11th SAGA Biennial Technical Meeting and Exhibition
Swaziland, 16 - 18 September 2009, pages 17 - 20

Orthogonal AMS and SPO fabrics in the MORB-like Rooi-Rand dyke swarm of South Africa and Swaziland

Warwick Hastie[1], C. Aubourg[2], M. K. Watkeys[3]

1. School of Geological Sciences, University of KwaZulu-Natal, South Africa, 203505849@ukzn.ac.za
2. University of Cergy Pontoise, Cergy, France, charly.aubourg@u-cergy.fr
3. School of Geological Sciences, University of KwaZulu-Natal, South Africa, watkeys@ukzn.ac.za

ABSTRACT

The cause of the ca. 185-175 Ma Karoo volcanism in southern Africa has been ascribed to the presence of a mantle plume centred on the Nuanetsi (now Mwenezi) Igneous Province, southern Zimbabwe. In the mantle plume model, this area is considered to represent a triple junction between the WNW-trending Okavango Dyke Swarm (ODS), the ENE-trending Sabi monocline and the N-S trending Lebombo monocline. The plume model predicts that magma flow in Karoo dykes of the Lebombo monocline should be away from the plume head and should be sub-horizontal in the distal regions. A brief study of the anisotropy of magnetic susceptibility (AMS) of 23 dykes in the MORB-like Rooi-Rand dyke swarm (RRDS) is presented. The AMS in the samples results from fine-grained, Ti-poor magnetite which in 20 dykes defines fabric sub-parallel to the dyke plane, consistent with the plume model. The magnetite defines a weakly anisotropic and dominantly oblate fabric. From a total of 10 dykes studied for plagioclase mineral shape preferred orientation (SPO), 8 have a dyke-parallel foliation most consistent with vertical magma flow. The plagioclase grains define a weakly anisotropic, oblate fabric, which is magmatic in origin. In 8 dykes this fabric is coaxial with the AMS fabric. However, in 40% of the dykes, the fabric defined by the SPO of opaque grains is non-coaxial with AMS and is at a high angle to the dyke plane and dips steeply. The non-coaxial AMS and SPO fabric, coupled with the orthogonal SPO fabrics suggests that late-stage lateral flow of relatively high viscosity magma has occurred. This results in a fabric which most workers would regard as "inverse" and/or non-magmatic, and, therefore, would misinterpret.

Key words: Lebombo monocline, Karoo mantle plume, AMS, magma flow

INTRODUCTION

Studies of the anisotropy of magnetic susceptibility (AMS) in magmatic rocks tend to focus on results which reveal flow-related fabrics, and are therefore geodynamically significant in terms of magmatic emplacement directions and conditions (Knight & Walker, 1988 ; Aubourg *et al.*, 2008). This study began as such, focusing on the magnetic fabrics of MORB-like dolerite dykes of the Rooi-Rand dyke swarm (RRDS). However, the appearance of significant "inverse" and irregular magnetic fabrics allowed a shift in focus of the study. Inverse magnetic fabrics are generally attributed to the appearance of very fine-grained single domain (SD) magnetite grains (Rochette *et al.*, 1999). The results of this study, however, show that the magnetic fabric, when compared to the silicate fabric (mineral shape preferred orientation [SPO]), suggests that both the AMS and SPO fabrics are the result of very late-stage flow of highly viscous magma.

The RRDS is a north-south (N-S) trending dyke swarm, approximately 200km long, extending from the Msunduze River in KwaZulu-Natal northwards into east-central Swaziland (Saggerson *et al.*, 1983 ; Duncan *et al.*, 1990 ; Meth, 1996) (Figure 1). The swarm is 10-22km thick and intruded basalts and sedimentary rocks of the Karoo Supergroup just to the west of the main Lebombo range, which comprises mostly rhyolites (Eales *et al.*, 1984). The Lebombo faulted monocline developed during extensive Karoo magmatism from ~184 Ma to ~174 Ma, during which some $3x10^6$ km^2 of basaltic lava covered parts of Southern Africa and Antarctica (Eales *et al.*, 1984 ; Encarnación *et al.*, 1996). The eastward tilting and domino-style faulting has resulted in a monocline-type appearance – owing to the separation of Antarctica from what is now the northeast coast of South Africa during the break-up of Gondwana (Eales *et al.*, 1984 ; Watkeys, 2002).

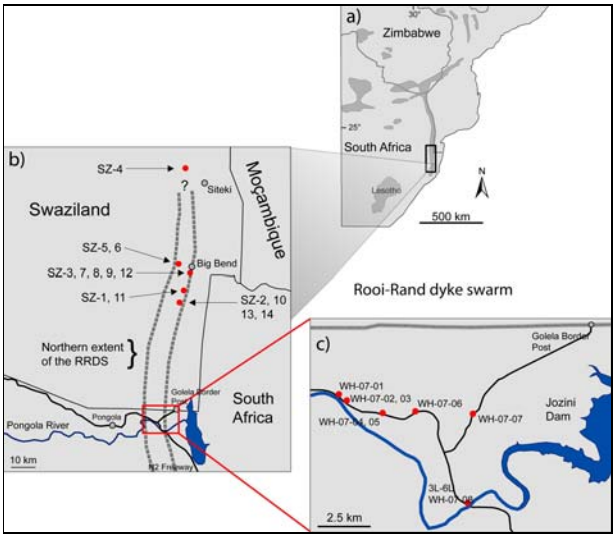

Figure 1: Locality maps of the Rooi-Rand dyke swarm showing a) the sampled area of the Lebombo monocline (dark grey) (re-drawn from Cox, 1992), b) south eastern Swaziland and the sampling sites of the northern RRDS and c) sampling sites of the central RRDS along the Pongola River in northern KwaZulu-Natal province, South Africa.

METHODOLOGY

Sampling

Core samples 25mm in diameter and 40-200mm in length were taken from opposing margins of a single dyke using a hand-held petroleum powered drill. Each sample is orientated using both a core-orientator magnetic compass and sun compass. For this study in particular, 12 samples from the central RRDS were used and 48 samples from the northern RRDS, representing a total of 7 dykes (see Figure 1).

Anisotropy of Magnetic Susceptibility

Anisotropy of magnetic susceptibility (AMS) has become a standard tool for the analysis of rock fabrics, most notably characterizing possible flow related fabrics in volcanic and intrusive rocks (Khan, 1962 ; Ellwood, 1978 ; Knight & Walker, 1988 ; Rochette *et al.*, 1992 ; Dragoni *et al.*, 1997). AMS is represented as an ellipsoid, the shape and orientation of which is most commonly described. The magnetic lineation is referred to as k1 and the pole to magnetic foliation as k3. In dykes, AMS ellipsoids are determined from opposing margins of an intrusion, which provide constraint on the original magma flow orientation because it is possible to recognize imbrication of either the magnetic foliation, lineation or both which may provide the magma flow sense (Geoffroy *et al.*, 2002). Minerals such as multi-domain (MD) magnetite, pyrrhotite, hematite and phyllosilicates are the most common carriers of magnetic susceptibility which have a normal magnetic fabric although single domain (SD) magnetite is commonly inverse (Potter and Stephenson, 1988 ; Rochette *et al.*, 1999). With increasing use of AMS it has become evident that complications arise during the interpretation of AMS data, mostly regarding the shape of the fabric, its relation to the rock fabric/orientation (e.g. the dyke plane in this case) and also the relationship between the magnetic minerals and the fabric which they produce (e.g. Launeau and Cruden, 1998). Thus, the aim here is to possibly unravel some causes of such complications through quantitative thermal experiments and the relationship between rock fabric and magnetic fabric is examined using the shape preferred orientation (SPO) of both opaque mineralogy and plagioclase grains.

Mineral Shape Preferred Orientation

Magmatic flow in intrusions results in rigid body rotation and movement of crystals in the magma (Cañón-Tapia and Chávez-Álvarez, 2004). As a result, the recognition of magmatic flow in the rock fabric is usually in the form of a shape preferred orientation (SPO) of inequant grains, such as plagioclase. Such data is therefore useful as it supplements AMS data for the purpose of determining magma flow direction. The work presented provides a detailed account of the mineral SPO in the RRDS, in which the ratio of AMS samples to SPO samples will be ~4:1, as opposed to ~9:1 (Callot *et al.*, 2001). Most of the pioneering work in studying mineral SPO's has arisen from the research of Patrick Launeau into methods of comparing SPO's with AMS, and evidently the determination of magma flow from such data (Launeau and Robin, 1996 ; Launeau and Cruden, 1998 ; Launeau, 2004). Some deviation in the orientation of the petro-fabric from the magnetic fabric is, however, to be expected (Archanjo and Launeau, 2004). The method employed in this work involves digitally filtering plagioclase and opaque grains from photomicrographs using Adobe® Photoshop®. The resulting Bitmap images are then analyzed using the program "SPO 2003" (Launeau and Cruden, 1998). Between 300 and 2800 grains are indexed per thin section. Each photomicrograph is analyzed using the inertia tensor method, as it is directly comparable to the AMS tensor. From such data the 3-D shape preferred orientation (SPO) of grains is determined (Launeau, 2004).

Thermal AMS Monitoring

It has been shown that thermally treating AMS samples can change and/or improve the magnetic fabric by: [1] oxidizing magnetite, leading to a decrease in susceptibility (Henry *et al.*, 2003), [2] growing new grains along pre-existing fabrics (Mintsa Mi Nguema *et al.*, 2002) and [3] revealing pre-existing tectonic fabrics (Souque *et al.*, 2002). Whether thermal stress (up to ~700°C) is a valuable test of normal magnetic fabric in dolerite remains to be established. However, it is expected that growth and/or destruction of magnetic minerals will occur. The method used in this study involves monitoring changes in magnetic fabric at 100°C intervals for 2 dykes (central RRDS) from room temperature to 700°C. A second experiment, carried out on 48 samples of the northern RRDS involves three steps in heating: room temperature, 300°C and 700°C. Furthermore, for these samples it is possible to calculate the orientation and intensity of the difference tensor between thermal steps, allowing a more detailed analysis of fabrics which have been removed or added. The AMS measurements were carried out on a Kappabridge KLY-3 anisotropy magnetometer. The principle AMS axes are represented as lower hemisphere equal area projections.

RESULTS

Magnetic Fabric

Results of an anisotropy of magnetic susceptibility (AMS) study of 23 dykes from the RRDS reveals a predominantly normal fabric (60% of total data) carried by relatively pure magnetite. The magnetic foliation, on average, is congruent with the average north-south dyke planes. The imbrication of the magnetic foliation is consistent with lateral magma flow from the north. This is consistent with the Karoo mantle plume model. However, the initial AMS assessment of the magnetic fabric of the RRDS also shows that 30% of the samples have "inverse" or irregular magnetic fabric in the natural state. Park *et al.* (1988) conducted one of the few thermal AMS treatment studies on the Mealy diabase dykes of Labrador, Canada. Essentially, they showed, similarly, that the magnetic fabric of the magnetite-bearing dykes was irregular and scattered in the natural state, as opposed to a better grouped and significant AMS fabric after heating to 640°C.

Thermal AMS Monitoring

The magnetic fabric, in general, appears to be initially flow related, but the fabric becomes increasingly poorly defined with increasing thermal treatment. Thermal demagnetization of samples reveals a pattern of "inverse" fabric, even after heating to 700°C. It is found that 28% of the total of 60 samples has a magnetic foliation which is orthogonal to the dyke plane of the respective dyke. The appearance of this fabric is associated with a decrease in bulk susceptibility (*Km*), evidently resulting from the loss of signal of a fine-grained magnetic phase (Henry *et al.*, 2003). Although this may be dismissed as inverse magnetic fabric, what cannot be ignored is the appearance of a similarly orientated fabric in the SPO results, as discussed above. The decrease of *Km* with heating, with an associated change in orientation in principle axes, indicates that minerals of the primary fabric are lost, and not replaced by a similar fabric. It is for this reason that it cannot be assumed that the enhancement of primary magnetic fabric can be achieved simply by heating samples (Mintsa Mi Nguema *et al.*, 2002).

Mineral Shape Preferred Orientation

A study of plagioclase and opaque grain orientations is consistent with AMS results. The plagioclase grains measured ($n=2.1x10^5$) define a weakly anisotropic, oblate fabric. This fabric is indicative of being magmatic in origin and in 8 dykes is coaxial with the AMS fabric. However, 40% of the data are not comparable because the foliation plane is orthogonal to the dyke plane. This unexpected fabric is most pronounced in the opaque grain fraction suggesting that macroscopic opaque (magnetite) grains are not necessarily controlling the magnetic signal of AMS.

CONCLUSIONS

The heating of samples has an effect on *Km* due to changes (e.g. oxidation) in the magnetic carriers (e.g. magnetite or sulphides). Correctly interpreting these changes in terms of AMS is important, because the AMS fabric inversion still persists in some sites and in others increases with increasing temperature (Souque *et al.*, 2002). It appears; firstly, that fine-grained magnetite in certain samples dominates the AMS signal, until they are demagnetized. This results in SD grains dominating the AMS signal after heating and the orientation of this fabric in essentially "inverse". This can be demonstrated by the orthogonal relationship between the magnetic foliation and dyke plane. Secondly, the results suggest that the measured AMS not only measures the grain shape, but also a change in orientation and/or distribution of the new magnetic phases. This provides a useful comparison to the orientation of SPO ellipsoids, which provide constraint on the true silicate petro-fabric. In summary, the results suggest that it is possible for secondary fabrics, whatever their cause, to mimic the primary silicate fabric. Aarnes *et al.* (2008) have found that a melt of basaltic viscosity can undergo significant post-emplacement flow, even if the matrix has 99% crystallized. This flow is strongly influenced by the crystal percentage and the cooling profile, which in dykes is controlled by internal magma pressure and the dyke width. The effect this may have on both AMS and SPO studies is clearly related to potentially picturing only the very late stage magma flow, which may provide little insight into the overall flow direction of the dyke as a whole. Thus, this work suggests that [1] unexpected fabrics may be preserved in the SPO of plagioclase and more commonly, by opaque grains, and thermally demagnetized AMS, [2] natural AMS is not strictly linked with the silicate (SPO) fabric, whether AMS is "inverse" or not and [3] the origin of the orthogonal SPO fabric may be related to late stage flow (post-emplacement) of viscous magma, resulting in grains "rolling" through the silicate mush, rather than imbricating against the dyke margin in the expected manner.

ACKNOWLEDGEMENTS

The authors are extremely grateful for the funding provided to this project by both the NRF in South Africa and the CNRS in France through the co-operative PICS programme. Without this funding, such international co-operation would not have been possible.

REFERENCES

Aarnes I., Podladchikov Y. Y. and Neumann E.-R., 2008, Post-emplacement melt flow induced by thermal stresses: Implications for differentiation in sills: Earth and Planetary Science Letters, 276, 152-166.

Archanjo C. J. and Launeau P., 2004, Magma flow inferred from preferred orientations of plagioclase of the Rio Cearf-Mirim dyke swarm (NE Brazil) and its AMS significance. In: Martin-Hernandez F., Luneburg, C. M., Aubourg, C. and Jackson, M. (eds.). Magnetic Fabric: Methods and applications, Geological Society of London, Special Publication, 238, 285-298.

Callot J. P., Geoffroy L., Aubourg C., Pozzi J. P. and Mege D., 2001, Magma flow directions of shallow dykes from the East Greenland volcanic margin inferred from magnetic fabric studies: Tectonophysics, 335, 313-329.

Cañón-Tapia E. and Chávez-Álvarez M. J., 2004, Theoretical aspects of particle movement in flowing magma: implications for the anisotropy of magnetic susceptibility of dykes. In: Martin-Hernandez F., Luneburg, C. M., Aubourg, C. and Jackson, M. (eds.). Magnetic Fabric: Methods and Applications, Geological Society of London, Special Publication, 238, 227-249.

Dragoni M., Lanza R. and Tallarico A., 1997, Magnetic anisotropy produced by magma flow: theoretical model and experimental data from Ferrar dolerite sills (Antarctica): Geophysical Journal International, 128, 230-240.

Ellwood B. B., 1978, Flow and emplacement direction determined for selected basaltic bodies using magnetic anisotropy measurements: Earth and Planetary Science Letters, 41, 254–264.

Geoffroy L., Callot J. P., Aubourg C. and Moreira M., 2002, Divergence between magnetic and plagioclase linear fabrics in dykes: a new approach for defining the flow vector using magnetic foliation: Terra Nova, 14, 183-190.

Henry B., Jordanova D., Jordanova N., Souque C. and Robion P., 2003, Anisotropy of magnetic susceptibility of heated rocks: Tectonophysics, 366, 241-258.

Khan M. A, 1962., The anisotropy of magnetic susceptibility of some igneous and metamorphic rocks: Journal of Geophysical Research, 67, 2873-2885.

Knight M. D. and Walker G. P. L., 1988, Magma flow directions in dikes of the Koolau Complex, Oahu, determined from magnetic fabric studies: Journal of Geophysical Research, 93, 4301-4319.

Launeau P., 2004, Mise en évidence des écoulements magmatiques par analyse d'images 2-D des distributions 3-D d'Orientations Préferentielles de Formes: Bulletin of the Geological Society of France, 175, 331-350.

Launeau P. and Cruden A. R., 1998, Magmatic fabric acquisition mechanisms in a syenite: Results of a combined anisotropy of magnetic susceptibility and image analysis study: Journal of Geophysical Research, 103, 5067-5089.

Launeau P. and Robin P.-Y. F., 1996, Fabric analysis using the intercept method: Tectonophysics, 267, 91-119.

Mintsa Mi Nguema T., Trindade R. I. F., Bouchez J.-L. & Launeau P., 2002, Selective thermal enhancement of magnetic fabrics from the Carnmenellis granite (British Cornwall): Physics and Chemistry of the Earth, 27, 1281-1287.

Park J. K., Tanczyk E. I. and Desbarats A., 1988, Magnetic fabric and its significance in the 1400 Ma Mealy diabase dykes of Labrador, Canada: Journal of Geophysical Research, 93, 13689-13704.

Potter D. K. and Stephenson A., 1988, Single-domain particles in rocks and magnetic fabric analysis: Geophysical Research Letters, 15, 1097-1100.

Rochette P., Aubourg C. and Perrin M., 1999, Is this magnetic fabric normal? A review and case studies in volcanic formations: Tectonophysics, 307, 219-234.

Rochette P., Jackson M. and Aubourg C., 1992, Rock magnetism and the interpretation of anisotropy of magnetic susceptibility: Reviews of Geophysics, 30, 209-226.

Souque C., Robion P. and Frizon de Lamotte D., 2002, Cryptic magnetic fabric of tectonic origin revealed by heating of sedimentary samples from the Corbières (France): Physics and Chemistry of the Earth, 27, 1253-1262.