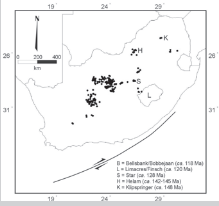
SYN-TECTONIC/SYN-EMPLACEMENT FIBROUS CALCITE VEINS IN KIMBERLITE DYKE-FRACTURE ARRAYS: IMPLICATIONS FOR INTRUSION MECHANISMS

[1]Ian Basson, [1]Giulio Viola and [2]Jodie Miller

1: Department of Geological Sciences, University of Cape Town
Private Bag Rondebosch, 7701, Western Cape, South Africa
2: Department of Geology, University of Stellenbosch, Private Bag X1
Matieland, 7602, South Africa

Introduction

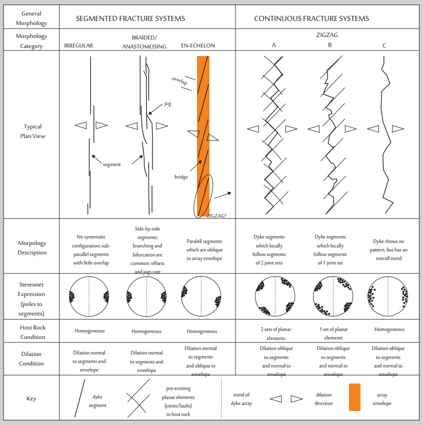
The mode of intrusion of mafic and ultramafic dykes has long been a topic of debate. Classic magmatism, as observed in dolerite dyke swarms, suggests an overpressured magma overcoming the elastic tensile strength of the host rock, thereby propagating laterally and upwards (Hoek, 1994). Recent structural analysis of fibrous calcite veins associated with kimberlite dyke-fracture arrays suggest that these dykes do not accord with classic "overpressured" magmatism. A new model, proposed here, is consistent with the low-volume, low-viscosity, non-Newtonian nature of kimberlitic fluids or magmas, their extremely rapid ascent rates and their coincidence with periods of crustal tension and break-up.



Location of the five Group II kimberlite dyke-fracture arrays in South Africa. Also shown are the Agulhas-Falkland Fracture Zone (Ben-Avraham *et al.*, 1997).

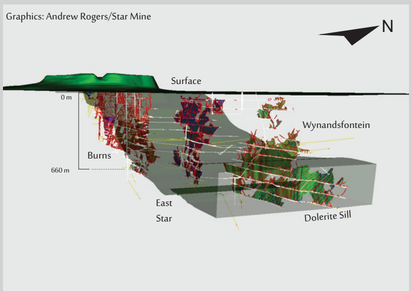
Fracture & Dyke-Fracture Arrays

Dilatant en-echelon fractures are found at a variety of scales, including fringe fractures on joints, quartz-filled veins, surface fractures in volcanic edifices, associated with shear zones and normal faults, and within strained and deformed metals and glasses (Pollard *et al.*, 1982; Lawn, 1993). ***Dyke-fracture*** systems combine a ***fracture system*** and a ***dilational vector field***, with a magma or fluid occupying the fractures. The more generic term ***array*** is applied to an en-echelon collection of dykes. It should be emphasized that ***en-echelon fracture arrays may form in the complete absence of a "driving" fluid or magma phase.***



Dyke-fracture array classification (modified after Hoek, 1994) relies on:
a) Orientation of dykes or dyke-fractures and the array envelope
b) Observed or measured dilation direction
c) The presence and extent of jogs, bifurcations and offsets
d) The presence and abundance of parallel, fully overlapping dykes

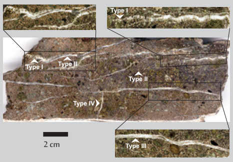
Star Mine



3-D model, based on underground mapping and surveying, of the Star dyke-fracture system. Individual dyke-fractures have been named (Burns, East Star, Wynandsfontein). Note the "twist" or change in trend with depth of the East Star dyke.

Fibrous Calcite Veinlets

The progressive opening of fractures and their infilling by crystalline material is a common ***syntectonic phenomenon***, exemplified by dilating, en-echelon fracture arrays (Ramsay, 1980; Cox and Etheridge, 1983; Cox, 1987; Nicholson, 1991; Urai *et al.*, 1991; Bons, 2000; Hilgers and Urai, 2002). The formation of veins within these dilating fracture arrays occurs by the deposition of quartz, calcite, chlorite, epidote and/or albite. ***Growth of various mineral species concomitant with dilation imparts a fibrous habit to these minerals***. Fibers typically link points that were once in contact with one another and ***define the incremental dilation direction of their host rock***. Abundant calcite veining is evident in all of the Group II dyke-fracture systems, such veins being parallel to the margins of their related or host dyke segments. Calcite veins are usually thin (maximum width of 7 mm), containing multiple fine calcite crystals. Veins occur within the host rock, at kimberlite:host rock contacts and within the kimberlite itself. Veining has traditionally been ignored or assigned to a "post-intrusion" phase of deformation, however, thin section, SEM and isotopic comparisons between veins and the kimberlite matrix indicate that ***at least one generation of calcite veins ("Type I Veins") are both syntectonic*** and ***syn-crystallization***.



Main Dyke
Helam Mine

Polished hand specimen of the Main Dyke (Helam Mine), showing a variety of cross-cutting fibrous and non-fibrous calcite vein types. The vein types (Type I to IV) in this specimen and in dykes from the other four dyke-fracture arrays in South Africa are detailed at right.

Classification

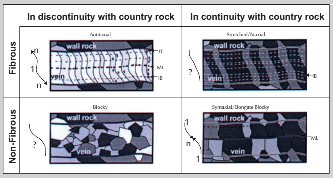
Natural syntectonic/fibrous and non-fibrous veins (modified after Hilgers and Urai, 2002). Arrows = opening direction: **"1"** = growth origin; **"n"** = recent growth. **ML** = Median Line, **IB** = Inclusion Band, **IT** = Inclusion Trail. **"?"** = ambiguous opening sequence.

Antitaxial -Vein minerals compositionally different from host rock minerals. Vein minerals not in crystallographic continuity with host rock minerals. Possible median line, consisting of host rock separated during dilation. Material crystallized along the vein:host rock contact.

Stretched / Ataxial - Vein minerals compositionally similar to those in the host rock. Elongated vein minerals crystallographically continuous across vein. Abundant inclusion bands possible.

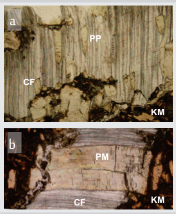
Syntaxial / Elongate Blocky - Vein minerals compositionally similar or identical to those in the host rock and may be "seeded" in host rock. Median line may be present.

Blocky - Vein minerals do not display preferred orientation and may show minor optical continuity with host rock material. Veins have no preferred crystal growth orientation and are not syntectonic.

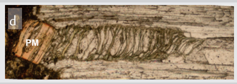


Type I - Stretched or Ataxial

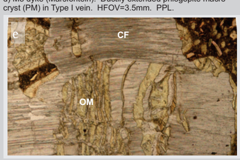
- Very fine, stretched calcite fibres (**CF**), with extremely high aspect ratio
- Calcite fibres are crystallographically continuous with fine-grained kimberlite matrix calcite
- Vein margins crosscut kimberlite matrix (**KM**) (veins typically do not crosscut competent olivine or phlogopite macrocrysts)
- Phenocrystic phlogopite crystals (**PP**) within the vein display sharp terminations, with their tips occurring at the contact of adjacent fine calcite fibers.
- Blocky, prismatic phlogopite is often crystallographically continuous across Type I veins
- Crack-seal inclusions within calcite fibres and strain-free phlogopite phenocrysts and macrocrysts are rare
- Minor extensional cracking of vein phlogopite suggests minor, post-veining extension



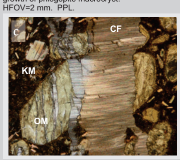
a) Main dyke (Helam Mine). Phlogopite phenocrysts (PP) with sharp terminations and "plucked" kimberlite matrix (KM).
HFOV=1.75 mm. PPL.
b) Main dyke (Helam Mine). Syn-extensional growth of phlogopite macrocryst.
HFOV=2 mm. PPL.



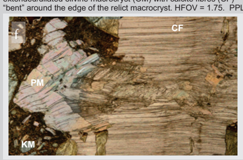
d) M8 dyke (Marsfontein). Ductily extended phlogopite macrocryst (PM) in Type I vein. HFOV=3.5mm. PPL.



e) Macrocrystic dyke (Limacres/Finsch): Type I vein, showing extended/dilated olivine macrocryst (OM) with calcite fibres (CF) "bent" around the edge of the relict macrocryst. HFOV = 1.75. PPL.

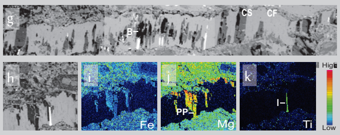


c) Macrocrystic dyke (Limacres/Finsch): Type I vein, showing briken olivine macrocryst (OM) with straight calcite fibres. Note the two phases of vein formation: thin (initial?) veins which exploited the cleavage in olivine, succeeded by a wider fibrous calcite vein (at right). HFOV= 2.75 mm. PPL.



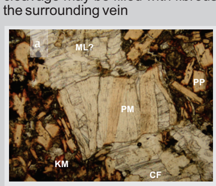
f) Macrocrystic dyke (Limacres/Finsch): Type I vein, showing ductily extended phlogopite macrocryst (PM) within calcite fibres (CF). HFOV = 3.2 mm. XP.

e) SEM Backscatter mosaic of Type I vein in Main Dyke (Helam Mine). Note calcite fibres and possible calcite-serpentine segregations (CS), containing secondary opaques. Highly-reflectant barite (B) extends across the vein. Width of vein = 1mm
h)-i) SEM Backscatter and Fe, Mg and Ti SEM-EDS images of a Type I vein, showing phenocrystic phlogopite (PP) and ilmenite (Ti) growth across the vein.

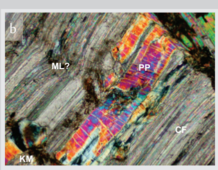


Type II - Stretched to Syntaxial-Elongate Blocky

- Medium-thick calcite fibres, often extending from one side of the host rock contact to the other
- Veins have irregular to planar margins that may crosscut olivine macrocrysts or phlogopite macrocrysts
- No clear median line, or an incipient median line (**ML**)
- Fractured phlogopite macrocrysts (**PM**) and phenocrysts commonly display re-sealing by very fine-grained matrix phlogopite. Their dilated cleavage may be filled with fibrous calcite with the same orientation as the surrounding vein

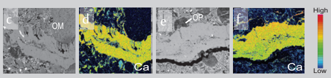


Main Dyke (Helam Mine). Extended and dilated phlogopite macrocryst (PM), showing growth zoning, defined by Fe concentration. Calcite fibres (CF) within the macrocryst show the same orientations as those in the vein itself. Calcite fibres do not transgress the incipient median line (ML?). HFOV = 1.75 mm. PPL.



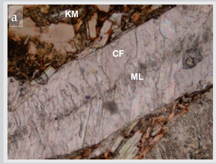
Main Dyke (Helam Mine). Partially chloritized phlogopite phenocryst (PP), displaying copious extension cracks along its length. Note the development of an incipient median line (ML?) through which calcite fibres (CF) do not grow. In contrast, calcite fibres show continuous ("Type I") growth on the opposite side of PP. HFOV = 1.75 mm. PPL.

Main Dyke (Helam Mine). SEM Backscatter and Ca images of Type II veins. The vein in f) shows minor Ca (and thereby low-level Mg) zoning.
HFOV = 1.75 mm.

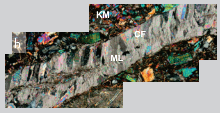


Type III - Antitaxial

- Irregular to highly planar margins that crosscut the kimberlite matrix (**KM**), olivine macrocrysts and phlogopite macrocrysts
- Calcite fibres, which are notably thicker than those in Type I veins, may not be continuous across the vein
- Calcite fibres are not "rooted" or "seeded" in matrix carbonate
- A clearly defined median line (**ML**) is present
- Small linear arrays of inclusions suggest crack-seal deformation
- Vein phlogopite shows extension along cleavage and only very occasionally shows portions of its margins parallel to vein fibres
- Type III veins may incorporate the products of further extension/dilation of Type II veins

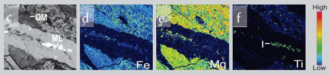


Main Dyke (Helam Mine). Note the well-defined median line (ML), thick/higher aspect ratio calcite fibres (CF) and planar vein:host rock contacts. HFOV = 1.75 mm. PPL.



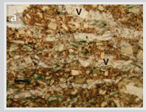
Main Dyke (Helam Mine). Note the well-defined median line (ML), thick/higher aspect ratio calcite fibres (CF) and planar vein:host rock contacts. HFOV = 3.7 mm. XP.

Main Dyke (Helam Mine). SEM Backscatter and Fe, Mg, Ti images of Type III veins. Note the well-defined median line, highlighted by secondary ilmenite (Fe+Ti)
HFOV = 1.75 mm.



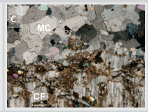
Type IV - Blocky

- Massive, non-fibrous, medium- to coarse-grained, mosaic-textured calcite (**CC**)
- Irregular, discontinuous, anastomosing vein network, which crosscuts matrix material (**KM**) and olivine/phlogopite macrocrysts
- Veining becomes more concentrated towards dyke margins, often culminating in 3-4 mm-wide massive/non-fibrous calcite veins
- No systematic crack-seal inclusions or median lines
- Possible very late-stage quartz infill



Changehouse Dyke (Helam Mine), showing irregular, dicontinuous, anastomosing, non-fibrous veins (V). HFOV = 1.75 mm. PPL.

Limacres/Finsch macrocrystic dyke. Kimberlite matrix shows multiple, irregular, discontinuous, blocky- or mosaic-textured veinlets. HFOV= 1.75mm. PPL.

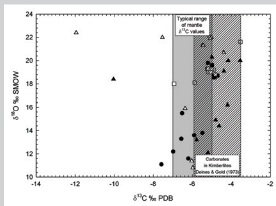


Bellsbank Dyke, showing mosaic/blocky-textured calcite (MC) abutting previously-formed Type II/III vein. Note relatively low aspect ratio calcite fibres (CF) and copious matrix material within the fibrous vein. HFOV=1.75. XP.

Isotopes

A total of 31 host rocks and 22 veins have been analysed for d^{13}C and d^{18}O values of calcite. The d^{18}O values of 13 samples of host/country rocks to the kimberlite dykes have also been determined. All the calcite samples were collected using a microdrill to accurately sample specific positions within hand-specimens of veined kimberlite. Thirteen samples of the host/country rocks to the kimberlite were treated with dilute HCl, to remove any carbonate material, and were analyzed for the d^{18}O value of their silicate fraction. The data show several features:

1) The great majority of calcite veins have uniform d^{13}C values of -5.5 ± 1.0‰ indicative of mantle carbon (typical value of -5.0‰), supporting the petrographic evidence of a "syn-intrusion/syn-dilation" origin, with the formation of fibrous calcite veinlets containing very low-viscosity CO_2-rich fluids. A single calcite vein has a noticeably lower d^{13}C value of -12.0‰. The origin of this is unclear but it may reflect input from marine carbonate material, possibly in the form of resorbed xenoliths.
2) The hypabyssal kimberlites which host the calcite veins have more variable and slightly more positive d^{13}C values of -4.9 ± 1.5‰ which may reflect the input of a minor fraction of carbonate material from the host rocks to the kimberlite dykes, again, possibly in the form of resorbed xenoliths.
3) The silicate portion of shales hosting the kimberlite dykes have significantly lower d^{18}O values than expected, by up to 5‰
4) Calcite veins have more variable d^{18}O values (10.8 - 22.4‰), possibly reflecting variable re-equilibration with fluids derived from the silicate host rocks to the kimberlite dykes
5) The d^{18}O values of the carbonate-rich matrix of the host kimberlite exhibit a similar range to the calcite veins themselves, but are in general slightly lower by approximately 1.0‰. The relationship between specific calcite veins and their immediate kimberlite host rocks is still being examined.



d^{18}O (smow) versus d^{13}C (pdb) plot for carbonate material from carbonate veins and their kimberlitic host rocks. Closed circles = kimberlite host rocks from Star, squares = Helam (open squares = veins, closed squares = host rocks), triangles = Klipspringer (open triangles = veins, closed triangles = host rocks). Typical mantle carbon is -6.0 ‰ (grey shading), whilst Deines & Gold (1973) found that carbonate material from 13 kimberlites had an average d^{13}C value of 4.7 ± 1.2 ‰ (cross-hatching). Helam samples plot in a narrow range, indicating that veins and host rocks have probably not undergone post-emplacement modification of stable isotope values. In contrast Klipspringer samples have variable stable isotope values, often much removed from mantle carbon values, suggesting post-emplacement modification, possibly through interaction with carbonate country rocks. d^{18}O values are variable across the three locations, suggesting a local control on the d^{18}O composition of the carbonate material.

Conclusions

· Kimberlite dyke-fracture systems contain thin, fibrous calcite veins, which were formed during dyke emplacement (particularly Type I and Type II fibrous veins), or repeated dilation on dyke-fracture systems (Type II and Type III veins).
· Such veins are ubiquitous throughout kimberlite dyke-fracture systems in South Africa (e.g. Star, Helam, Klipspringer, Bellsbank/Bobbejaan, Limacres/Finsch).
· Stable isotope analyses confirm that fibrous calcite veins originate from mantle fluids, and not from post-emplacement fluids circulating in the vicinity of the dyke-fracture systems. This, in turn, suggests a two-phase "partitioning" of, firstly, low-viscosity kimberlitic magmas into the dilating en-echelon fracture system, followed by partitioning of a highly volatile, CO2-rich phase into actively dilating areas within the kimberlite.
· Fibrous veins and other macroscopic dilational features in the kimberlites suggest that the country rock was actively dilating during dyke emplacement, i.e. that the dyke-fracture system was not overpressured ("passive emplacement"; Basson and Viola, 2003).

Acknowledgements

The authors express their gratitude to Andrew Rogers, Jim Davidson, Flynn Nothling and Louwrens du Plessis of Star and Helam mines, for allowing access to the geology, guidance through the stopes/structural features and for permission to publish this work. James Napier and Izak van Vuuren of Southern Era Klipspringer are thanked for their assistance at Klipspringer Mine. Andrew and Sheridan Rogers, Flynn Nothling, Damian Smith and Ruth Stenhouse are thanked for providing accommodation during fieldwork. The base map for Gp II localities was supplied by Hielke Jelsma, with permission from Craig Smith (De Beers). This study was undertaken as part of a National Research Foundation Post-Doctoral Fellowship and was partly supported by a grant from the Kent Trust, administered by the Geological Society of South Africa. UCT's Kimberlite Research Group (KRG) is thanked for its contribution towards running costs.

References

Basson, I.J. and Viola, G. (2003). Structural overview of selected Group II kimberlite dyke arrays in South Africa: Implications for kimberlite emplacement mechanisms. *South African Journal of Geology*, **106(4)**, 375-394.
Ben-Avraham, Z., Hartnady, C.J.H. and Kitchin, K.A. (1997). Structure and tectonics of the Agulhas-Falkland fracture zone. *Tectonophysics*, **282**, 83-98.
Bons, P.D. (2000). The formation of veins and their microstructures. In: Jessell, M.W. and Urai, J.L. (Eds.), *Stress, Strain and Structure: A volume in honour of W.D. Means. Journal of the Virtual Explorer*, **2**.
Cox, S.F. (1987). Antitaxial crack-seal microstructures and their relationship to displacement paths. *Journal of Structural Geology*, **9(7)**, 779-787.
Cox, S.F. and Etheridge, M.A. (1983). Crack-seal fibre growth mechanisms and their significance in the development of oriented layer silicate microstructures. *Tectonophysics*, **92**, 147-170.
Deines, P. and Gold, D.P., 1973. The isotopic composition of carbonatite and kimberlite carbonates and their bearing on the isotopic composition of deep-seated carbon. *Geochimica et Cosmochimica Acta*, **37**, 1709-1733.
Hilgers, C. and Urai, J.L. (2002). Microstructural observations on natural syntectonic fibrous veins: implications for the growth process. *Tectonophysics*, **352**, 257-274.
Hoek, J.D. (1994). *Mafic Dykes of the Vestfold Hills, East Antarctica*. Ph.D. Thesis (unpubl.), University of Utrecht, 134pp.
Lawn, B.R. (1993). *Fracture of Brittle Solids - Second Edition*. Cambridge University Press, Cambridge, United Kingdom, 378 pp.
Nicholson, R. (1991). Vein morphology, host rock deformation and the origin of the fabrics of echelon mineral veins. *Journal of Structural Geology*, **13(6)**, 635-641.
Pollard, D.D., Segall, P. and Delaney, P.T. (1982). Formation and interpretation of dilatant echelon cracks. *Geological Society of America Bulletin*, **93**, 1291-1303.
Ramsay, J.G. (1980). The crack-seal mechanism of rock deformation. *Nature*, **284**, 135-139.
Urai, J.L., Williams, P.F. and van Roermund, H.L.M. (1991). Kinematics of crystal growth in syntectonic fibrous veins. *Journal of Structural Geology*, **13(7)**, 823-836.