of the equilibrated model is insensitive to the actual parameters used (e.g. Young's Modulus, Poissons Ratio, cohesion and friction angle). A simple Mohr-Coulomb failure criterion is used.

The most important model parameters are the applied boundary stress conditions, specifically the ratio (not magnitude) and orientation of the maximum (σ_H) and minimum (σ_h) horizontal components of stress. The models were standardized by making sure that the stress ratio (σ_H:σ_h) is high enough to allow all structures in the model to undergo permanent strain. The orientation of the stress tensor was then rotated in successive experiments to determine a unique model stress distribution for each possible stress orientation. Each numerical model result was only determined once the model had equilibrated such that there were relatively low model grid point velocities. Modeling results were imported into ArcGIS for further analysis and plotting.

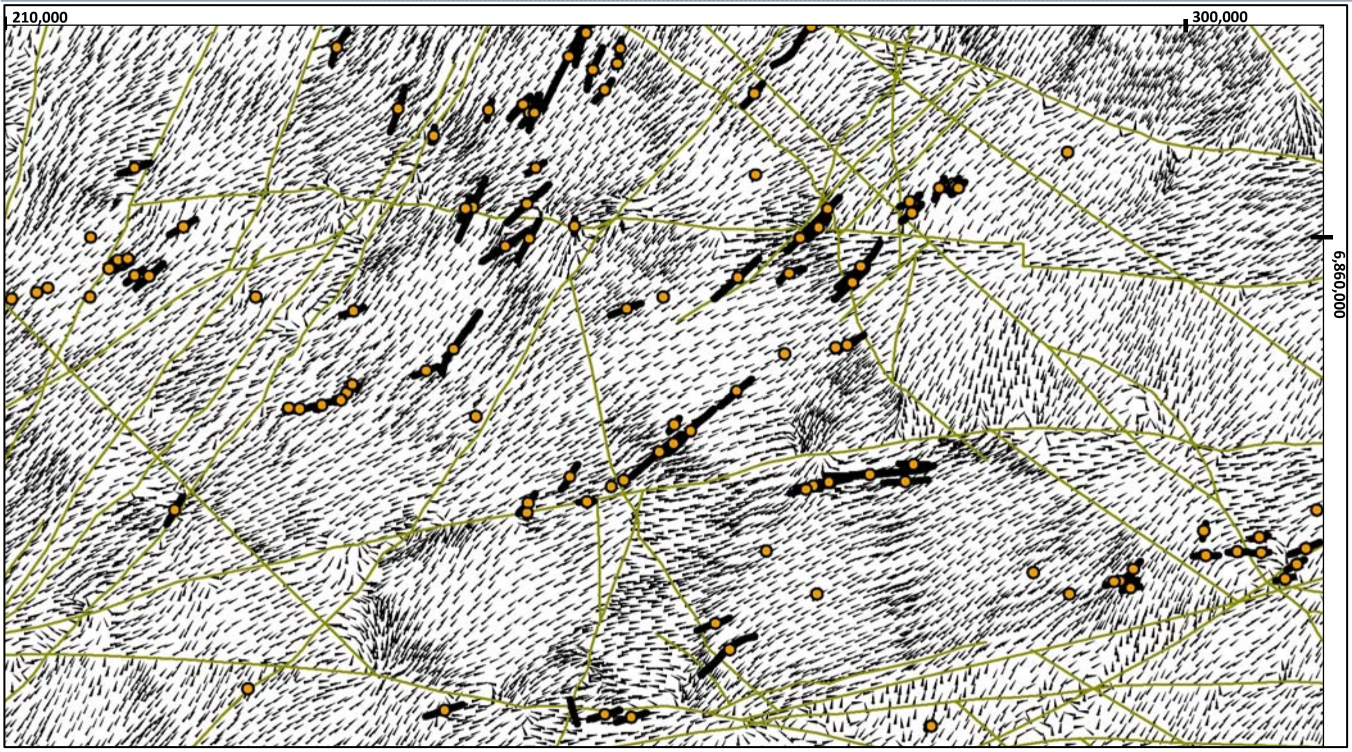

Figure 3: Numerically modeled local σ_H stress vector trends influenced by the crustal fabric, and dykes appear influenced by the stress.

ANALYSIS AND RESULTS

Both visual inspection and quantitative analysis of the stress mapping results was undertaken. The spatial distribution of the known kimberlites show no indication of being correlated to the differential stress (σ_H-σ_h), σ_h magnitude or σ_H magnitude. The sum of stresses (σ_H+σ_h; i.e. 2 x mean stress) model, however, showed positive results in agreement with the theory of dyke emplacement discussed above.

In order to quantify the results, the statistical frequency distribution of background stress values in the entire study area was compared to the frequency distribution of modeled stress values at the location of the kimberlites (the "kimberlite stress" values). If the kimberlites are spatially influenced by the stress and biased towards a particular range of stresses then it would be expected that the stress distribution of the background would be different to that of the kimberlites. If the kimberlites were uninfluenced by the background stress then the stress values at the kimberlite locations would have been a random sample of the background population, with a frequency distribution similar to the background frequency distribution. The statistical assumption that the mean of the kimberlite stress distribution was equivalent to the mean of the background stress was tested with an analysis of variance (ANOVA test) at the 95% confidence level.

The review of all the stress model results relative to the Group 1 kimberlite distribution demonstrated that there was only a 1% probability that the kimberlites were randomly distributed in the models where the σ_H was orientated between N140^{o}E (Figure 2) and N150^{o}E. The corollary of this statement is that there is a 99% chance that the kimberlite is influenced by the stress distribution. Similarly, a comparison of the stress models with the Group 2 kimberlites indicates that there is a 87% chance that the kimberlite is influenced by the stress distribution towards low mean stress regions in models where the σ_H was orientated towards N050^{o}E.

It should be clear after reviewing Figure 1 that the kimberlite occurrences are seldom located on major crustal lineaments, even though the trend of the dykes and clusters of dykes tend towards being parallel to the structures (this can be demonstrated with spatial statistics). A review of the equilibrated model stress orientations on a local scale (Figure 3) demonstrates that the stress refracts through the model, often rotating towards being parallel with local structures. It can therefore be speculated that the trend of the kimberlites is related to the local orientation of the stress tensor, such that it tends to be parallel to the local σ_H. A visual study of the kimberlite dyke orientations in Figure 3 suggests that local variations in σ_H are reflected by the kimberlite orientations.

Aerial and satellite image studies (Hunting Geology and Geophysics (Australia) Pty Ltd, 1983; Greeff, 1968) and local mapping show that the minor, local structures (e.g. faults and joints) are parallel to the regional lineaments in the Kimberley area. Kimberlites therefore either intrude minor structures sub-parallel to the major crustal fabric or intrude parallel to the local σ_H stress. The influence of the mean stress on the location of kimberlites suggests the latter stress-control possibility, even though minor structures are often observed parallel to kimberlite dykes.

LOCAL MINOR STRUCTURES

There is a lack of published case studies documenting the structural patterns around kimberlite dykes. Barnett (1998) shows that the dykes at Finsch Mine (South Africa) are locally parallel to a regional joint set, but the frequency of jointing is much greater within approximately 10 m of the dyke contacts. Exposures of dykes at the Koidu mining operation (Sierra Leone) are excellent and one surface exposure of a dyke system was systematically grid photographed for further studies. At least four ENE trending zones of kimberlite dykes have been historically identified at Koidu (King, 1972). The strong ENE trend is remarkable and the control is considered to be structural. Parallel ENE trending lineaments are identified on satellite images locally and regionally. We present observations of cross-cutting relationships on Koidu dyke exposures that demonstrate that the kimberlite dykes intruded a fracture system that formed in association with the dyke system, not a pre-existing fault zone. It is suggested that the regional ENE trending crustal fabric indirectly controlled the ENE kimberlite trend by means of the local stress orientation.

CONCLUSIONS

We hypothesize that regional structures influence the local stress tensor, which in turn determines the trend of dyke emplacement. In this way the structural architecture of the crust, in combination with regional boundary stress, imparts an indirect control over kimberlite intrusion trends. The regional structures also influence the local stress magnitudes such that kimberlites are preferentially located in areas of low horizontal mean stress. We postulate that areas of high mean stress may form crustal barriers preventing kimberlite from reaching the surface, depending on the magma pressure.

The research results have practical kimberlite exploration benefits, but should also encourage further studies to improve our understanding of how the lithosphere's structural architecture influences kimberlite emplacement; and to use known kimberlites as a key source of information to reconstruct the tectonic palaeo-stress conditions at the time of emplacement.

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