COPYRIGHT AND CITATION CONSIDERATIONS FOR THIS THESIS/ DISSERTATION

This copy has been supplied on the understanding that it is copyrighted and that no quotation from the thesis may be published without proper acknowledgement.

Please include the following information in your citation:

- Name of author
- Year of publication, in brackets
- Title of thesis, in italics
- Type of degree (e.g. D. Phil.; Ph.D.; M.Sc.; M.A. or M.Ed. …etc.)
- Name of the University
- Website
- Date, accessed

Example

Paleomagnetism of post-Transvaal sill complexes, selected dykes and the Uitkomst Complex - relation to the Bushveld Complex

by

Hervé Wabo

THEESIS

Presented in fulfillment of the requirements for the degree of

PHILOSOPHIAE DOCTOR

in

GEOLOGY

in the

FACULTY OF SCIENCE

of the

UNIVERSITY OF JOHANNESBURG

Supervisor
Dr. M.O. de Kock

Co-supervisor
Prof. N.J. Beukes

February 2013
Declaration

I declare that this thesis is my own original work, conducted under the supervision of Dr. M.O. de Kock and Prof. N.J. Beukes. It is submitted for the degree of Doctor of Philosophy at the Faculty of Science at the University of Johannesburg, Johannesburg. No part of this research has been submitted in the past, or is being submitted for a degree or examination at any other University.

H. Wabo
CONTENTS

CONTENTS I
ABSTRACT IX
ACKNOWLEDGMENTS XI

CHAPTER 1

INTRODUCTION AND PURPOSE OF THE THESIS 1

1.1. INTRODUCTION 1
1.1.1. The Bushveld Large Igneous Province 1
1.1.2. Age and duration of the Bushveld Complex 3
1.1.3. Previous paleomagnetic work 5
1.1.3.1. Lower Waterberg Formation 6
1.1.3.2. Bushveld Complex 8
1.1.3.3. Phalaborwa Complex 9
1.1.3.4. Vredefort Impact Structure 10
1.1.3.5. Post-Phalaborwa dolerite dykes 10
1.1.3.6. Paleoproterozoic dykes of the Archean Basement 11
1.1.3.7. Previously suggested APWPs 13
1.2. PROBLEM STATEMENT 14
1.3. AIMS AND METHODOLOGY OF THE STUDY 15
1.4. BIBLIOGRAPHIC REFERENCES 16

CHAPTER 2

CHARACTERIZATION OF AN EXTENSIVE POST-TRANSVAAL SILL SUITE IN THE MPUMALANGA PROVINCE 22

2.1. INTRODUCTION 22
2.2. SAMPLING 24
2.3. PETROGRAPHY 27
2.4. PALEOMAGNETISM 29
2.4.1. Method 29
2.4.2. Demagnetization results 29
2.4.2.1. HWQ 31
2.4.2.2. HWR 31
2.4.2.3. HWA 32
2.4.2.4. HWB 33
2.4.2.5. HWD 33
2.4.2.6. HWS 34
2.4.2.7. HWM 34
2.4.2.8. HLW 37
2.4.2.9. HWF 37
2.4.2.10. HWE 38
CHAPTER 3

PALEOMAGNETISM OF POST-TRANSVAAL
SILLS IN THE WESTERN KAAPVAAL
CRATON AND CORRELATIONS
TO THE EASTERN SILL COMPLEX

3.1. INTRODUCTION

3.2. SAMPLING

3.3. PETROGRAPHY

3.4. PALEOMAGNETISM

3.4.1. Method

3.4.2. Demagnetization results

3.4.3. Sites in Bronkhorstspruit area

3.4.3.1. BRD

3.4.3.2. BRA

3.4.3.3. BRC

3.4.3.4. BRB

3.4.3.5. BRE

3.4.4. Sites in Rustenburg area

3.4.4.1. RUE

3.4.4.2. RUF

3.4.4.3. RUG

3.4.4.4. RUI

3.4.4.5. RUH

3.4.4.6. HKP

3.4.4.7. RUB

3.4.4.8. RUJ

3.4.4.9. RUA

3.4.4.10. RUD

3.4.3.11. RUC

3.4.5. Summary

3.4.6. Interpretation

3.4.6.1. Low stability component (PF)

3.4.6.2. High stability components

3.4.6.2.1. B component

3.4.6.2.2. C+/- component

3.4.6.2.3. E+ component

3.4.6.2.4. F+ component

3.4.6.2.5. D component

3.5. RECONCILIATION OF DATA FROM
EASTERN AND WESTERN LIMBS AND
COMBINED POLE CALCULATION

3.5.1. B remanence

3.5.1.1. Regional bootstrap test

3.5.1.2. B paleopole

3.5.2. C+/- Component

3.5.2.1. Regional bootstrap test

3.5.2.2. C+/- pole and relation to the ~2.05 Ga Bushveld Complex

3.5.3. D component and implications for > 2.05 Ga aged sills

3.6. SUMMARY AND CONCLUSIONS

3.7. BIBLIOGRAPHIC REFERENCES
CHAPTER 4

PALEOMAGNETIC CONSTRAINTS FROM
THE UITKOMST COMPLEX, SOUTH AFRICA:
IMPLICATIONS FOR TIMING OF INTRUSION

4.1. INTRODUCTION 125
4.2. SAMPLING 128
4.3. PALEOMAGNETISM 129
4.3.1. Method 129
4.3.2. Demagnetization results 129
4.3.2.1. Uitkomst Complex (Basal Group) 130
4.3.2.1.1. NKB 130
4.3.2.1.2. NKC 130
4.3.2.1.3. NKD 131
4.3.2.2. Uitkomst dyke 132
4.3.3. Summary 134
4.3.4. Interpretation 135
4.4. GEOCHEMISTRY (UITKOMST DYKE) 136
4.4.1. Method 136
4.4.2. Weathering and alteration 137
4.4.3. Major elements 137
4.4.5. Trace elements (Co, Ni, Sc, Cu, Zn, and V) 139
4.4.6. Rare earth elements 139
4.4.7. Multi-element plot (spidergram) 140
4.4.8. Comparison to strata-bound igneous suites 141
4.4.9. Summary 142
4.5. RECONCILIATION OF DATA AND DISCUSSION 143
4.5.1. Calculation of Uitkomst Complex pole position 143
4.5.2. Uitkomst Complex VGP and implication for the timing of intrusion 144
4.6. CONCLUSION 147
4.7. BIBLIOGRAPHIC REFERENCES 148

CHAPTER 5

CHARACTERIZATION OF A POST-TRANSVAAL DYKE SWARM IN THE MPUMALANGA PROVINCE

5.1. INTRODUCTION 152
5.2. SAMPLING AND METHOD 153
5.3. PETROGRAPHY 155
5.4. DEMAGNETIZATION RESULTS 157
5.4.1. Dykes southeast of Lydenburg 160
5.4.1.1. Site LDH 160
5.4.1.2. Site LDB 160
5.4.1.3. Site LDC 163
5.4.1.4. Site LDA 163
5.4.2. Dykes northeast of Lydenburg 163
5.4.2.1. Site LDI 163
5.4.2.2. Site LDJ 164
5.4.2.3. Site LDG 164
5.4.2.4. Site LDD 167
5.4.2.5. Site LDE 167
1.2.2. Geochemistry of the B1 subgroup vii
1.2.3. Gabbros syn-Bushveld sills (B2, B3 subgroup) viii
1.2.3.1. Microgabbro syn-Bushveld sills viii
1.2.3.2. Gabbronorite and norite syn-Bushveld sills ix
1.2.3.3. Gabbro syn-Bushveld sills associated with the Critical Zone (B2 subgroup) ix
1.2.4. Geochemistry of the B2 and B3 subgroups ix
1.2.5. Geochronological data of syn-Bushveld sills xi
1.3. BIBLIOGRAPHIC REFERENCES xi

APPENDIX 2

PETROGRAPHY AND GEOCHEMISTRY OF POST-TRANSVAAL INTRUSIONS IN THE EASTERN KC

1. DESCRIPTION OF THIN SECTIONS xiii
1.1. HWQ xiii
1.2. HWR xiii
1.3. HWA xv
1.4. HWB xv
1.5. HWD xv
1.6. HWS xv
1.7. HWM xvii
1.8. HWL xvii
1.9. HWF xvii
1.10. HWG xvii
1.11. HWT xviii
1.12. HWN xviii
1.13. HWU xx
1.14. HWY xx
1.15. HWX xx
1.16. HWI xxi
1.17. HWP xxi
1.18. HWH xxi
1.19. HWW xxiii
1.20. HWO xxiii
1.21. HWV xxiii

2. CORRELATIONS OF GEOCHEMICAL RESULTS FROM POST-TRANSVAAL INTRUSIONS OF THE EASTERN KC TO THE STRATA-BOUND IGNEOUS SUITES ON THE KC xxiv
2.1. >2.05 Ga Dullstroom Lavas xxv
2.1.1. HWD xxv
2.1.2. HWA, HWB, HWF, HWH, and HWG xxv
2.2. Marginal rocks and sills of the eastern Bushveld Complex xxvii
2.1.1. HWD xxvii
2.1.2. HWA, HWB, HWF, HWH and HWG xxviii
2.3. ~1.9 Ga post-Waterberg sills and Black Hills dykes xxix
2.3.1. HWD xxix
2.3.2. HWA, HWB, HWF, HWH and HWG xxx
2.4. ~1.1 Ga Umkondo sills xxxi
2.4.1. HWD xxxi
APPENDIX 3

1. PETROGRAPHY OF POST-TRANSVAAL SILLS IN THE WESTERN KC

3.1. Sites in Bronkhorstspruit area
3.1.1. BRD
3.1.2. BRA
3.1.3. BRC
3.1.4. BRB
3.1.5. BRE
3.2. Sites in Rustenburg area
3.2.1. RUE
3.2.2. RUF
3.2.3. RUG
3.2.4. RUI
3.2.5. RUH
3.2.6. HKP
3.2.7. RUB
3.2.8. RUJ
3.2.9. RUD
3.2.10. RUC

APPENDIX 4

PETROGRAPHY AND GEOCHEMISTRY OF POST-TRANSVAAL DYKES NEAR LYDENBURG, EASTERN KC

1. DESCRIPTION OF THIN SECTIONS
1.1. Dykes southeast of Lydenburg
1.1.1. LDH
1.1.2. LDB
1.1.3. LDC
1.1.4. LDA
1.2. Dykes northeast Lydenburg
1.2.1. LDD
1.2.2. LDE
1.2.3. LDF
1.2.4. LDG
1.2.5. LDI
1.2.6. LDJ

2. CORRELATIONS OF GEOCHEMICAL RESULTS FROM LYDENBURG DYKES TO THE STRATA-BOUND IGNEOUS SUITES ON THE KC
2.1. ~2.2 Ga Hekpoort Lavas
2.2. > 2.05 Ga Machadodorp Member
2.3. >2.05 Ga Dullstroom Lavas
2.4. Marginal rocks and sills of the eastern Bushveld Complex lv
2.5. ~1.9 Ga post-Waterberg sills and Black Hills dykes lvii
2.6. ~1.1 Ga Umkondo sills lvii
2.7. ~180 Ma Karoo lavas, sills and dykes lviii
3. BIBLIOGRAPHIC REFERENCES lx
ABSTRACT

Paleomagnetism of post-Transvaal sill complexes, selected dykes and the Uitkomst Complex - relation to the Bushveld Complex

by

H. Wabo

The Paleoproterozoic (i.e. 2500 Ma to 1600 Ma) apparent polar wander path (APWP) for the Kaapvaal craton (KC) is not well constrained, due to the lack of reliable paleopoles and absence of numerical ages for existing poles. In addition, the duration of emplacement, and timing of remanence acquisition of the Rustenburg Layered Suite (RLS) and other units of the Bushveld Large Igneous Province (LIP) are still unclear. During the present paleomagnetic study, samples were collected from the small intrusions that occur around the RLS and that are believed to be related to the Bushveld LIP for the establishment of new paleomagnetic and virtual geomagnetic poles. In addition, samples from post-Transvaal sills and dykes were targeted for U-Pb dating and geochemical analyses. Geochronological and geochemical data helped to constrain the timing of the newly defined paleopoles. These paleopoles were used in conjunction with previously published ones from KC to evaluate the APWP for this craton during the Paleoproterozoic.

Two of the studied post-Transvaal sills in the eastern KC revealed U-Pb ages that are identical to the age recently reported from the Marginal Zone of the RLS. Geochemical signatures of sill samples were in very good agreement with the newly obtained ages. New ages and geochemical data provided constraints on the magnetic components recorded by the sills. The results confirm the existence of B1 Bushveld magma-related sills on KC as well as pre and post-Bushveld sills as previously suggested. Particularly, dataset from the B1 Bushveld magma-related sills allowed for understanding the magnetic history of the RLS at the early stages (Marginal Zone) of its formation.

Paleomagnetic sampling of the Uitkomst Complex provided constraints on the remanence acquisition of this complex and also helped to understand the timing of the Bushveld magmatism outside of the main complex. Paleomagnetic data from a post-Transvaal dolerite dyke swarm near Lydenburg revealed a complex magnetic history. Characteristic magnetic components constrained by geochemical analyses were not similar to the RLS, but indicate probable relationship to other units of the Bushveld LIP.
The new ages generated in this study coupled to those previously obtained from the upper layers of the RLS suggested that this suite emplaced within a time period of at least 4 million years. Paleomagnetic results from the B1 Bushveld magma-related sills and available data from the upper layers of the RLS reveal that during the RLS emplacement, the Earth’s magnetic field reversed at least eight times. These results, together with data from the Lydenburg dykes, further indicate a minimum of nine changes in polarity of the Earth’s magnetic field during the formation of the Bushveld LIP.

During the present study, new pole positions of different reliability were added to the existing paleomagnetic database for the KC. Paleopoles from the Paleoproterozoic database of the KC (including those generated in the present study) were used to propose a new APWP for this craton from ~2200 Ma to ~1800 Ma. Particularly, poles from the B1 Bushveld magma-related sills and Uitkomst Complex provide the information to identify striking features in the APWP of the Paleoproterozoic KC.

Keywords: Kaapvaal craton, Bushveld Large Igneous Province, paleomagnetism, apparent polar wander path.
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to the following people and organizations:

- I would like to thank my supervisor Dr M.O. de Kock who guided me with a remarkably positive spirit. Thank you for your patience, motivation, teaching, advices and help.
- I am eternally grateful to my co-supervisor Prof N.J. Beukes who gave me the opportunity to undertake a doctoral program at the University of Johannesburg (UJ) by awarding me a four years grant via the Paleoproterozoic mineralization research group (PPM group).
- I express my deepest gratitude to Prof H.M. Rajesh who taught me all I know about the interpretation of geochemical data.
- Special Thanks to Prof B. Cairncross, the Head of UJ Geology Department, for always being available for my many administrative queries as international student.
- Thanks to Dr H.S. van Niekerk who helped me with the microscopy petrography. I will also always remember his conviviality and leadership role during the field trip in Mozambique.
- Thanks to Dr M.O. de Kock who always accompanied me in the field and undertook most of the drilling work. I also thank him for his financial support during my trip in USA.
- I say many thanks to Prof U. Söderlund, in whose laboratory in Sweden the U-Pb dating of my samples was achieved.
- I would like to thank my PPM colleague Mr. A. Gumsley for his help during the dating of my samples in Sweden.
- I would also like to thank the whole staff at the Department of Geology at UJ. Special thanks go to Mr. H Yonker and Mrs. E Maritz for their logistic support. Ms D. Faseka (Khoza) is particularly thanked for her conviviality and for handling all the financial and administrative related queries.
- Special thanks go to Ms K. van den Berg, the Faculty officer for postgraduate studies at UJ, for her conviviality, and her availability for all my administrative queries.
- I would like to thank all my PPM colleagues. Special thanks go to Mr J.C. Beyeme Zogo, Mr D.H. Rose and Mrs G. Mishra for their friendship, help, and advices.
- I am grateful to my early manager, Mr E. Tatianou, and Geobase Consultants in Cameroon for the role that they played in my professional career.
- I say many thanks to my wife, Stephanie, and my daughter, Audrey Ange, for their patience, love and support.
- Special thanks go to my brother, Giscard, his wife, Edith and my nieces, Aude and Adora, for always encouraging me.
- I am eternally indebted to my parents and my whole family for their financial and moral support during all my studies.
- I would like to express my gratitude to my wife’s family for their support and advices.
- I will never forget my early mentor, the late Prof A. Nono (1954-2012) who played a crucial role in my career.
CHAPTER 1
INTRODUCTION AND PURPOSE OF THE THESIS

The present thesis aims to evaluate and expand the Paleoproterozoic apparent polar wander path for the Kaapvaal craton. To achieve this objective, a comprehensive paleomagnetic study is conducted on sill complexes, a dyke swarm and the Uitkomst Complex that intrude the Pretoria Group around the Rustenburg Layered Suite of the Bushveld Complex. These units are introduced here. The Bushveld Large Igneous Province is briefly reviewed in terms of its age, timing of cooling and remanence acquisition. Paleoproterozoic paleomagnetic data from the Kaapvaal craton are reviewed and existing discrepancies and gaps in the database are highlighted.

1.1. INTRODUCTION

The Paleoproterozoic eon (i.e. 2500 Ma to 1600 Ma) is of particular interest when studying the geotectonic evolution of the Kaapvaal craton (KC). In this time period, the Bushveld Complex, the world’s largest layered igneous complex intruded at ~2.05 Ga, the Zimbabwe craton amalgamated with the KC along the Limpopo metamorphic belt at ~2.0 Ga to form the Kalahari craton. Voluminous red bed successions were deposited on the craton in the late Paleoproterozoic. At ~2.02 Ga, the Vredefort Impact Structure formed in the central craton by bolide collision. Apart from the Bushveld Complex, at least two other Large Igneous Provinces (LIPs) intruded the KC; one at ~1.9 Ga and one at ~1.1 Ga. In addition, some of the Paleoproterozoic units in the KC host world-class ore deposits. Despite extensive study on the Paleoproterozoic KC, many controversies remain. A lot of these concern the Bushveld LIP.

1.1.1. The Bushveld Large Igneous Province

The Bushveld LIP (Figure 1.1) is famous for the Rustenburg Layered Suite (RLS) which is the largest mafic layered complex on Earth and is rich in platinum group elements, chromite, and vanadium (Cawthorn et al., 2006). The RLS comprises the Marginal,
Lower, Critical, Main and Upper zones, and is associated with pre, syn, and post-Bushveld marginal sills and other small intrusions (Barnes et al., 2010; Cawthorn et al., 1981; Eales and Cawthorn, 1996; Sharpe, 1982; Sharpe and Hulbert, 1985). These sill suites are subjects of Chapter 2 and 3 of this thesis. Voluminous granites of the Bushveld Granite Suite (locally termed the Lebowa Granite Suite) overlie, and in some places crosscut the RLS. Along the contacts of the granites and the RLS, the Rashoop Granophyre Suite of metamorphosed sediments and intrusive acidic rocks is developed. Various satellite intrusions such as the Uitkomst Complex have been linked to the Bushveld LIP. Chapter 4 deals with the Uitkomst Complex. Up to date, no Bushveld related dyke swarms have been recognized on the KC despite considerable attempts (e.g. Olsson et al., 2010). An uncharacterized north east-trending post-Transvaal Supergroup dyke swarm is the subject of Chapter 5 of this thesis.

1.1.2. Age and duration of the Bushveld Complex

The Bushveld Complex was emplaced into ~2061 Ma precursor volcanics of the Rooiberg Group (Walraven, 1997) as well as sedimentary units of the Transvaal Supergroup (Figure 1.1B). Red bed successions of the Waterberg Group sit uncomfortably on top of the Rooiberg Group and zircons from volcanic members have been dated at 2054 ± 4 Ma and 2051 ± 8 Ma (Dorland et al., 2006). Theses ages are within error of those from the Lebowa Granite Suite (Figure 1.2), and the Waterberg sedimentation occurred concurrent or immediately after the emplacement of the Bushveld Complex (Dorland et al., 2006). Intrusion of the Bushveld Complex can thus be bracketed between 2061 Ma and 2054 Ma. Zircon and rutile ID-TIMS U-Pb ages bracket the emplacement and cooling of the Merensky Reef of the RLS to a few million years around 2054 Ma (Scoates and Friedman, 2008). These ages are in agreement with most unpublished constraints, like those listed by Harmer and Armstrong (2000). The ages are also indistinguishable (Figure 1.2) with those from many of the satellite intrusions like the Marble Hall Diorite (de Waal and Armstrong, 2000), Lindeques Drift (de Waal et al., 2005), Rookedraal Complex (de Waal et al., 2005), Moshaneng Complex (Mapeo et al.,
2004), and Segwagwa-Masoke Complex (Mapeo and Wingate, 2009). The Uitkomst Complex appears to be somewhat younger at 2044 ± 8 Ma (de Waal et al., 2001).

Figure 1.2. Events on the KC between ~2057 Ma and ~2035 Ma based on U-Pb and $^{207}$Pb-$^{206}$Pb baddeleyite ages (filled squares), U-Pb and $^{207}$Pb-$^{206}$Pb zircon ages (open squares), U-Pb and $^{207}$Pb-$^{206}$Pb titanite and rutile ages (open diamonds). 1 = Walraven (1997); 2, 3, 6, 7, 12, 13, 16, 18 = Harmer and Armstrong (2000); 4 = Olsson et al. (2010); 5 = Curl (2001); 8, 9 = Scoates and Friedman (2008); 10 = Nomade et al. (2004); 11 = Buick et al. (2001); 15 = Walraven and Hattingh (1993); 17 = de Waal and Armstrong (2000); 18 = de Waal et al. (2005); 19 = Mapeo et al. (2004); 20 = Mapeo and Wingate (2009); 21 = de Waal et al. (2001); 22 = Kruger (1989); 23, 24 = Dorland et al. (2006)
An older U-Pb age of 2058.9 ± 0.8 Ma has been determined on titanite from retrogressed xenoliths in the Upper Zone of the RLS (Buick et al., 2001). This age overlaps with that of the Rooiberg Group volcanics (Figure 1.2), and it has been suggested that the titanite is the metamorphic product of the Rooiberg magmatism that was partially reset during incorporation into the RLS. More recently, however, Olsson et al. (2010) reported a U-Pb baddeleyite age of 2057 ± 1.6 Ma from the Marginal Zone of the RLS. Based on the available geochronological data, emplacement of the RLS thus occurred over 5 million year period (Olsson et al., 2010) instead of over the few million years as inferred by Scoates and Friedman (2008). Bushveld magmatism may have continued for a longer period, see Rajesh et al. (2013).

The relationship between the Marginal Zone and the rest of the Bushveld Complex, however, is still unclear, and although it is generally regarded as the lowest part of the RLS, it may also represent an earlier phase of the intrusion (Zintwana and Wilson, 2012). Based on thermal modeling, Cawthorn and Walwaren (1998) estimated that the Bushveld Complex was emplaced and cooled within 75 000 years. Recently, Letts et al. (2009) reported a maximum of seven magnetic reversals of the Earth’s magnetic field during the intrusion of the RLS. When compared to available age data (i.e., intrusion in ~5 million years) a reversal rate of one reversal every 1.4 million years can be calculated. This is not near as rapid as calculated rates that would approach and exceed the maximum reversal rates in the geological history (i.e., 5 reversals per million year) if the Bushveld Complex cooled in a few million years or less.

1.1.3. Previous paleomagnetic work

Published paleomagnetic poles for the Bushveld Complex and other late Paleoproterozoic units were summarized by Evans et al. (2002). This review has been updated by de Kock et al. (2006) with new data from the Waterberg Group. More recently, additional paleomagnetic data has become available primarily from Paleoproterozoic igneous units. These new poles, which are summarized here, were used in conjunction with the existing ones to construct various apparent polar wander paths (APWPs) for the Paleoproterozoic
KC (Figure 1.5). Existing paleomagnetic data for the Paleoproterozoic KC is shown in Figure 1.3.

Figure 1.3. Aitoff projection of paleopoles for the Paleoproterozoic KC. Also shown is the associated confidence limit of each pole as well as the approximate age. The today position of the KC is represented in red. MAM-1: Mamatwan type manganese ore component 1 (Evans et al., 2001); ONG: Ongeluk lavas (Evans et al., 1997); BGM: basal Gamagara/Mapedi Formation (Evans et al., 2002); PB1i: Phalaborwa Complex (Morgan and Briden, 1981); PB1ii: Phalaborwa Complex (Letts et al., 2010); BVC: Bushveld Complex (Letts et al., 2009); BVC Main and Upper zones recalculated by Evans et al.(2002); P3 pole: NW-trending dyke of the Archean Basement (Mare and Fourie, 2012); WUBS-I: lower Waterberg Formation (de Kock et al., 2006); VRED: Vredefort Impact Structure (Salminen et al., 2009); WUBS-II: upper part of Swaershoek Formation and Alma Formation (de Kock et al., 2006); KRB: Klipriviersberg Group (Strik, 2004); WITS: Witwatersrand overprint (Layer et al., 1988); LMA: Limpopo metamorphism A (Morgan, 1985); HAR: Hartley Lavas (Evans et al., 2002); MAM-2 Mamatwan type manganese ore component 2 (Evans et al., 2001); BHD: Black Hills dykes (Lubinina et al., 2010); SRB: Sand River dikes (Morgan, 1985); PB2i: post-Phalaborwa dykes (Morgan and Briden, 1981); PB2ii: post-Phalaborwa dykes (Letts et al., 2010); PBD: post-Bushveld dykes (Letts et al., 2010); WSD: post-Waterberg intrusions (Hanson et al., 2004). Pole color represents their reliability according to quality scale of Van der Voo (1990). Yellow = Q value of 3, 4 or 5 Green = Q value of 6 or 7.

1.1.3.1. Lower Waterberg Formation

Paleomagnetic studies were undertaken by Jones and McElhinny (1967) and McElhinny (1968) on the purple and red strata of the Waterberg Group and Soutpansberg Group followed by Maré et al. (2006) who sampled the red beds of the Swaershoek and Wilgeriver Formations. This was followed by de Kock et al. (2006) who reported
paleomagnetic results from about 250 samples of the lower part of the Waterberg Group (Nylstroom Subgroup). Primary poles (constrained by a positive fold test, a positive reversal and a positive conglomerate test) were obtained (de Kock et al., 2006). The paleopole from the lower Swaershoek Formation at the base of the Waterberg Group overlapped with the early W1 Waterberg pole of McElhinny (1968). Both poles were combined to generate a mean pole (named WUBS-I) for the lower Waterberg Formation to which de Kock et al. (2006) assigned the age of the quartz porphyry near the base of the Swaershoek Formation (i.e. 2054 ± 4 Ma (Dorland et al., 2006)). Similarly, the corresponding pole from the upper Swaershoek and Alma formations for the HIG2+/-components compared well with the W3 pole of McElhinny (1968) and these results were thus combined to produce the WUBS-II mean pole. Given the absence of radiometric age for the upper Swaershoek Formation, de Kock et al. (2006) could only constrain the age of WUBS-II paleopole stratigraphically between 2054 Ma and ~1870 Ma.

When compared to existing poles on the KC, the WUBS-I pole does overlap with the 1928 Ma Hartley lavas pole of Evans et al. (2002). The WUSB-I pole also overlaps with the pole of Morgan and Briden (1981) from the ~2.06 Ga Phalaborwa Complex, but not with the mean Bushveld pole recalculated by Evans et al. (2002) from Main and Upper zones of the RLS (Figure 1.3). De Kock et al. (2006) attributed this discrepancy to the possible long cooling history of the Bushveld Complex that delayed the magnetic remanence acquisition and/or to post-intrusion thermal fluid flow events. De Kock et al. (2006) therefore considered the WUBS-I pole as a better representative of the KC position during the emplacement of the Bushveld Complex. Letts et al. (2010) attributed the discrepancy between the Bushveld Complex poles and the lower Waterberg pole to inclination shallowing of the Waterberg pole. During the sedimentation process, it is possible for a rock to record a flattened magnetic inclination that results in a shallow bias in the estimated magnetic record (Tauxe, 2005). Inclination shallowing does not affect igneous rocks. Letts et al. (2010) therefore regarded the pole of de Kock et al. (2006) as inaccurate. The WUBS-II pole from the upper Swaershoek and Alma formations plotted widely removed from the 2054 Ma WUBS-I pole, leading de Kock et al. (2006) to suggest significant movement of the KC in the interval of Waterberg Group deposition.
1.1.3.2. Bushveld Complex

The Bushveld Complex has been subject of numerous paleomagnetic studies, including work from Hattingh (1986a; 1986b; 1986c; 1989) and Hattingh and Pauls (1994) who produced five paleopoles (all of single polarity) from the northern, eastern and western zones of the complex (Figure 1.4A.). These poles have received criticism from Letts et al. (2009). They (Letts et al., 2009) noted that the assumption of Hattingh that the RLS was formed in a horizontal position contrasted with the author’s field test results, as only one of the five paleopoles resulted from data that passed the paleomagnetic fold test. Another inconstancy noted by Letts et al. (2009) was that the APWP proposed by Hattingh (1995) suggested that the RLS was intruded or cooled over a time period of about 50 million years. This contrasted with the available published radiometric ages.

Letts et al. (2009) attempted to clarify the above inconsistencies by conducting a new paleomagnetic study in the Bushveld Complex. During demagnetization, all sites (100 sampling sites and 966 core samples were studied) revealed two distinct magnetic directions. One at low temperature and one revealed during high temperature demagnetization steps. The high temperature components displayed better grouping after bedding correction for each zone as well as for the whole complex (Letts et al., 2009). These components also displayed dual polarities contrary to Hattingh’s data. Two positive fold tests and several magnetic reversals tests attested to the primary nature of the high temperature components. Letts et al. (2009) suggested that the Bushveld Complex was formed in a near-horizontal position. These authors produced a total of five paleopoles that all overlapped at 95% significance unlike Hattingh’s poles (Figure 1.4). Letts et al. (2009) attributed the better grouping of their poles to better demagnetization techniques. The resultant mean paleopole of the Bushveld Complex did not overlap with the WUBS-I pole of de Kock et al. (2006), despite being contemporaneous (Figure 1.3). Based on their results, Letts et al. (2009) suggested a minimum cooling-interval for the Bushveld Complex of 1.4 million years. During this time interval, the Earth’s geomagnetic field underwent at least seven magnetic reversals and the KC experienced little to no movement (Letts et al., 2009).
1.1.3.3. Phalaborwa Complex

Following an early paleomagnetic study of the Phalaborwa Complex by Morgan and Briden (1981), Letts et al. (2010) investigated the pyroxenites of this complex. They (Letts et al., 2010) sampled 8 sites in the Foskor pit at the Phalaborwa mine for a total of 90 cores samples. Although no field tests of paleomagnetic stability were done, Letts et al. (2010) considered the characteristic components (all of single polarity) obtained to be of primary origin. The corresponding paleomagnetic pole overlapped with the early Phalaborwa pole of Morgan and Briden (1981), with a difference in position of about 10º (Letts et al., 2010) (Figure 1.3). Letts et al. (2010) attributed this slight variation between poles to the now-outdated procedures of demagnetization and calculations of primary directions that were used in Morgan and Briden (1981). The newly calculated Phalaborwa pole also compared well with the Bushveld Complex pole of Letts et al. (2009), but not with the younger than the 2054 Ma WUBS-I pole of de Kock et al. (2006) from the lower Waterberg Formation (Figure 1.3.).
1.1.3.4. Vredefort Impact Structure

The pre, syn and post-impact lithologies from the region of the 2023 ± 4 Ma Vredefort Impact Structure were sampled by Salminen et al. (2009). Demagnetization results from pre-impact rocks were of low quality, in contrast to Vredefort granophyres and pseudotachylytic breccia samples that displayed a characteristic remanent magnetization (ChRM) after removal of low-coercivity components (Salminen et al., 2009). Salminen et al. (2009) suggested this ChRM to be of primary origin based on a baked contact test. Given the limited number of sampling sites (16), only a VGP could be calculated from the ChRM. This VGP, however, could be combined to existing data to provide a mean pole for the Vredefort Impact Structure. When compared to known paleopoles for KC, the newly defined Vredefort Impact Structure pole was statistically indistinguishable from existing mid-Paleoproterozoic poles for the KC (Salminen et al., 2009) (Figure 1.3).

1.1.3.5. Post-Phalaborwa and post-Bushveld dykes

Letts et al. (2005) reported paleomagnetic data for a set of northeast-southwest dykes that crosscut the Bushveld Complex. Both normal and reversely magnetized remanences were obtained (Letts et al., 2005). The corresponding mean pole overlaps with the pole from the 1.87 Ga post-Waterberg intrusions (Hanson et al., 2004). A 1650 Ma \(^{40}\text{Ar}/^{39}\text{Ar}\) age from one of these dykes may represent a later thermal disturbance (Letts et al., 2005).

Following the paleomagnetic work from Morgan and Briden (1981) on dolerite dykes and older syenite Hills of the Phalaborwa Complex, Letts et al. (2010) sampled 9 dykes that crosscut this complex (four dykes in the Foskor pit, three dykes in the main Phalaborwa, and two dykes in the Vermiculite pit) and obtained a total of 79 oriented cores. 43 of these cores were subjected to progressive thermal demagnetization while the remaining 36 were used for alternating field demagnetization. Both methods revealed the existence of high stability components that were believed to be of primary origin based on the existence of magnetic reversals.

The corresponding paleopole overlapped with the pole obtained from dolerite dykes that crosscut the Bushveld Complex (Letts et al., 2005) (Figure 1.3) and led Letts et al. (2010)
to suggest that the post-Phalaborwa and post-Bushveld dykes are possibly related to the same magmatic event. The paleopole of post-Phalaborwa dykes also compared well with the poles from the ~1.87 Ga post-Waterberg intrusions (Hanson et al., 2004), and the 1.876 ± 68 Ma (Barton, 1979) Sand River dikes (Morgan, 1985) (Figure 1.3). The new post-Phalaborwa dyke pole partially overlapped with the early pole produced by Morgan and Briden (1981). The latter plotted more to the west (Figure 1.3). This was probably due to the fact that Morgan and Briden’s pole was obtained through combining sites of dolerite dykes and older syenite hills (Letts et al., 2010). The new paleopole of post-Phalaborwa dykes does not overlap with the ~1.9 Ga Hartley lava pole (Evans et al., 2002) (Figure 1.3). Letts et al. (2010) attributed this discrepancy to the low grade metamorphism that affected the Hartley Lavas (Cornell et al., 1998) and suggested that the paleomagnetic pole of Evans et al. (2002) may represent a younger magnetic overprint. Although the reliability rating of the pole from the post-Phalaborwa dykes is five, the use of this pole is limited by the absence of radiometric age for the relevant rock units.

1.1.3.6. Paleoproterozoic dykes of the Archean Basement

A paleomagnetic study was conducted on dolerite dykes, of three age groups, that intrude the Archean Basement of the eastern KC (Lubnina et al., 2010). Of the total of 17 sites targeted for this study, 8 sites in the south easternmost, the south eastern and the northern eastern areas involved the NE-trending dykes of the 1.9 Ga Black Hills dyke swarm. The paleomagnetic results from these 1.9 Ga dykes reveal the existence of high-coercivity dual polarity magnetic directions. Lubnina et al. (2010) used a positive baked contact, conglomerate and reversal tests to demonstrate the primary origin of this magnetization. The BHD pole obtained was close to the paleopole of the ~1.87 Ga post-Waterberg intrusions (Hanson et al., 2004) (Figure 1.3).

Adjacent to the sampling areas of Lubnina et al. (2010), NW-trending and NE-trending dykes intruding the Archean Basement were sampled by Maré and Fourie (2012) for geochemical and paleomagnetic studies. Thermomagnetic analysis revealed that the
dykes resulted from several magma influxes and were subjected to remagnetization. Although samples responded poorly to demagnetization, Maré and Fourie (2012) were able to identify three high temperature magnetizations from the NW-trending dykes, all believed to be of primary origin. One of the paleomagnetic poles (P3 pole) (Figure 1.3.) recalculated from these remanences compared well with the Bushveld Complex pole of Hattingh (1986a), and led Maré and Fourie (2012) to suggest a link between the relevant dykes and the Uitkomst and Bushveld complexes. One poorly constrained remanence similar to the post-Waterberg intrusions and the Black Hills dykes was obtained from the 1.9 Ga NE-oriented dykes (Mare and Fourie, 2012). The geochemical signatures of the studied dykes did not follow the paleomagnetic distinction among samples.

1.1.3.7. Previously suggested APWPs

Evans et al. (2002) sampled the Basal Gamagara/Mapedi Formation and the Hartley Lavas and published two new paleopoles (i.e. BGM and HAR) for the KC. However, the age of the BGM pole was unknown as no radiometric age was available for the sub-Gamagara/Mapedi unconformity and paleoweathering profile. Evans et al. (2002) also averaged data from 70 sites in the Main and Upper zones of the Bushveld Complex to produce the BVMU pole (Figure 1.3.). These authors used the above paleopoles and other existing ones on KC to propose two pictures of cratonic movements from ~2.2 Ga to 1.75 Ga, depending on whether the BGM pole was considered as predating or postdating the Bushveld Complex.

Based on stratigraphic correlations across Griqualand West and into the Transvaal Supergroup, the sub-Gamagara/Mapedi unconformity and paleoweathering profile is older than the Bushveld Complex (Beukes et al., 2002). The APWP proposed by Evans et al. (2002) for this option (Figure 1.5A1) suggested that from the low-paleolatitude Ongeluk lavas at 2.2 Ga, the path defined a swath towards the BGM pole position though moderate paleolatitudes from the ~2060 Ma Phalaborwa Complex pole and the Bushveld Complex pole through the Vredefort Impact Structure pole at 2023 ± 4 Ma , continuing westward to the 1930 Ma pole for the Hartley Lavas (Figure 1.5A1).
If the BGM pole is assumed to be younger than the Bushveld Complex pole (according to the correlations of the basal Olifantshoek succession with the post-Bushveld Waterberg Group (Beukes, 1986; Cheney et al., 1990)), it means that from the low-paleolatitude Ongeluk lavas at 2.2 Ga, the KC APWP streaked towards the Phalaborwa Complex pole at 2060.6 ± 0.5 Ma, the Bushveld Complex at about the same age and the Vredefort Impact Structure pole at 2023 ± 4 Ma (Evans et al., 2002) (Figure 1.5A2). From here, the APWP did a loop to join the BGM pole before continuing westward to the 1800-1900 Ma poles (Evans et al., 2002) (Figure 1.5A2).

![Figure 1.5](image)

**Figure 1.5.** Different APWPs as suggested in previous studies. The panels A1 and A2 depict the two options of cratonic movements of the KC during the Paleoproterozoic as proposed by Evans et al. (2002) while the panels B and C respectively show the APWPs defined by de Kock et al. (2006) and Letts et al. (2010). See Figure 1.3 for information (authors and reliability) on the poles used.

De Kock et al. (2006) used the WUSB-I and II paleopoles from the Waterberg Group with other existing poles to construct a Paleoproterozoic APWP for the KC (see Figure 1.5 B). According to these authors, the APWP of the KC defined a swath from 2222 Ma towards the BGM pole, crossing the 30ºN latitude (present coordinates) towards the 2054 Ma WUBS-I pole (de Kock et al., 2006) (Figure 1.5B). This path contrasts with that of Evans et al. (2002) that rather used the BVMU pole from Main and Upper zones of the Bushveld Complex to constrain the KC position at 2054 Ma (see Figure 1.5A). After 2054 Ma, the APWP shifted steadily southwest, embracing the east coast of Brazil
(WUBS-II pole) before ~1.88 Ga and did a loop back to Central Africa at ~1.88 Ga (de Kock et al., 2006) (Figure 1.5B).

Letts et al. (2010) proposed a APWP for the Paleoproterozoic KC, based on existing paleopoles including those obtained from the 2058-2054 Ma RLS, the 2061 ± 4 Ma (Reischmann, 1995) Phalaborwa Complex, the post-Phalaborwa dolerite dykes and the post-Bushveld dolerite dykes (Letts et al., 2005) (see Figure 1.5C). These authors did not consider the WUBS-I pole of de Kock et al. (2006) in their APWP, and rather used the Bushveld Complex mean pole of Letts et al. (2009) to constrain the KC position at ~2.05 Ga. Letts et al. (2010) did also not consider the WUBS-II pole of de Kock et al. (2006) in their APWP and interpret the pole for the Hartley Lavas of Evans et al. (2002) to be a magnetic overprint. According to Letts et al. (2010), the APWP for the Paleoproterozoic KC remained below the 30ºN latitude at 2056 Ma (Figure 1.5C), contrary to the suggestion of de Kock et al. (2006), and moved slowly in a south easterly between 2056 Ma and 1950 Ma, before crossing West Africa during the time period from 1950 Ma to 1830 Ma.

Salminen et al. (2009) compared the mean paleopole that they obtained from the 2024 ± 4 Ma (Kamo et al., 1996) Vredefort Impact Structure to existing Paleoproterozoic paleopoles in the KC and found similarities with the WUSB-I pole from the lower Waterberg Formation (de Kock et al., 2006) and the BVMU pole from Upper and Main zones of the RLS (Evans et al., 2002). This led Salminen et al. (2009) to suggest that the KC experienced no or little plate movement between 2054 Ma (intrusion of the Bushveld Complex ) and 2023 Ma (the age of the Vredefort Impact Structure). This idea contrasts with the APWP s proposed by Evans et al. (2002), de Kock et al. (2006), but resembles the thoughts of Letts et al. (2010).

1.2. PROBLEM STATEMENT

The suggested APWP s for the KC between ~2.2 Ga and ~1.8 Ga were reviewed above. Insufficient reliable paleopoles and scarce age data limit the use of these APWP s. An
important issue that remains to be explained or cleared is the duration of the Bushveld LIP and particularly the RLS. Was the RLS intruded and cooled over 5 million years or was it intrude in a much shorter time around 2054 Ma? The answer in part depends on how the paleomagnetic record is interpreted, and on what the timing of magnetic remanence lock-in for the Bushveld Complex was. The question of relatively rapid plate movement versus a more stationary KC in the Paleoproterozoic also remains to be further explored. To do so, the paleomagnetic database for the KC in this time interval has to be expanded.

Many Bushveld LIP-related intrusions have the advantage to the main complex in being small in size (with presumably quick and simpler cooling histories compared to the RLS). No paleomagnetic study has previously been undertaken on the Bushveld LIP-related intrusions (sill suite, possible Bushveld-related dykes, and satellite intrusions). These intrusions present the means to evaluate and strengthen the existing APWPs of the KC between ~2.2 Ga and ~1.8 Ga, and to verify the occurrence and evaluate the rate of magnetic reversals during the intrusion of the RLS.

1.3. **AIMS AND METHODOLOGY OF THE STUDY**

The main aim of the thesis is to evaluate and strengthen the Paleoproterozoic APWP of the KC. Many secondary objectives fall underneath of this main problem. These are introduced in the various chapters of the thesis.

To achieve the aim of this thesis, Bushveld LIP-related intrusions (post-Transvaal sills, possible Bushveld-related dykes, and satellite intrusions) were studied. In the northern parts of the craton, it was very difficult to find sill or dyke exposures while in the southern KC, previous paleomagnetic work has failed to produce reasonable results (e.g. Salminen et al., 2009). This is probably due to the influence of the ~2023 Ma Vredefort Impact Structure. Instead, the post-Transvaal Supergroup sill complexes to the east and west of the Bushveld Complex, a post-Transvaal dyke swarm in the eastern KC, and the ~2044 Ma Uitkomst Complex, which occur far away from the Vredefort dome, were targeted.

Targeted areas and units can be grouped as follows:
Chapter 1

- The post-Transvaal sill complex in the eastern KC (Chapter 2)
- The post-Transvaal sill complex in the western KC (Chapter 3)
- The ~2044 Ma Uitkomst Complex at the eastern KC (Chapter 4)
- A post-Transvaal dyke swarm in the eastern KC (Chapter 5)

A review of literature on the intrusive units sampled for this study reveals the absence of precise radiometric data and a relative paucity of geochemical data (particularly trace and rare earth elements). The Uitkomst Complex is an exception. No radiometric age is available for the post-Transvaal sills and dykes, except for the poorly constrained errorchron age of 2015 ± 211 Ma reported by Harmer and Sharpe (1985) from marginal rocks that occur along the basal contact of the Bushveld Complex.

Thus during the present study, suitable samples were processed for baddeleyite. Baddeleyite (ZrSiO$_2$) is a relatively easily extractable mineral (Söderlund and Johansson, 2002) that can be precisely dated by the U-Pb isotopic system. Selected sill and dyke samples were also analyzed for geochemistry, in order to constrain the different magmatic lineages of the studied units. With such combined dataset (paleomagnetic, geochemical and geochronological data), possible links between the studied units and the Bushveld magmatism and other LIPs can be investigated. This information can also be used to characterize primary magnetic components and to define new pole positions (either virtual geomagnetic poles or paleomagnetic poles). A pole position calculated from a single observation of the Earth’s magnetic field is called a virtual geomagnetic pole (or VGP) (Butler, 1991). A paleomagnetic pole is calculated from a group of VGP’s that is believed to represent the geomagnetic field over a sufficient time so as to average out the palaeosecular variation (Butler, 1991).

The newly defined pole positions will be compared to those previously published for the KC and will ultimately add to the growing paleomagnetic database of this craton.

1.4. BIBLIOGRAPHIC REFERENCES


Chapter 1


Olsson, J.R., Söderlund, U., Klausen, M.B. and Ernst, R.E., 2010. U-Pb baddeleyite ages linking major Archean dyke swarms to volcanic - rift forming events in the Kaapvaal craton (South Africa), and a precise age for the Bushveld Complex. Precambrian Research, (Special Issue), 183: 490-500.


Chapter 2

CHAPTER 2

CHARACTERIZATION OF AN EXTENSIVE POST-TRANSVAAL SILL SUITE IN THE MPUMALANGA PROVINCE

Ultramafic-mafic sills that intrude the sediments of the Pretoria Group in the eastern KC have been previously subdivided into pre and syn-Bushveld groups based upon field evidence, petrography and geochemistry. Syn-Bushveld sills were further arranged into either the B1, B2 and B3 magma classes, respectively related to the Lower and lower Critical zones, the upper Critical Zone, and the Main Zone of the RLS of the Bushveld Complex. In this chapter paleomagnetic results are presented, coupled with geochemical analyses and new U-Pb ages from intrusions in the Belfast and Dullstroom areas. Demagnetization results revealed the existence of three distinct primary remanences. The interpreted timing of these magnetizations is in good agreement with the classification previously proposed for the post-Transvaal sills in the eastern KC. Two new U-Pb ages and geochemical signatures obtained from the samples confirm the magnetic reversals during the emplacement of the RLS as suggested by previous authors. A new paleomagnetic pole for the syn-Bushveld intrusions from Mpumalanga Province was calculated. A lower intercept age of ~180 Ma for one of the dated sills, together with the B remanence suggests the presence of Karoo-aged intrusions within the suite. One sill of the suite may predate the Bushveld Complex and could be as old as ~2.1 Ga.

2.1. INTRODUCTION

Ultramafic-mafic sills intrude the ~2.2 Ga upper Transvaal Supergroup (i.e. the Pretoria Group) in the Mpumalanga Province (eastern KC) (Figure 2.1), with highest sill concentration above the Magaliesberg Quartzite Formation and towards the contact zone with the Bushveld Complex. The sills have been studied in some detail in the past (e.g., Sharpe and Hulbert, 1985; Sharpe, 1982; Frick, 1967; 1973 amongst others), and more recently by Barnes et al. (2010). Early attempts at classification of post-Transvaal sills were proposed by Lombaard (1934), Willemse (1959) and Frick (1967; 1973). Widely accepted, however, is the classification made by Sharpe (1982) and Sharpe and Hulbert (1985) who mapped the sills in the area around Lydenburg and
along the contact zone between the floor rocks and the RLS. These authors subdivided the post-Transvaal sills into two major groupings (i.e. pre-Bushveld and syn-Bushveld sills), based upon field relationships, petrography (mostly) and geochemistry (a detailed review of previous work on these units are available in Appendix 1). The pre-Bushveld group of older sills that intruded prior to the Bushveld Complex emplacement was further subdivided into hornblende-rich, tremolite-rich and ultramafic types. The syn-Bushveld units are thought to have been emplaced at about the same time as the RLS and were further subdivided into the pyroxenitic group (micropyro xenites, pyroxenites, ultramafic rocks, and norites) related to the Bushveld B1-type parental magma of the Lower and lower Critical Zone, and the gabbroic group (microgabbros, gabbronorites, norites) linked to the Bushveld B2 and B3-type parental magmas of the upper Critical and Main zones (Sharpe and Hulbert, 1985) (Figure 2.1). Forty new geochemical analyses of Bushveld marginal rocks and related sills from the eastern KC have recently been published by Barnes et al. (2010). These data are believed to provide reliable estimates of the parental magma compositions which formed the RLS. Barnes et al. (2010) reached to the same conclusion as Sharpe and Hulbert (1985) regarding the relationships between the sills and the different Bushveld parental magmas.

In the present study, new paleomagnetic results from samples of twenty post-Transvaal sills, one post-Transvaal dyke and four sites of country rock, coupled with geochemical analyses from the dyke and six of the sampled sills, all localized in the areas around Belfast and Dullstroom are reported. In addition, new precise U-Pb baddeleyite ages obtained from two of the studied sills are presented. The study was conducted with the following aims in mind:

- To provide new constraints on the timing of intrusion of the post-Transvaal sills in the eastern KC.
- To refine the classification previously proposed for these sills by Sharpe (1982)
- To investigate the existence and nature of magnetic reversals during the RLS emplacement recently reported from the main Bushveld Complex by Letts et al. (2009).
Figure 2.1. Diagrammatic outlines of post-Transvaal sills’ distribution in the Pretoria Group and rocks of Marginal Zone between the country rocks and the RLS near the eastern limb of the Bushveld Complex, after Sharpe (1982) and Sharpe and Hubert (1985).

2.2. SAMPLING

During field work, twenty sills and one dyke, as well as country rocks (~2.2 Ga Pretoria Group) to some of these intrusions were collected at different sampling sites around Belfast (north and southeast areas) and Dullstroom (central and northern sides of the town) (Figure 2.2). In order to avoid overprint directions and promote the chances of identifying primary magnetic directions, all sites targeted for the study are localized outside of the outer limit of the contact metamorphic aureole of the Bushveld Complex (Cawthorn et al., 2006) (Figure 2.2). The sampling sites are summarized in Table 2.1. Samples originate from sills from different stratigraphic levels within the ~2.2 Ga Pretoria Group (Figure 2.3).
Figure 2.2: Summary geological map of the Transvaal Supergroup in the Mpumalanga Province, showing the different sampling areas of the study. The outer limit of the Bushveld contact aureole is drawn after Cawthorn et al. (2006). More detailed maps for three of the sampling areas (i.e., Eastern Belfast, northern Belfast, and Dullstroom area) are also showed.

Samples include fine to medium-grained norite, dolerite, and pyroxenite that generally show a predominance of pyroxene and plagioclase minerals. In some samples, amphibole and quartz are present. The detailed petrography of these rocks is presented in Appendix 2.

Paleomagnetic sampling was achieved by drilling individual oriented core samples with a portable, hand-held petrol drill. Orientation of the cores was completed in all cases by magnetic compass and when possible with a sun compass as well. At each site, about 6 to 9 oriented cores were collected. In addition to the sill and dyke samples, country rocks of intrusion samples were collected from the Bowen Shale Member, the Machadodorp Member, the Vermont Formation.
and the Steenkampsberg Formation. Together with the paleomagnetic sampling, large (at least fist sized) hand samples were taken from fresh, coarse-grained portions of sill sites by hammer, for geochemical analyses (six sites) and U-Pb baddeleyite geochronology (two sites).

Figure 2.3: Stratigraphic setting of sampling sites of the study in the Pretoria Group.
### Table 2.1. Summary of sampling sites. N: number of paleomagnetic oriented cores drilled per site. * = sample with geochemistry, underlined = sample with baddeleyite U-Pb geochronology

<table>
<thead>
<tr>
<th>Site</th>
<th>GPS coordinates</th>
<th>Nature</th>
<th>Thickness</th>
<th>Strike</th>
<th>dip</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWA*</td>
<td>S 25°43’44.6” E 030°07’12.0”</td>
<td>dyke</td>
<td>~5m</td>
<td>90</td>
<td>subvertical</td>
<td>9</td>
</tr>
<tr>
<td>HWB*</td>
<td>S 25°43’03.2” E 030°06’50.3”</td>
<td>sill</td>
<td>~15m</td>
<td>11°</td>
<td>10°W</td>
<td>9</td>
</tr>
<tr>
<td>HWC</td>
<td>S 25°44’01.9” E 030°18’41.6”</td>
<td>host rock (Machadodorp Mb)</td>
<td>5°</td>
<td>15°W</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>HWD*</td>
<td>S 25°43’13.1” E 030°06’41.3”</td>
<td>sill</td>
<td>~15m</td>
<td>11°</td>
<td>10°W</td>
<td>8</td>
</tr>
<tr>
<td>HWE</td>
<td>S 25°43’11.8” E 030°06’29.4”</td>
<td>host rock (Vermont Fm)</td>
<td>8°</td>
<td>37°W</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>HWF*</td>
<td>S 25°43’16.2” E 030°06’25.5”</td>
<td>sill</td>
<td>~5m</td>
<td>189°</td>
<td>37°W</td>
<td>8</td>
</tr>
<tr>
<td>HWG*</td>
<td>S 25°43’17.0” E 030°06’19.6”</td>
<td>sill</td>
<td>60-80m</td>
<td>330°</td>
<td>10°SW</td>
<td>6</td>
</tr>
<tr>
<td>HWH*</td>
<td>S 25°33’15.8” E 030°03’36.8”</td>
<td>sill</td>
<td>~350m</td>
<td>40°</td>
<td>14°NW</td>
<td>8</td>
</tr>
<tr>
<td>HWI</td>
<td>S 25°24’46.6” E 030°06’47.3”</td>
<td>sill</td>
<td>~350m</td>
<td>40°</td>
<td>14°NW</td>
<td>8</td>
</tr>
<tr>
<td>HWJ</td>
<td>S 25°22’07.2” E 030°08’42.2”</td>
<td>host rock (Steenkempsberg Fm)</td>
<td>8°</td>
<td>14°NW</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>HWK</td>
<td>S 25°52’39.1” E 030°12’37.1”</td>
<td>host rock (Boven Shale Mb)</td>
<td>8°</td>
<td>14°NW</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>HWL</td>
<td>S 25°41’55.” E 030°03’01.5”</td>
<td>sill</td>
<td>~350m</td>
<td>15°</td>
<td>12°W</td>
<td>7</td>
</tr>
<tr>
<td>HWM</td>
<td>S 25°37’06.0” E 030°03’52.1”</td>
<td>sill</td>
<td>~150m</td>
<td>0°</td>
<td>14°W</td>
<td>5</td>
</tr>
<tr>
<td>HWN</td>
<td>S 25°34’17.4” E 030°03’49.5”</td>
<td>sill</td>
<td>~150m</td>
<td>0°</td>
<td>14°W</td>
<td>7</td>
</tr>
<tr>
<td>HWO</td>
<td>S 25°32’25.2” E 030°03’46.5”</td>
<td>sill</td>
<td>~20m</td>
<td>22°</td>
<td>14°W</td>
<td>6</td>
</tr>
<tr>
<td>HWP</td>
<td>S 25°29’51.9” E 030°04’58.4”</td>
<td>sill</td>
<td>~300m</td>
<td>50°</td>
<td>15°W</td>
<td>5</td>
</tr>
<tr>
<td>HWQ</td>
<td>S 25°13’18.8” E 030°20’39.1”</td>
<td>sill</td>
<td>~5m</td>
<td>25°</td>
<td>15°W</td>
<td>6</td>
</tr>
<tr>
<td>HWR</td>
<td>S 25°15’57.7” E 030°14’58.7”</td>
<td>sill</td>
<td>~5m</td>
<td>25°</td>
<td>15°W</td>
<td>6</td>
</tr>
<tr>
<td>HWS</td>
<td>S 25°17’37.4” E 030°14’04.4”</td>
<td>sill</td>
<td>~130m</td>
<td>25°</td>
<td>15°W</td>
<td>6</td>
</tr>
<tr>
<td>HWT</td>
<td>S 25°18’12.8” E 030°13’18.3”</td>
<td>sill</td>
<td>~250m</td>
<td>32°</td>
<td>15°W</td>
<td>6</td>
</tr>
<tr>
<td>HWU</td>
<td>S 25°19’11.9” E 030°12’27.0”</td>
<td>sill</td>
<td>~5m</td>
<td>25°</td>
<td>15°W</td>
<td>6</td>
</tr>
<tr>
<td>HWV</td>
<td>S 25°23’23.7” E 030°07’52.0”</td>
<td>sill</td>
<td>~100m</td>
<td>25°</td>
<td>15°W</td>
<td>6</td>
</tr>
<tr>
<td>HWW</td>
<td>S 25°22’10.1” E 030°08’41.3”</td>
<td>sill</td>
<td>~25m</td>
<td>50°</td>
<td>15°W</td>
<td>10</td>
</tr>
<tr>
<td>HWX</td>
<td>S 25°21’25.2” E 030°09’41.8”</td>
<td>sill</td>
<td>~10m</td>
<td>22°</td>
<td>15°W</td>
<td>6</td>
</tr>
<tr>
<td>HWY</td>
<td>S 25°19’45.8” E 030°11’10.2”</td>
<td>sill</td>
<td>~10m</td>
<td>90°</td>
<td>15°N</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>173</strong></td>
</tr>
</tbody>
</table>

### 2.3. PETROGRAPHY

Petrographic study of intrusions sampled from the sill suite that intrudes into the Pretoria Group was done to note textures and fabrics in these rocks as well as to document the different mineral phases. This is important for the purposes of classification, and constraining the affinities of the magma from which the samples crystallized. Hand specimens of the different units appeared fairly similar in terms of the mineralogy which was dominated by plagioclase and pyroxene, but varied in terms of grain size (from fine to medium and rarely coarse-grained), and degree of alteration. These observations have been broadly confirmed under the microscope. In addition, microscopic observations revealed that pyroxene and plagioclase minerals occur in some
samples together with amphibole and quartz. The presence of olivine as accessory mineral phase in some samples, and amphibole and clay minerals (chlorite and sericite) as secondary minerals was also observed. The bulk of samples possess a sub-ophitic texture. However, granular, poikilophitic and hypocristalline textures have also been observed in few samples. In general, phenocrysts make up about twenty to thirty per cent by volume. Intergrowth of plagioclase, pyroxene and amphibole (when present) is very common. The matrix is dominated by fine-grained pyroxene, plagioclase, opaque minerals and other small sized mineral species that can only be identified under a petrographic microscope with difficulty. Individual descriptions of different sampled intrusions are available in Appendix 2.

Based on petrographic features, the studied intrusive units can be subdivided into four groups (Table 2.2). Group 1 (HWQ) includes highly altered units, Group 2 (HWA, HWB) sills have a mineralogy dominated by orthopyroxene, Group 3 (HWD, F, G, H, I, M, N, S, and Y) sills have orthopyroxene, clinopyroxene, plagioclase and sometimes quartz as dominant minerals, and Group 4 (HWL, P, R, T, U, V, W and X) sills have clinopyroxene and plagioclase as main mineral phases.

**Table 2.2. Summary of petrography of the studied post-Transvaal sills and dyke**

<table>
<thead>
<tr>
<th>PETROGRAPHIC GROUP</th>
<th>SITES</th>
<th>COUNTRY ROCKS</th>
<th>MINERALOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>HWQ</td>
<td>Silverton Formation</td>
<td>amphibole, orthopyroxene, and plagioclase few amount of quartz also occurs (highly altered)</td>
</tr>
<tr>
<td>Group 2</td>
<td>HWA and HWB</td>
<td>Vermont Formation</td>
<td>orthopyroxene and opaques</td>
</tr>
<tr>
<td>Group 3</td>
<td>HWD, HWS, HWF, HWG, HWM, HWN</td>
<td>Vermont Formation</td>
<td>orthopyroxene, clinopyroxene, plagioclase and opaques minerals</td>
</tr>
<tr>
<td>Group 4</td>
<td>HWL, HWR, HWT</td>
<td>Lakenvalei Formation</td>
<td>olivine and abundant granophyric quartz occur in some samples</td>
</tr>
<tr>
<td></td>
<td>HWU</td>
<td>Lakenvalei Formation</td>
<td>quartz occur in some samples</td>
</tr>
<tr>
<td></td>
<td>HWX</td>
<td>Nederhorst Formation</td>
<td>clinopyroxene and plagioclase few amounts of orthopyroxene and granophyric quartz occur in some samples</td>
</tr>
<tr>
<td></td>
<td>HWP, HWV, HWW</td>
<td>Steenkampsberg</td>
<td></td>
</tr>
</tbody>
</table>

28
Comparison of the above sill groups to the classification proposed by Sharpe (1982) for marginal rocks and sills that occur along the basal contact of the RLS in the sampling area (see Appendix 1) allows for correlation of Group 1 sill (HWQ), which occurs stratigraphically far below the other groups to the pre-Bushveld group described by Sharpe. Group 2 and 3 sills share similarities with the members of the pyroxenitic subgroup (i.e., B1 subgroup of syn-Bushveld sills) of Sharpe’s classification (i.e., the micropyroxenites, the feldspar pyroxenites and norites), and the characteristics revealed by Group 4 sills bear some resemblance to the post-Transvaal sill group in the classification of Sharpe.

2.4. PALEOMAGNETISM

2.4.1. Method

Oriented cores were cut into a standard paleomagnetic specimen of ~ 2 cm length. One specimen of each core was subjected to demagnetization using the vertical 2G Enterprises DC-4K (liquid helium free) superconducting rock magnetometer housed at the University of Johannesburg. After measurements of natural remanent magnetization (NRM) and pre-treatment of low-field-strength alternating field (AF) demagnetization using a Molspin 2-axis tumbling AF-demagnetizer (four steps up to 10 mT), the samples were thermally demagnetized in a shielded furnace, at decreasing intervals, from 100°C up to 570°C or 585°C depending on the site. Magnetic components were obtained via least-squares principal component analysis (Kirchvink, 1980). The calculations, together with all subsequent statistical analyses utilized the Macintosh™ based software Paleomag 3 (Jones, 2002) and PaleoMac (Cogne, 2003).

2.4.2. Demagnetization results

During demagnetization, individual intrusions and samples from country rock to some of these intrusions displayed varied responses, but some generalizations can be made. As is quite common in paleomagnetic studies, some sites (i.e., HWG, HWN and HWP) displayed single random linear demagnetization trajectories, believed to be the adverse effects of the lightning.
strikes. One site (HWC) proved to be a poor recorder of the Earth’s magnetic field and yielded unusable results. Apart from these exceptions, all other sites yielded interpretable results.

Table 2.3. Summary of the different magnetic components obtained from the studied post-Transvaal sills and dyke in the eastern KC. D = declination, I = inclination, n = number of samples used to calculate the site mean declination/inclination, N = number of samples drilled per site, α_{95} = semi-angle of 95% cone of confidence about mean direction, k = precision parameter of Fisher (1953).

<table>
<thead>
<tr>
<th>Component</th>
<th>Site</th>
<th>n/N</th>
<th>D in deg.</th>
<th>I in deg.</th>
<th>α_{95}</th>
<th>k</th>
<th>D in deg.</th>
<th>I in deg.</th>
<th>α_{95}</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present coordinates</td>
<td>Relatively low stability magnetic components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>HWR</td>
<td>6/6</td>
<td>160.0</td>
<td>-36.8</td>
<td>10.32</td>
<td>35.93</td>
<td>151.7</td>
<td>-32.9</td>
<td>11.77</td>
<td>27.80</td>
</tr>
<tr>
<td>A</td>
<td>HWA</td>
<td>5/9</td>
<td>183.7</td>
<td>-65.3</td>
<td>8.81</td>
<td>61.16</td>
<td>162.0</td>
<td>-64.9</td>
<td>8.81</td>
<td>61.17</td>
</tr>
<tr>
<td>A</td>
<td>HWD</td>
<td>6/8</td>
<td>195.6</td>
<td>-31.7</td>
<td>10.58</td>
<td>34.20</td>
<td>189.4</td>
<td>-34.8</td>
<td>10.60</td>
<td>34.11</td>
</tr>
<tr>
<td>A</td>
<td>HWS</td>
<td>4/6</td>
<td>158.9</td>
<td>-45.7</td>
<td>22.03</td>
<td>13.77</td>
<td>147.5</td>
<td>-37.6</td>
<td>22.03</td>
<td>13.78</td>
</tr>
<tr>
<td>A</td>
<td>HWT</td>
<td>6/6</td>
<td>153.1</td>
<td>-49.7</td>
<td>11.88</td>
<td>27.28</td>
<td>142.4</td>
<td>-36.2</td>
<td>11.86</td>
<td>27.38</td>
</tr>
<tr>
<td>PLF</td>
<td>HWU</td>
<td>6/6</td>
<td>66.1</td>
<td>-50.0</td>
<td>14.93</td>
<td>17.57</td>
<td>72.2</td>
<td>-36.6</td>
<td>15.43</td>
<td>16.47</td>
</tr>
<tr>
<td>PLF</td>
<td>HWY</td>
<td>5/7</td>
<td>290.4</td>
<td>-46.3</td>
<td>23.18</td>
<td>9.48</td>
<td>296.1</td>
<td>-60.8</td>
<td>23.20</td>
<td>9.46</td>
</tr>
<tr>
<td>PLF</td>
<td>HWK</td>
<td>6/6</td>
<td>4.1</td>
<td>-59.7</td>
<td>13.27</td>
<td>22.35</td>
<td>24.0</td>
<td>-52.5</td>
<td>13.17</td>
<td>22.37</td>
</tr>
<tr>
<td>HWF</td>
<td>8/8</td>
<td>186.6</td>
<td>75.8</td>
<td>13.70</td>
<td>15.14</td>
<td>212.4</td>
<td>73.3</td>
<td>13.72</td>
<td>15.10</td>
<td></td>
</tr>
<tr>
<td>HWF</td>
<td>4/8</td>
<td>295.5</td>
<td>81.0</td>
<td>29.46</td>
<td>8.02</td>
<td>284.2</td>
<td>74.4</td>
<td>29.46</td>
<td>8.02</td>
<td></td>
</tr>
<tr>
<td>HWX</td>
<td>5/6</td>
<td>314.4</td>
<td>3.2</td>
<td>21.09</td>
<td>11.29</td>
<td>314.8</td>
<td>-8.4</td>
<td>21.09</td>
<td>11.29</td>
<td></td>
</tr>
<tr>
<td>HWW</td>
<td>5/8</td>
<td>249.4</td>
<td>-67.1</td>
<td>7.40</td>
<td>107.96</td>
<td>216.1</td>
<td>-76.5</td>
<td>7.39</td>
<td>108.02</td>
<td></td>
</tr>
<tr>
<td>HWH</td>
<td>8/8</td>
<td>286.6</td>
<td>51.1</td>
<td>13.06</td>
<td>16.49</td>
<td>288.4</td>
<td>37.1</td>
<td>13.08</td>
<td>16.52</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tilt-corrected coordinates</th>
<th>Relatively high stability magnetic components</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>HWR</td>
</tr>
<tr>
<td>B</td>
<td>HWD</td>
</tr>
<tr>
<td>B</td>
<td>HWL</td>
</tr>
<tr>
<td>B</td>
<td>HWT</td>
</tr>
<tr>
<td>B</td>
<td>HWU</td>
</tr>
<tr>
<td>B</td>
<td>HWX</td>
</tr>
<tr>
<td>B</td>
<td>HWW</td>
</tr>
<tr>
<td>B</td>
<td>HWV</td>
</tr>
<tr>
<td>C+</td>
<td>HWA</td>
</tr>
<tr>
<td>C+</td>
<td>HBW</td>
</tr>
<tr>
<td>C-</td>
<td>HWS</td>
</tr>
<tr>
<td>C+</td>
<td>HWM</td>
</tr>
<tr>
<td>C+</td>
<td>HWF</td>
</tr>
<tr>
<td>C+</td>
<td>HWE</td>
</tr>
<tr>
<td>C-</td>
<td>HWY</td>
</tr>
<tr>
<td>C+</td>
<td>HWI</td>
</tr>
<tr>
<td>C+</td>
<td>HWH</td>
</tr>
<tr>
<td>C+</td>
<td>HJH</td>
</tr>
<tr>
<td>C+</td>
<td>HWO</td>
</tr>
</tbody>
</table>

| D | HWQ | 3/6 | 77.9 | 11.7 | 28.04 | 20.39 | 77.3 | 26.7 | 28.04 | 20.43 |
| E | HWK | 5/6 | 204.6 | 0.9 | 12.79 | 29.40 | 203.9 | -8.4 | 12.80 | 29.36 |

During low field strength alternating field and low temperature demagnetization steps, many of the sites (HWR, A, D, S, and T) are characterized by southerly oriented, upward inclined directions named “A”. A large amount of sites (HWQ, B, M, L, E, I, O and V), however, revealed randomly oriented components at low levels of demagnetization. Only a few number of sites (HWU, HWY, and HWK) displayed northerly oriented, negatively inclined components.
that are near parallel to the Earth’s present dipole field and thus named “PF”. Lastly some sites (HWX, F, H, J, and L) revealed various well-grouped but widely separated components. At higher levels of demagnetization, components of more geological significance unblocked. Most sites (HWA, B, M, F, E, Y, I, H, J, S, and O) displayed northerly oriented and positively inclined (C+) or southerly directed and negatively inclined (C-) components. A large amount of sites (HWR, D, L, T, U, X, W, and V) were characterized by south easterly directed and positively inclined components, named “B”. One site (HWQ) revealed easterly and shallow poorly constrained components, named “D”. Another site (HWK) displayed southerly shallow components named “E+”. A detailed description of the results from each sampling site is given from the base of the Pretoria Group upwards. The demagnetization results are summarized in Table 2.3

2.4.2.1. HWQ

Site HWQ is located ~17 km south east of Lydenburg along the road R540 to Dullstroom, (Figure 2.2) and consists of weathered dolerite with fresher core stones. Three such fresh core stones were collected to provide six oriented samples. The paleomagnetic results reveal that the lithology is a poor recorder of the Earth’s magnetic field as all samples completely demagnetized by 350°C. Two magnetic components can be identified in most samples (Figure 2.4A). All samples displayed randomly oriented low stability components removed during low strength alternating field demagnetization steps, see Figure 2.5. During high temperature demagnetization, two samples demagnetized along trajectories towards the origin and reached easterly and shallow stable endpoint of demagnetization (named D). A further two samples demagnetized along great circle paths towards a similar easterly shallow region. These samples can be combined to calculate a site mean with decl. = 77.9°, incl. = 11.7°, $\alpha_{95} = 28.04$, k = 20.39, n = 3 (stratigraphic correction: decl. = 77.3°, incl. = 26.7°, $\alpha_{95} = 28.04$, k = 20.43, n = 3).

2.4.2.2. HWR

Six paleomagnetic samples were collected from fresh core stones of a highly weathered dolerite sill that outcrops ~28 km due southeast of Lydenburg along the road R540 towards Dullstroom
(Figure 2.2). Sample behaviour during the demagnetization was consistent and two well-defined magnetic components were revealed. AF pre-treatment and thermal demagnetization up to 350°C revealed a low stability magnetic component in all six samples. This component is directed southerly with a positive inclination (A component) (Figure 2.5). The site mean calculated for the A component has a declination of 160.0°, an inclination of -36.8°, with α95 = 10.32, k = 35.93 and n = 6 (stratigraphic correction: decl. = 151.7°, incl. = -32.9°, α95 = 11.77, k = 27.80, n = 6) (Figure 2.5). At higher temperature demagnetization steps up to 565°C, samples demagnetized along straight line trajectories towards the origin and stable endpoints of demagnetization that are oriented south easterly and downward (B component) (Figure 2.4B). The site mean for the B component has a declination of 114.5°, an inclination of 51.0°, with α95 = 6.27, k = 95.93 and n = 6 (stratigraphic correction: decl. = 125.6°, incl. = 60.9°, α95 = 8.88, k = 48.20, n = 6) (Figure 2.5).

2.4.2.3. HWA

Nine oriented cores were collected from a ~5 m thick E-W trending dyke located on the farm Inyamazane, just outside Belfast along the highway N4 to Machadodorp (Figure 2.2). The dyke is an unaltered fresh-looking medium to coarse-grained pyroxenite that intrudes the Vermont shales of the Pretoria Group (Figure 2.2). During AF pre-treatment and thermal demagnetization up to 350°C (Figure 2.4C), five samples display well-grouped low stability magnetizations that are directed southerly with a negative inclination (A component: decl. = 183.7°, incl. = -65.3°, α95 = 8.81, k = 61.16, n = 5; stratigraphic correction: decl. = 162.0°, incl. = -64.9°, α95 = 8.81, k = 61.17; n = 5) (Figure 2.5). The stratigraphic correction corresponds to the assumption that dyke intrusion predated tilting of regional sedimentary layering. The remainder of the samples display upward directed but random low stability components. At higher levels of thermal demagnetization (350°C to 570°C) all samples demagnetize along straight line trajectories towards the origin and reach stable endpoints of demagnetization that are northerly and downward directed (C+ component: decl. = 26.3°, incl. = 54.0°, α95 = 3.47, k = 196.34, n = 9; stratigraphic correction: decl. = 12.7°, incl. = 58.1°, α95 = 3.47, k = 196.24, n = 9) (Figures 2.4C and 2.5).
2.4.2.4. HWB

Sill HWB is a ~15 m thick, medium-grained fairly altered pyroxenite and intrudes the Vermont Formation on the farm Inyamazane about 50 m stratigraphically above site HWA. In order to ensure sample freshness, long oriented cores were drilled. This, however, was variably successful as attested by demagnetization results. Two samples (HWB 01 and 03) displayed poorly grouped straight line components that were stable up to 580°C; the remainder of samples displayed shallow, but randomly oriented low stability components during AF pre-treatment. All other samples displayed high stability components during thermal demagnetization up to ~560°C. In four samples, stable end-points of demagnetization were northerly and downward (Figure 2.4E). In the remaining samples, straight stable end-points are somewhat removed from this grouping (i.e., HWB 09 is oriented easterly and downward (Figure 2.4E), while HWB 07 is oriented northerly and downward). Sample HWB 08 does not reach a stable endpoint, but here demagnetization behaviour is constrained by a great circle arc towards the northerly and downward grouping. With the exclusion of samples HWB 07 and 09 a site mean is calculated for the C+ component at decl. = 22.6°, incl. = 30.5°, α95 = 15.10, k = 31.28, n = 4.5; stratigraphic correction: decl. = 16.9°, incl. = 35.2°, α95 = 15.09, k = 31.32, n = 4.5) (Figure 2.5).

2.4.2.5. HWD

HWD represents a ~15 m thick sill that intrudes the Vermont Formation on the farm Inyamazane 20 m stratigraphically above HWB. Here eight oriented cores samples were taken. Two of these (i.e. HWD 07 and 08) displayed demagnetization behaviour that was disparate from the remainder of samples. During AF pre-treatment and low temperature thermal demagnetization steps up to ~350°C, five of the six samples displayed southerly and upward directed components (Figure 2.4D) (A component) while in sample HWD 06 this component remained stable up to 565°C. A site mean for the A component was determined from these six samples (decl. = 195.6°, incl. = -31.7°, α95 = 10.58, k = 34.20, n = 6; stratigraphic correction: decl. = 189.4°, incl. = -34.8°, α95 = 10.60, k = 34.11, n = 6) (Figure 2.5). During high temperature thermal demagnetization steps, four samples displayed endpoints of demagnetization and straight line
trajectories towards the origin (Figure 2.4D). These components are all oriented south east and downwards (B component). One sample (HWD 05) revealed a straight line component that plots between the lower stability (A component) direction and the B component. Exclusion of this sample results in a B component at decl. = 144.1°, incl. = 29.1°, α₀⁹⁵ = 11.04, k = 52.67, n = 4 (stratigraphic correction: decl. = 149.5°, incl. = 33.7°, α₀⁹⁵ = 11.04, k = 52.70, n = 4) (Figure 2.5).

2.4.2.6. HWS

On a comparable stratigraphic height within the Vermont Formation as HWD, but ~ 48 km to the north-northeast along the road R540 between Dullstroom and Lydenburg, (Figure 2.2) a fairly unaltered ~130 m thick sill was sampled. Of six oriented cores, four samples display a poorly developed low stability component removed by AF pre-treatment and low temperature steps up to 200°C (A component: decl.= 158.9°, incl. = -45.7°, α₀⁹⁵ = 22.03, k = 13.77, n = 4; stratigraphic correction: decl. = 147.5°, incl. = -37.6°, α₀⁹⁵ = 22.03 k = 13.78, n = 4) (Figures 2.6A and 2.7). All six samples were dominated by a well-developed magnetization that was either present as single components or in the interval between 200°C and 560°C as origin seeking straight line trajectories on orthogonal plots, that reach stable endpoints of demagnetization that are southeasterly and upward oriented (C- component) (Figure 2.6A). The only exception is sample HWS 05 which plots removed from this grouping in the north western quadrant. Exclusion of this sample results in the C- component site mean at decl. = 240.5°, incl. = -66.5°, α₀⁹⁵ = 2.87, k = 570.65, n = 5; stratigraphic correction: decl. = 204.4°, incl. = -76.0°, α₀⁹⁵ = 2.87, k = 570.65, n = 5 (Figure 2.7).

2.4.2.7. HWM

HWM represents a ~50m thick sill some ~10 km north of Belfast along the road R540 to Dullstroom (Figure 2.2). The sill intrudes into the upper stratigraphic layers of the Vermont shales below the Lakenvalei quartzites (one of several sills sampled in this relative level). All samples display randomly oriented components during demagnetization (AF pre-treatment up to high temperature steps, ~565°C). Four samples, however display well-grouped high-stability magnetizations (removed between 200°C and 560°C) either as straight line trajectories towards
the origin (HWM 04 and 05) or as great circle arc paths without reaching stable end points (HWM 03 and 01) (Figure 2.6B). These four magnetizations can be combined to calculate a C+ component mean for this site (decl. = 52.8°, incl. = 68.3°, α₉₅ = 30.29, k = 17.62, n = 3 (stratigraphic: decl. = 25.2°, incl. = 80.4°, α₉₅ = 30.28, k = 17.64, n = 3) (Figure 2.7).

Figure 2.4. Examples of demagnetization behaviour, in situ coordinates of some studied post-Transvaal sill samples in the eastern KC. A: HWQ, B: HWR, C: HWA, D: HWD, and E: HWB. Open symbols = vertical plane; close symbols = horizontal plane, NRM = natural remanent magnetization, mT = milli Tesla
Figure 2.5. Equal area plots of results from sites HWQ, HWR, HWA, HWB and HWD. The left-hand panel depicts relatively low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts the relatively high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits. Squares = pole to the plane of best-fit great circle arcs.
2.4.2.8. HWL

From a similar relative stratigraphic level as HWM, but ~ 8 km to the south just outside of Belfast on the road R540 to Dullstroom (Figure 2.2), a very thick (~100m) dolerite sill crops out along the road. Apart from poorly defined northerly downward or northerly and upward low stability components removed during AF pre-treatment and thermal demagnetization up to 250°C, all samples displayed stable south easterly downward oriented magnetizations that unblocked between 250°C and 565°C (B component: decl. = 133.6°, incl. = 56.8°, α95 = 7.37, k = 58.38, n = 7; stratigraphic correction: decl. = 156.0°, incl. = 61.1°, α95 = 7.36, k = 58.44, n = 7) (Figures 2.6C and 2.7).

2.4.2.9. HWF

HWF is a ~5 m thick sill some 40 km stratigraphically above HWD within the Vermont Formation on the farm Inyamazane. Oriented cores (eight in total) generally exhibited up to three magnetic components each. The first of these, and generally the less stable, unblocked during AF pre-treatment (and in the case of samples HWF 06 persisted up to 530°C during subsequent thermal demagnetization). In samples HWF 08 and 09, this component was present as a single straight line trajectory towards the origin and was stable up to 560°C (Figure 2.6D). This southerly and steep downward component, fairly similar to high temperature B component revealed at some sites, has a decl. = 188.6°, incl. = 75.8°, α95 = 13.70, k = 15.14, n = 8 (stratigraphic correction: decl. = 212.4°, incl. = 73.3°, α95 = 13.72, k = 15.10, n = 8) (Figure 2.7). Four samples exhibit a northerly and steep downward component during thermal demagnetization between 100°C and 530°C. This poorly constrained overprint is situated at decl. = 295.5°, incl. = 81.0°, α95 = 29.46, k = 8.02, n = 4 (stratigraphic correction: decl. = 284.2°, incl. = 74.4°, α95 = 29.46, k = 8.02, n = 4) (Figure 2.7). Six of the nine samples displayed a high temperature component (above 530°C up to 560°C) that was located northerly and downward at a moderate to steep inclination (C+ component: decl. = 23.8°, incl. = 62.8°, α95 = 17.60, k = 12.87, n = 6; stratigraphic correction: decl. = 10.2°, incl. = 64.9, α95 = 17.60, k = 12.86, n = 6) (Figure 2.7).
2.4.2.10. HWE

Backed shale (5 cores) of the Vermont Shale located 1.5-2 m above sill HWF was sampled. Four shale samples revealed poorly grouped southerly lower stability components, but the magnetization of all five cores was dominated by stable magnetic components in the temperature range of 450°C to 565°C that formed a tight northerly downward oriented cluster (C+ component: decl. = 31.8°, incl. = 57.2°, α95 = 7.10, k = 93.70, n = 5; stratigraphic correction: decl. = 21.3°, incl. = 64.0°, α95 = 7.10, k = 93.71, n = 5) (Figures 2.6E and 2.7).

2.4.2.11. HWG

Site HWG is located about ~20 m stratigraphically above sill HWF and its backed contact at site HWE. It is an exposure of an unaltered ~15 m thick mafic sill that forms a prominent ridge to the east of HWF on the farm Inyamazane. Paleomagnetic results from six cores reveal the presence of randomly oriented mostly single straight line zero seeking demagnetization trajectories (Figure 2.8A). No obvious grouping of components could be identified and it is assumed that samples have been affected by lightning.

2.4.2.12. HWT

Site HWT is from a ~ 250 m thick sill that intruded along the contact between the Vermont Formation and the Lakenvlei Formation. This sill was sampled along the road R540 between Belfast and Dullstroom approximately 17 km south east of the site HWS (Figure 2.2). During AF pre-treatment and thermal demagnetization steps up to 350°C, southerly and upward oriented components unblocked in all six samples taken from this site (A component: decl. = 153.1°, incl. = -49.7°, α95 = 11.88, k = 27.28, n = 6; stratigraphic correction: decl. = 142.4°, incl. = -36.2°, α95 = 11.86, k= 27.38, n = 6) (Figures 2.6F and 2.9). At higher temperature steps until sample become unstable (above 565°C), south-easterly and downward oriented components unblocked in all samples as origin seeking straight line demagnetization trajectories (B component: decl. = 126.4°, incl. = 53.3°, α95 = 4.98, k = 151.72, n = 6; stratigraphic correction: decl. = 139.8°, incl. = 66.2°, α95 = 4.98, k = 151.68, n = 6) (Figures 2.6F and 2.9).
Figure 2.6. Examples of demagnetization behaviour, in situ coordinates, of some studied post-Transvaal sill samples in the eastern KC. A: HWS, B: HWM, C: HWL, D: HWF, E: HWE and F: HWT. Open symbols = vertical plane; close symbols = horizontal plane, NRM = natural remanent magnetization, mT = milli Tesla.
Figure 2.7. Equal area plots of results from sites HWS, HWM, HWL, HWF and HWE. The left-hand panel depicts relatively low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts the relatively high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.

See paragraph 2.4.4.3.1. and Figure 2.22 for baked contact test at sites HWF and HWE.
2.4.2.13. HWN

At similar relative stratigraphic level as HWT, but ~ 37 km to the south east (Figure 2.2), a ~ 50 m thick dolerite outcrops. Despite the relative freshness of the dolerite, no consistent components could be identified from this site, which is believed to have been affected by lightning (based on relatively high initial magnetizations and the randomly oriented singular and straight line components).

2.4.2.14. HWU

HWU is a thin mafic sill that intruded near the base of the Lakenvalei Formation stratigraphically above sill HWT. The six samples from this site generally display two magnetic components. The first to unblock does so during AF pre-treatment up to ~350°C during thermal demagnetization (Figure 2.8D). The components form a northerly and upward grouping (decl. = 66.1°, incl. = -50.0°, α95 = 14.93, k = 17.57, n = 6; stratigraphic correction: decl. = 72.2°, incl. = -36.6°, α95 = 15.43, k = 16.47, n = 6) (Figure 2.9). High stability components form a well-defined southeasterly and downward oriented grouping (B component) with decl. = 110.8°, incl. = 52.0°, α95 = 8.26, k = 55.57, n = 6; stratigraphic correction: decl. = 118.6°, incl. = 66.1°, α95 = 6.46, k = 90.57, n = 6) (Figures 2.8D and 2.9).

2.4.2.15. HWY

HWY is a thin sill that intrudes into the upper stratigraphic levels of the Lakenvalei Formation along the road R540 between Dullstroom and Lydenburg (Figure 2.2). During AF pre-treatment, samples displayed poorly grouped north easterly and upward oriented components. After the removal of the low stability components, thermal demagnetization revealed zero seeking straight line trajectories that defined a well-grouped steep southerly cluster (C- component: decl. = 252.0, incl. = -65.8, α95 = 8.39, k = 45.17, n = 7; stratigraphic correction: decl. = 222.1°, incl. = -77.7°, α95 = 8.39, k = 45.18, n = 7) (Figures 2.8B and 2.9).
2.4.2.16. HWX

Along the contact between the Nederhost Shale and the Steenkampsberg Formation, several sills intrude. HWX is one such sill that outcrops along the road R540 about 4.5 km southeast from HWY (Figure 2.2). The site consists of a ~20m thick weathered gabbroic sill. With the exception of sample HWX 01, all samples displayed shallow north westerly components that were stable up to 500°C (decl. = 314.4°, incl. = 3.2°, α₉₅ = 21.09, k = 11.29, n = 5; stratigraphic correction: decl. = 314.8°, incl. = -8.4°, α₉₅ = 21.09, k = 11.29, n = 5) (Figure 2.8C). During higher temperatures steps up to 565°C, well-grouped and stable south easterly and downward oriented components unblocked (B component: decl. = 110.7°, incl. = 53.1°, α₉₅ = 11.97, k = 26.92, n = 6; stratigraphic correction: decl. = 119.8°, incl. = 67.2°, α₉₅ = 11.96, k = 26.94, n = 6) (Figure 2.9).

2.4.2.17. HWI

Another sill that intrudes along the contact between the Nederhorst and Steenkampsberg formations is HWI, which is exposed within a road cut immediately outside Dullstroom (Figure 2.2). Apart from poorly defined and poorly grouped low stability components removed during AF pre-treatment and thermal demagnetization up to 350°C, all samples display a stable magnetic component that is oriented downward in a northerly direction (C+ component: decl. = 67.5°, incl. = 62.9°, α₉₅ = 11.09, k = 33.64, n = 6.5; stratigraphic correction: decl. = 47.8°, incl. = 74.9°, α₉₅ = 11.09, k = 33.65, n = 6.5) (Figures 2.8E and 2.9).

2.4.2.18. HWP

Approximately 7 km south of Dullstroom, five oriented samples were taken from outcrops of a ~300 m thick sill within the basal stratigraphic level of the Steenkampsberg Formation (Figure 2.2). Samples were characterized by strong initial magnetization and randomly oriented univectorial components (Figure 2.10A). No clear grouping of these components could be discerned. Magnetizations from this sill are believed to be adversely affected by lightning.
Figure 2.8. Examples of demagnetization behaviour, in situ coordinates, of some studied post-Transvaal sill samples in the eastern KC. A: HWG, B: HWY, C: HWX, D: HWU, and E: HWI. Open symbols = vertical plane, closed symbols = horizontal plane, NRM = natural remanent magnetization, mT = milli Tesla.
Figure 2.9. Equal area plots of results from sites HWT, HWU, HWY, HWX and HWI. The left-hand panel depicts relatively low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts the relatively high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.
2.4.2.19. HWH

Also near the base of the Steenkampsberg Formation, and ~6.5 km south of HWP, a thick sill that appears weathered was sampled from fresh centers of several core stones (Figure 2.2). Demagnetization reveals two magnetic components, one of which was removed before 400°C (decl. = 286.6°, incl. = 51.1°, α₀₉₅ = 13.06, k = 16.49, n = 8; stratigraphic correction: decl. = 288.4°, incl. = 37.1°, α₀₉₅ = 13.08, k = 16.52, n = 8) (Figures 2.10B and 2.11). The second magnetic component is of high-stability with a downward inclination and a declination that is northerly (C+ component: decl. = 39.7°, incl. = 59.8°, α₀₉₅ = 5.26, k = 97.71, n = 8; stratigraphic correction: decl. = 15.0°, incl. = 60.7°, α₀₉₅ = 5.25, k = 98.13, n = 8) (Figure 2.11). This C+ component unblocks in the temperature range of 400°C to 570°C (Figure 2.10B).

2.4.2.20. HWW

About 40 km north of Dullstroom along the road R540 to Lydenburg, the contact between a ~25m thick dolerite sill and quartzite from the basal Steenkampsberg quartzite is exposed (Figure 2.2). Here eight samples were taken from the dolerite, two samples from baked quartzites 0.5 m from the contact with the sill, and two quartzite samples 1 m below the contact. All dolerite samples displayed three magnetic components. The first was removed by AF pre treatment and thermal steps up to 250°C (Figure 2.10C). This low stability component formed a very poor grouping of components that tended to be easterly and upwards. Sample HWW 06 is an exception in that its low stability component is downward and westerly oriented. Between 250°C and 450°C all dolerite samples display upward westerly components. Again sample HWW 06 does not fall with the main grouping and is excluded in the calculation of the mean site (decl. = 249.4°, incl. = -67.1°, α₀₉₅ = 7.40, k = 107.96, n = 5; stratigraphic correction: decl. = 216.1°, incl. = -76.5°, α₀₉₅ = 7.39, k = 108.02, n = 5). All samples displayed high stability components between 450°C and 565°C. These were east southeasterly and downward oriented. Again sample HWW 06 is on outlier and was excluded in the calculation of the mean site (B component: decl. = 98.1°, incl. = 42.6°, α₀₉₅ = 11.88, k = 42.43, n = 5; stratigraphic correction: decl. = 96.6°, incl. = 56.5°, α₀₉₅ = 11.87, k = 42.52, n = 5) (Figure 2.11).
Quartzites samples similarly displayed three magnetic components. The first, revealed during the AF pre-treatment, formed a poor grouping of southeasterly upward directed components, while the second (100°C to 560°C) formed an equally poor grouping in a southeasterly upward direction. The third component was only identified as great circle arc demagnetization trajectories away from this southeasterly component. Great circle arcs however tend towards either southeasterly down oriented components (HWW 07 and 09) or north downward oriented directions (HWW 08 and HWW 10).

2.4.2.21. HWJ

Quartzite of the Steenkampsberg Formation was sampled at the baked contact to sill site HWW (± 10 m stratigraphically below the sill). All samples display two magnetic components. The first unblocks during AF pre-treatment mostly, but sometimes persist up to 450°C (Figure 2.10D). These are shallow, southerly and downward or fall along a north easterly trending great circle arc as upward directed components (Figure 2.11). At higher levels of demagnetization stable northerly downward directions unblock (C+ component: decl. = \(15.2^\circ\), incl. = \(50.2^\circ\), \(\alpha_{95} = 9.18\), \(k = 28.81\), \(n = 9\); stratigraphic correction: decl. = \(359.1^\circ\), incl. = \(48.1^\circ\), \(\alpha_{95} = 9.18\), \(k = 28.79\), \(n = 9\)) (Figure 2.11).

2.4.2.22. HWO

HWO is a ~20 m thick fairly weathered dolerite sill near the base of the Steenkampsberg Formation. Six samples were demagnetized with variable success. During AF pre-treatment and thermal demagnetization, all samples (except HWO 01 and 06) were characterized by two linear components (both non zero seeking) (Figure 2.10E). These components were in all cases upward directed but poorly grouped. Samples HWO 02 to 05 displayed demagnetization along great circle arc paths towards a northerly downward direction (C+ component) without reaching stable endpoints. Sample HWO 06 did reach a stable endpoint as well and here the high stability component could be quantified with an origin anchored straight line. The C+ component mean
Chapter 2

for this site has decl. = 34.6°, incl. = 37.9°, \( \alpha_{95} = 26.61 \), k = 22.52, n = 3; stratigraphic correction: decl. = 23.6°, incl. = 44.4°, \( \alpha_{95} = 26.58 \), k = 22.57, n = 3) (Figure 2.11).

2.4.2.23. HWV

Six oriented cores were taken from sill HWV, a very thick (~200m) sill near the base of the Steenkampsberg Formation. After the removal of randomly distributed shallow low stability components during the AF pre-treatment, southeasterly and downward magnetic directions (B component) unblocked as origin seeking linear trajectories (decl. = 133.4°, incl. = 80.7°, \( \alpha_{95} = 8.07 \), k = 58.27, n = 6; stratigraphic correction: decl. = 210.6°, incl. = 81.9°, \( \alpha_{95} = 7.76 \), k = 62.87, n = 6) (Figures 2.10F and 2.11).

2.4.2.24. HWK

At least 19 km southeast from the other sampling sites and approximately 3000 m stratigraphically below, six samples of unbaked chocolate brown shale from the Bowen Shale of the Silverton Formation were collected along the R36 between Carolina and Machadodorp (Figure 2.2). Below 350°C all samples are characterized by northerly upward magnetizations (PF: decl. = 4.1°, incl. = -59.7°, \( \alpha_{95} = 13.17 \), k = 22.35, n = 6; stratigraphic correction: decl. = 24.0°, incl. = -52.5°, \( \alpha_{95} = 13.17 \), k = 22.37, n = 6) (Figure 2.11). At higher temperatures of demagnetization, the behaviour is more noisy, but in five samples clear southerly shallow components unblock (decl. = 204.6°, incl. = 0.9°, \( \alpha_{95} = 12.79 \), k = 29.40, n = 5; stratigraphic correction: decl. = 203.9°, incl. = -8.4°, \( \alpha_{95} = 12.80 \), k = 29.36, n = 5) (Figures 2.10G and 2.11).

2.4.2.25. HWC

No interpretable results were acquired from volcanoclastic rocks of the Machadodorp Member exposed along a road cut ~10 km southeast from Machadodorp. Samples were weakly magnetic and displayed erratic demagnetization behavior (Figure 2.10H).
2.4.3. Summary of magnetic components

Two prolific (A and PF), and several less well-developed low stability components were identified within intrusions and country rocks (Pretoria Group). During high temperature demagnetization steps, samples mainly displayed B components and C+/– components. Component means are summarized in Figure 2.12. Component A is developed as a low stability component for both samples that display C+/– and B high stability components.

Figure 2.10. Examples of demagnetization behaviour, in situ coordinates, of some studied post-Transvaal sill samples in the eastern KC. A: HWP, B: HWH, C: HWW, D: HWJ, E: HWO, F: HWV, G: HWK and H: HWC. Open symbols = vertical plane, closed symbols = horizontal plane, NRM = natural remanent magnetization, mT = milli Tesla.
Figure 2.11. Equal area plots of results from sites HWH, HWW, HWJ, HWO, HWV and HWK. The left-hand panel depicts relatively low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts the relatively high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.
Figure 2.12. Summary of different mean site components obtained from the post-Transvaal sills and one dyke in the eastern KC
2.4.4. Paleomagnetic field tests

In this section, field tests for paleomagnetic stability that were conducted in order to constrain the timing of different magnetic components obtained from the studied sill and dyke samples are described.

2.4.4.1. Tilt correction tests (Fold tests)

Fold tests constrain the positions of the sills and dyke (geographic, tilt corrected or somewhere in between) during which remanence acquisition occurred. For this purpose, the bootstrap fold test of Tauxe et al. (1991) was applied to each of the magnetic components that were identified. The dips and strikes used are listed in Table 2.1.

2.4.4.1.1. A Component

The bootstrap fold test for the A components reveals that these magnetizations are most tightly clustered between -10 and 12 per cent of tilt restoration (Figure 2.13). The fact that the tilting restoration interval includes the zero per cent value strongly supports the idea that samples HWR, A, D, S, and T recorded the A component after tilting. This observation suggests that the A component represents a magnetic overprint.

2.4.4.1.2. B Component

During the bootstrap fold test, B components display a maximum grouping near zero percent of tilting restoration (Figure 2.14). The bootstrap test for component B is considered as negative and this allows the interpretation that this magnetization was recorded in sills HWR, D, S, L, T, U, X, and V when these intrusions were already tilted. Component B thus either is a younger magnetic overprint or it represents the primary magnetization of sills that intruded already tilted strata of the Pretoria Group. It may also be secondary in some cases and primary in others.
Figure 2.13. Bootstrap fold test for A components. Note that the interval of tilt restoration (-10%-12%) (blue lines) corresponding to the largest values of Y axis (tau_1) includes 0%.

Figure 2.14. Bootstrap fold test for B components. Note that the interval of tilt restoration (-10%-10%) (blue lines) corresponding to the largest values of Y axis (tau_1) includes 0%.
2.4.4.1.3. C+/- Component

The bootstrap fold test for C+/- components reveals that the different site means are most tightly clustered for a tilt restoration between 80 and 149 percent (Figure 2.15). Since this interval includes the hundred per cent level of tilting, the bootstrap test is considered to be positive, and indicates that the C+/- component was recorded by intrusions HWA, B, S, M, F, Y, I, H and O when they were not yet tilted. Tilting of Pretoria Group strata is generally believed to have occurred after the intrusion of the Bushveld Complex. The positive result of the bootstrap test of C+/- component suggests that this magnetization is of primary origin.

![Bootstrap fold test for C+/- components. Note that the interval of tilt restoration (80% - 149%) (blue lines) corresponding to the largest values of Y axis (tau_1) includes 100%.](image)

**Figure 2.15.** Bootstrap fold test for C+/- components. Note that the interval of tilt restoration (80% - 149%) (blue lines) corresponding to the largest values of Y axis (tau_1) includes 100%.

2.4.4.2. Reversal test (C+ component, C- component)

A bootstrap reversal test (Tauxe et al., 1991) is implemented in order to determine the antipodality of C- remanence (sites HWS and HWY) and the C+ remanence (sites HWA, B, F, H, I, M and O). Results of the test indicate that the X and Z components of the two magnetizations are statistically distinguishable at 95 per cent level of confidence, while the Y
Chapter 2

component reveals a relative overlap of C+ and C- remanences at the same level of confidence (Figure 2.16).

![Bootstrap reversal test for C+ and C- components](image)

**Figure 2.16.** Bootstrap reversal test for C+ and C- components. On X and Z components, spectrums of the two magnetizations (blue and red) plot separated. Although the spectrums show a relative overlap for Y component, the test reveals the two magnetizations to be statistically distinguishable at 95 per cent level of confidence

This result, which prevents the reversal bootstrap test for C remanence from being positive, can be re-examined in regard of some considerations such as the fact that each sill represents a snapshot of the geomagnetic field (i.e. a particular instant of time). Due to palaeosecular
variation, slightly different directions can be expected from sills of similar age. For palaeosecular variations to be adequately averaged out, a large sampling is generally needed (Butler, 1991). In the sampling area, very few sills recorded negative polarity (C-) components (only two such sills have been found in the sampling area). This strongly suggests that the palaeosecular variation of the C- remanence has not been adequately averaged out. The reversal test is thus interpreted as not being conclusive.

2.4.4.3. Baked-contact tests

Baked-contact tests were conducted in a total of three sites (HWE, HWJ and HWK) and aimed to investigate the existence of extensive remagnetization in the sampling area, with which to better constrain the timing of B and C+- magnetic remanences.

2.4.4.3.1. HWF and HWE

Sill HWF, which was sampled within the Vermont Formation on the farm Inyamazane, revealed three magnetic components during demagnetization. Two of these magnetizations were generally removed at low levels of demagnetization. Six of the nine samples displayed relatively scattered high temperature components (above 530°C up to 560°C) that were located northerly and downward at a moderate to steep inclination (C+ component: decl. = 23.8°, incl. = 62.8°, α95 = 17.6°, k = 12.87, n = 6; stratigraphic correction: decl. = 10.2°, incl. = 64.9°, α95 = 17.60, k = 12.86, n = 6) (Figure 2.17). The scattered nature of C+ components is probably due to the weathered character of sill HWF. In site HWE, (i.e. 1.5-2 m above sill HWF), baked Vermont shales (5 oriented cores) were sampled and revealed poorly grouped southerly and upward directed low stability components. More importantly, all five cores appeared to have recorded stable magnetic directions in the temperature range of 450°C to 565°C that formed a tight northerly downward oriented cluster (C+ component: decl. = 31.8°, incl. = 57.2°, α95 = 7.10, k = 93.70, n = 5; stratigraphic correction: decl. = 21.3°, incl. = 64.0°, α95 = 7.10, k = 93.71, n = 5) similar to component identified elsewhere.
Figure 2.17. Paleomagnetic baked-contact test at sites HWF and HWE. High temperature C+ components obtained from sill HWF and a baked contact sampled 1.5-2 m above the sill are very similar in geographic coordinates and after tilt-correction. Magnetic directions from previous studies on 2.15 Ga and 2050 Ma-2200 Ma units on KC are displayed for comparison.

Since thermal remagnetization of the country rock is expected to be extensive near the contact with an intrusion (Butler, 1991), and since the fine-grained Vermont shales are probably a better magnetic recorder than the weathered dolerite sill HWF, the northerly downward (C+)
remanence of the baked shales is considered to be equivalent to sill HWF’s primary thermo-remanent magnetization. The unaffected Vermont shales could not be sampled at a greater distance from the sill HWF to complete the test because of the lack of good outcrops. It is therefore difficult to demonstrate that the C+ magnetization was superimposed on a preexisting primary stable remanence. However, demagnetization results obtained from units of comparable age with the Pretoria Group (i.e., a ~2.15 Ga dyke that intrudes the Archean Basement and the 2060 Ma-2200 Ma Basal Gamagara/Mapedi Formation) generally revealed shallow magnetic components at higher demagnetization levels (Evans et al., 2002; Lubnina et al., 2010) that are clearly distinct from C+ components (Figure 2.17). This constitutes a positive baked-contact test which provides evidence that the C+ magnetization has been stable since the time of the intrusion of sill HWF.

2.4.3.2. HWW and HWJ

Sill HWW sampled within the basal Steenkampsberg quartzites generally displayed three magnetic components; the first, oriented easterly and upwards, is poorly constrained and was removed by AF pre-treatment and thermal steps up to 250°C. Between 250°C and 450°C, all samples displayed intermediate upward westerly components (Figure 2.18). High stability components were revealed between 450°C and 565°C. These were east southeasterly and downward (B component: decl. = 98.1°, incl. = 42.6°, α95 = 11.88, k = 42.43, n = 5; stratigraphic correction: decl. = 96.6°, incl. = 56.5°, α95 = 11.87, k = 42.52, n = 5). Four additional samples were taken from baked Steenkampsberg quartzites respectively 0.5 m and 1 m below the contact with sill HWW (Figure 2.18). Quartzites samples similarly displayed three magnetic components. The first (AF pre-treatment) consisted of poorly grouped southeasterly upward directed components. Between 100°C to 560°C, a component with a southeasterly downward direction was revealed. The third component was only identified as great circle arc demagnetization trajectories away from this southeasterly component.
Figure 2.18. Paleomagnetic baked-contact test at sites HWW and HWJ. High temperature components obtained from sill HWW and a baked Steenkampsberg quartzite sampled 0.5 m above the sill are similar in geographic coordinates and after tilt-correction. High temperature components obtained from a baked Steenkampsberg quartzite sampled at a more distant position (~1 m) from sill are similar to the remanence recorded by the unaffected quartzite far from the sill. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits, squares = pole to the plane of best-fit great circle arcs.
In sample HWW 08 which was sampled 0.5 m from the sill, the great circle arc tends towards a magnetic direction similar to that revealed at high temperature in the intrusion (i.e. southeasterly and downward oriented), while the circle follows a different direction (i.e. north downward oriented) in sample HWW 09 sampled 1m below the intrusion (Figure 2.18). It is interesting to note that similar, and otherwise better defined, high temperature north downward components, (C+ component: decl. =15.2°, incl. = 50.2°, α95 = 9.18, k = 28.81, n = 9; stratigraphic correction: decl. = 359.1°, incl. = 48.1°, α95 = 9.18, k = 28.79, n = 9) were revealed during demagnetization of unaffected Steenkampsberg quartzites (9 oriented cores) at a greater distance (site HWJ) from sill HWW (Figure 2.18). The same quartzites also yielded shallow southerly and downward components and easterly upward directed components during AF pre-treatment mostly, and sometimes up to 450°C. This constitutes a positive baked contact test for the B component which has been stable since the intrusion of sill HWW.

2.4.4.3.3. HWK

In site HWK, chocolate brown shales from the Bowen Shale of the Silverton Formation were collected (six samples) ~19 km away and stratigraphically far below the previous sampling sites. Below 350°C, all samples revealed northerly upward components (Figure 2.11). At higher temperatures, five samples revealed clear southerly shallow components (decl. = 204.6°, incl. = 0.9°, α95 = 12.79, k = 29.40, n = 5; stratigraphic correction: decl. = 203.9°, incl. = -8.4°, α95 = 12.80, k = 29.36, n = 5). The southerly shallow remanence which has not been obtained in any of the previous sampling sites, together with the presence of near dual polarity directions C+/- (sites HWA, B, E, F, H, I, J, M, O, S and Y), and the fact that the different sampling sites in the area yielded widely separated paleomagnetic directions (A, B, and C+/-) negate arguments for a pervasive remagnetization in the sampling area.

2.4.5. Interpretation

In this section, low-stability and high-stability directions obtained from the sill and dyke samples are compared to previously published paleomagnetic results from the KC. The aims are to
constrain the ages of PF, A, B and C+- components as well as to investigate the timing of acquisition of these magnetizations.

### 2.4.5.1. Low temperature components (A and PF Component)

The first low temperature (before 400°C) magnetization (A remanence) was revealed in few samples (HWA, D, R, S, and T) generally as poorly grouped southerly and upwards pointing directions (Figure 2.12). Since the A mean site directions display a maximum grouping between -10 and 12 percent of tilt restoration (Figure 2.13), and since the sites HWD, HWR and HWT yielded high temperature directions that are similar to ~180 Ma Karoo directions (Hargraves et al., 1997) (see next section), the A remanence is interpreted to be a post-Karoo-aged magnetic overprint that was acquired after the intrusions have undergone tilting. After exclusion of site HWS which has a large uncertainty ($\alpha_{95} = 22$), an in situ mean A direction was calculated at decl. $= 173.1^\circ$, incl. $= -47.2^\circ$, k = 15.6, $\alpha_{95} = 24.0$, N = 4. The corresponding pole position is located at 34.0°N, 22.6°E, K = 13.4, $A_{95} = 26.0^\circ$, N = 4.

The second low temperature magnetization (PF) was revealed during pre-treatment and before 350°C in sills HWK, HWU and HWY. The PF overprint consisted of poorly grouped northerly and upwards directions that are near parallel to the Earth’s present dipole field as defined by most current International Geomagnetic Reference Field (IGRF). This suggests some remanence acquisition during recent weathering.

### 2.4.5.2. B Component

Above 500°C, sill samples HWD, L, R, T, U, V, W and X recorded B components (southeasterly and down) (Figure 2.12), generally as origin seeking straight line demagnetization trajectories. During the bootstrap fold test, the B components displayed a maximum clustering without much tilt restoration (Figure 2.14). This behaviour combined with one positive baked contact test in site HWW indicates that the B magnetization may be of primary nature, but postdates the tilting of strata. If compared to known paleomagnetic directions for KC, the B components bear
resemblance to the ~180 Ma Karoo magmatic event, although the Karoo directions (Hargraves et al., 1997) are typically more south directed with a moderate inclination (Figure 2.19). The age of 180 Ma of the Karoo magmatic province is interpreted to probably be the age of the B components recorded in sites HWD, L, R, T, U, V, W and X. Geochemical analysis of sample HWD is done in Section 2.5 and results are expected to provide additional constrains on the timing of B magnetization and to test whether this is Karoo-aged. Afterwards, a mean B component as well as the corresponding pole position will be calculated.

![Figure 2.19. Comparisons of the south-easterly and down B components identified in HWD, HWL, HWR, HWT, HWU, HWV, HWW and HWX with the site means for the ~180 Ma Karoo LIP after Hargraves et al. (1997)](image)

2.4.5.3. C+/- Component

A positive baked contact test (sites HWE and HWF), a regional positive baked-contact test (HWK), a positive bootstrap fold test with a maximum grouping of different site means between 80 and 149 per cent unfolding, and the reversal test result strongly support the primary nature of the C+/- magnetization recorded in sites HWA, B, F, H, I, M, O, S and Y. If compared to known paleomagnetic directions from the KC, the C+/- components correlate well with the Bushveld Complex directions as recently obtained from the 2058-2054 Ma RLS by Letts et al. (2009) (Figure 2.20). This strongly supports the idea that the C+/- remanence recorded in intrusions HWA, B, F, H, I, M, O, S and Y is related to the Bushveld Complex. Geochemistry of samples
HWA, HWB, HWF, and HWH are studied in Section 2.5 and will help better constrain the interpreted timing of the C+/− remanence. Afterwards (Section 2.7), a C+/− mean component is calculated and the corresponding pole position is presented.

![Diagram](image)

**Figure 2.20.** Comparisons of the northerly downward (C+) / southerly upward (C-) components identified in sites HWA, B, F, H, I, M, O, S and Y with the 2058 Ma-2054 Ma RLS of the Bushveld Complex after Letts et al. (2009)

### 2.4.5.4. D remanence

Demagnetization results for site HWQ reveal poorly constrained directions. Components in three samples are easterly and shallow oriented and allow for calculating a site mean for HWQ at declination = 77.3°, inclination = 26.7°, k = 20.43, α95 = 28.04, n = 3. Although no field tests were done to constrain the timing of this component, it is interpreted as representative of a primary magnetization recorded by sample at the time of sill emplacement. The interpretation is based on the resemblance to known directions in KC. The D remanence shares similarities with the mean components obtained by Lubnina et al. (2010) from a 2.15 Ga dyke that intrudes the southeastern Archean Basement (Figure 2.21) and the reversely polarized MAM-1 directions from the Mamatwan ore (Hotazel Formation). This suggests an age of ~2.1 to ~2.2 Ga for the D remanence of sill HWQ. A VGP can be calculated for site HWQ at 05.1°N, 102.1°E, dp = 16.5,
dm = 30.4, n = 3. This VGP will be discussed together with the results from the western sill complex in the next chapter.

![Figure 2.21](image)

**Figure 2.21.** Comparisons of the easterly and shallow D component identified in sill HWQ from the present study with the 2.15 Ga dyke in the southeastern Archean Basement after Lubnina et al. (2010) and the MAM-1 directions after Evans et al. (2001).

### 2.5. GEOCHEMISTRY

#### 2.5.1. Method

Six of the studied intrusions (i.e. HWA, B, D, F, G and H) were subjected to geochemical analyses. Major and trace element contents were determined by X-ray fluorescent spectrometry at the ACME Labs, Canada, on glass beads prepared from powdered whole-rock samples with a sample-to-flux (lithium tetra borate) ratio of 1:10. Volatiles were determined by loss on ignition. Trace and rare earth element (REEs) were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) also at the ACME Labs. The geochemical results are presented in Table 2.4.
Table 2.4. Geochemical results from the studied sill and dyke (*) samples

<table>
<thead>
<tr>
<th>element</th>
<th>HWA*</th>
<th>HWB</th>
<th>HWD</th>
<th>HWF</th>
<th>HWG</th>
<th>HWH</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ (%)</td>
<td>55.26</td>
<td>55.15</td>
<td>57.78</td>
<td>54.3</td>
<td>54.92</td>
<td>55.25</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>12.78</td>
<td>12.89</td>
<td>11.94</td>
<td>11.27</td>
<td>14.89</td>
<td>15.22</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>9.79</td>
<td>10.27</td>
<td>8.92</td>
<td>10.32</td>
<td>10.19</td>
<td>9.18</td>
</tr>
<tr>
<td>MgO</td>
<td>10.36</td>
<td>10.16</td>
<td>9.69</td>
<td>13.01</td>
<td>5.55</td>
<td>5.59</td>
</tr>
<tr>
<td>CaO</td>
<td>7.11</td>
<td>7.11</td>
<td>5.85</td>
<td>6.58</td>
<td>8.42</td>
<td>7.35</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.72</td>
<td>2.01</td>
<td>2.07</td>
<td>1.47</td>
<td>2.17</td>
<td>2.36</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.1</td>
<td>0.87</td>
<td>1.43</td>
<td>0.77</td>
<td>1.18</td>
<td>1.6</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.43</td>
<td>0.45</td>
<td>0.34</td>
<td>0.29</td>
<td>0.54</td>
<td>0.46</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.08</td>
<td>0.08</td>
<td>0.1</td>
<td>0.06</td>
<td>0.11</td>
<td>0.1</td>
</tr>
<tr>
<td>MnO</td>
<td>0.16</td>
<td>0.16</td>
<td>0.14</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.12</td>
<td>0.15</td>
<td>0.102</td>
<td>0.192</td>
<td>0.026</td>
<td>0.03</td>
</tr>
<tr>
<td>LOI</td>
<td>0.8</td>
<td>0.4</td>
<td>1.4</td>
<td>1.2</td>
<td>1.6</td>
<td>2.4</td>
</tr>
<tr>
<td>Sum</td>
<td>99.75</td>
<td>99.75</td>
<td>99.74</td>
<td>99.72</td>
<td>99.8</td>
<td>99.77</td>
</tr>
<tr>
<td>Ni (ppm)</td>
<td>243</td>
<td>232</td>
<td>195</td>
<td>304</td>
<td>98</td>
<td>88</td>
</tr>
<tr>
<td>Sc</td>
<td>32</td>
<td>32</td>
<td>27</td>
<td>34</td>
<td>34</td>
<td>27</td>
</tr>
<tr>
<td>Co</td>
<td>54.3</td>
<td>54.6</td>
<td>52.8</td>
<td>64.8</td>
<td>44.2</td>
<td>41.4</td>
</tr>
<tr>
<td>Hf</td>
<td>1.9</td>
<td>2.3</td>
<td>2.4</td>
<td>1.3</td>
<td>2.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Nb</td>
<td>3.8</td>
<td>3.9</td>
<td>4.4</td>
<td>4.4</td>
<td>5.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Rb</td>
<td>45.8</td>
<td>36.8</td>
<td>57.7</td>
<td>30.1</td>
<td>49</td>
<td>64.4</td>
</tr>
<tr>
<td>Sn</td>
<td>&lt;1</td>
<td>1</td>
<td>1</td>
<td>&lt;1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sr</td>
<td>177.9</td>
<td>181.2</td>
<td>254.5</td>
<td>180.1</td>
<td>237.7</td>
<td>278</td>
</tr>
<tr>
<td>Ta</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Th</td>
<td>4.5</td>
<td>4.3</td>
<td>4.1</td>
<td>3.6</td>
<td>5.4</td>
<td>4.8</td>
</tr>
<tr>
<td>U</td>
<td>0.9</td>
<td>1</td>
<td>1.1</td>
<td>0.9</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>V</td>
<td>190</td>
<td>222</td>
<td>179</td>
<td>188</td>
<td>211</td>
<td>187</td>
</tr>
<tr>
<td>W</td>
<td>0.7</td>
<td>1.3</td>
<td>0.8</td>
<td>&lt;0.5</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Zr</td>
<td>71</td>
<td>76.2</td>
<td>87.3</td>
<td>53.9</td>
<td>96.4</td>
<td>97.8</td>
</tr>
<tr>
<td>Y</td>
<td>12.6</td>
<td>12.9</td>
<td>11.8</td>
<td>8.9</td>
<td>16.7</td>
<td>16.6</td>
</tr>
<tr>
<td>La</td>
<td>14</td>
<td>14.4</td>
<td>18.8</td>
<td>12.2</td>
<td>20.6</td>
<td>19.5</td>
</tr>
<tr>
<td>Ce</td>
<td>29.2</td>
<td>29.4</td>
<td>38.5</td>
<td>25.6</td>
<td>40.9</td>
<td>38.4</td>
</tr>
<tr>
<td>Pr</td>
<td>3.3</td>
<td>3.36</td>
<td>4.39</td>
<td>2.89</td>
<td>4.8</td>
<td>4.32</td>
</tr>
<tr>
<td>Nd</td>
<td>12.7</td>
<td>12.8</td>
<td>16.4</td>
<td>10.9</td>
<td>17.8</td>
<td>15.2</td>
</tr>
<tr>
<td>Sm</td>
<td>2.35</td>
<td>2.3</td>
<td>2.73</td>
<td>1.91</td>
<td>3.32</td>
<td>3</td>
</tr>
<tr>
<td>Eu</td>
<td>0.65</td>
<td>0.65</td>
<td>0.68</td>
<td>0.52</td>
<td>0.87</td>
<td>0.84</td>
</tr>
<tr>
<td>Gd</td>
<td>2.19</td>
<td>2.25</td>
<td>2.36</td>
<td>1.62</td>
<td>3.01</td>
<td>2.65</td>
</tr>
<tr>
<td>Tb</td>
<td>0.38</td>
<td>0.38</td>
<td>0.37</td>
<td>0.27</td>
<td>0.5</td>
<td>0.45</td>
</tr>
<tr>
<td>Dy</td>
<td>2.1</td>
<td>2.18</td>
<td>1.97</td>
<td>1.58</td>
<td>2.82</td>
<td>2.58</td>
</tr>
<tr>
<td>Ho</td>
<td>0.44</td>
<td>0.46</td>
<td>0.42</td>
<td>0.32</td>
<td>0.59</td>
<td>0.51</td>
</tr>
<tr>
<td>Er</td>
<td>1.32</td>
<td>1.34</td>
<td>1.2</td>
<td>0.95</td>
<td>1.68</td>
<td>1.54</td>
</tr>
<tr>
<td>Tm</td>
<td>0.19</td>
<td>0.21</td>
<td>0.17</td>
<td>0.14</td>
<td>0.26</td>
<td>0.23</td>
</tr>
<tr>
<td>Yb</td>
<td>1.26</td>
<td>1.31</td>
<td>1.12</td>
<td>0.93</td>
<td>1.63</td>
<td>1.47</td>
</tr>
<tr>
<td>Lu</td>
<td>0.2</td>
<td>0.2</td>
<td>0.17</td>
<td>0.15</td>
<td>0.25</td>
<td>0.23</td>
</tr>
<tr>
<td>Mo</td>
<td>2.2</td>
<td>12.1</td>
<td>4.2</td>
<td>1.9</td>
<td>3.4</td>
<td>4.3</td>
</tr>
<tr>
<td>Cu</td>
<td>44.3</td>
<td>41.7</td>
<td>45.9</td>
<td>46</td>
<td>67.2</td>
<td>53.2</td>
</tr>
<tr>
<td>Pb</td>
<td>4.2</td>
<td>4.7</td>
<td>7.9</td>
<td>6.8</td>
<td>24.6</td>
<td>12.3</td>
</tr>
<tr>
<td>Zn</td>
<td>28</td>
<td>20</td>
<td>26</td>
<td>17</td>
<td>61</td>
<td>49</td>
</tr>
<tr>
<td>Ni</td>
<td>67.3</td>
<td>65.8</td>
<td>58.5</td>
<td>83.4</td>
<td>32.9</td>
<td>52.6</td>
</tr>
<tr>
<td>As</td>
<td>2.2</td>
<td>1.2</td>
<td>1.8</td>
<td>3.3</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Cd</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Sb</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Bi</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Ag</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Au</td>
<td>1.6</td>
<td>1.9</td>
<td>2.2</td>
<td>2.5</td>
<td>1.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Hg</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Tl</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Se</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>
2.5.2. Weathering and alteration

Samples for geochemistry were taken from least weathered, fresh looking sections of outcrop. Based on petrographic observations the sampled intrusions are variably altered and can be subdivided into three general groups in terms of degree of alteration: 1) fresher samples (HWD) that have undergone little to no alteration, 2) altered samples (HWA, HWB, HWG, HWH) that had undergone limited alteration, and 3) highly altered samples (HWF) that had experienced extensive alteration. In the fresher samples, the original texture and mineralogy are generally intact. Alteration, when present, is limited to the outer rims, or along cracks of primary mineral phases (e.g., plagioclase and pyroxene). In the altered samples, the igneous texture is variably affected. Secondary amphibole and clay minerals partially replace some primary pyroxene and plagioclase minerals. In the highly altered samples, the igneous texture is obliterated. The pyroxenes are near completely replaced by secondary minerals.

Loss of ignition (LOI) content of rocks can also be taken as approach to recognizing alteration, as high LOI content generally corresponds to more altered rocks. The sampled intrusions had LOI values that vary between 0.4 and 2.4, which is relatively low (Table 2.4). During alteration, the alkalis, SiO$_2$, MgO, CaO, as well as the light rare earth elements (LREE) and large lithophile elements such as Rb, Ba, and Sr may be considered mobile. Rb, Ba, K$_2$O, and Sr are particularly mobile during alteration, and these display in all cases positive correlation with LOI content of samples, which may suggest that alteration affected the chemistry of the samples. To investigate this further, and to evaluate the intensity and mode of alteration, the alteration box plot of Large et al. (2001) is used (Figure 2.22). This reveals that none of the samples is strongly altered, and samples, with the highest LOI values are in fact the least altered (Figure 2.22). Samples HWA, HWB, and HWF display some weak hydrothermal chlorite-pyrite-(sericite) alteration, with sample HWF being the most affected (Figure 2.22). The chemistry of the intrusions is thus not believed to be significantly affected by alteration.
2.5.3. Major element geochemistry

The compositions of the sampled intrusions, although relatively similar, vary in terms of SiO$_2$, MgO, and TiO$_2$ contents. All but one sample reveal moderate SiO$_2$ contents (54.3-55.2 wt %) (Table 2.4). HWD is richer in SiO$_2$ (~57 wt %). It is interesting to note that this mirrors the paleomagnetic distinction amongst samples (HWD displayed the B characteristic remanent magnetization while the remainder, with the exclusion of HWG which is lightning affected, displays C+/− characteristic remanence). This suggests two distinct magmatic events perhaps far removed in time from one another. The intrusions also display some separation in terms of TiO$_2$ contents, which range between 0.29 and 0.54 wt % (Table 2.4). Samples HWF and HWD are characterized by lower TiO$_2$ relative to samples HWA, HWB, HWG and HWH (Table 2.4). The Mg# (= Mg$^{2+}$/Mg$^{2+}$ + Fe$^{2+}$) for the various intrusions show a range of values between ~53 and 72. This indicates that none of the intrusions are entirely primitive. The relatively high Mg# and low TiO$_2$ contents of HWF and HWD place these samples on the less evolved end of the spectrum, while HWG and HWH are more evolved. For samples HWA, HWB, HFW, HWH, and
possibly HWG, which are believed to be related to the same magmatic event (C+/- magmatism). Na$_2$O, K$_2$O, P$_2$O$_5$, and CaO decrease with increasing of MgO content, while MnO and total FeO do not display any clear trend. The trends mentioned here are best explained by the fractional crystallization of pyroxene (± plagioclase), while the variation in major element chemistry between HWH and the other samples may also suggest the involvement of more than one parental magma. Samples HWG and HWH are confirmed to be the most evolved while the samples HWA, HWB and HWF are the least evolved.

2.5.4. Magma types

The sampled intrusions were classified as tholeiitic (less evolved HWA, HWB and HWF) to calc-alkaline (more evolved HWG and HWH) basaltic andesites with the exception of HWD, which is classified as a tholeiitic andesite using IUGS total alkali versus silica (TAS) system (Le Bas et al., 1986) and the total alkali, FeO and MgO (AFM) ternary system of Irvine and Baranger (1971) (Figures 2.23A and B).

![Discrimination diagrams for major elements showing the behaviour of samples HWA, B, D, F, G and H. A: AFM diagram (Irvine and Baragar, 1971). B: bivariate diagram of total alkali vs. silica (Le Bas et al., 1986)](image)

**Figure 2.23.** Discrimination diagrams for major elements showing the behaviour of samples HWA, B, D, F, G and H. A: AFM diagram (Irvine and Baragar, 1971). B: bivariate diagram of total alkali vs. silica (Le Bas et al., 1986)
2.5.5. Trace elements (Co, Ni, Sc, Cu, Zn and V)

Site HWD (B remanence) is characterized by low Co and Ni, which exhibits a positive correlation with the MgO. This is attributed to early formed mafic minerals (e.g., pyroxene). Site HWD is enriched in Sc, Cu, Zn, and V, which display a negative correlation with MgO (Figure 2.24). In fractionation process, Sc, Cu, Zn, and V are generally known as incompatibles elements which tend to concentrate in residual liquids. For samples HWA, HWB, HWF, HWH which are believed to be related to the same magmatic event (C+/-- remanence), the more evolved nature of HWH is clearly reflected in its generally low trace element abundance. Trace elements of HWH positively correlate with MgO, which are involved in the fractionation of pyroxene. The evolved nature of HWH is also confirmed by the enrichment of this site in incompatible elements (Sc, Cu, Zn, and V) which are known as preferentially remaining in residual liquid during fractionation. Site HWF (C+ remanence) appears to be the less evolved sample as it exhibits the highest MgO, and which positively correlates with the elements Sc, Ni, and Co (Figure 2.24). The evolved character of site HWG (lightning affected) as previously suggested is not clear here, as this site display relatively high Ni, Cu, Co, and Zn, similarly to samples HWA and HWB (Figure 2.24). Site HWG also stands out from samples HWA, HWB, HWF, HWH (C+/- remanence) and HWD (B remanence)) for elements Sc and V.

Figure 2.24. Diagrams of selected trace elements vs. MgO of the studied post-Transvaal intrusions.
2.5.6. Rare earth elements

Rare earth element (REE) geochemistry of the studied intrusions is displayed on a chondrite normalized plot (McDonough and Sun, 1995). All intrusions are enriched in REE by several orders of magnitude relative to chondritic values, and show a strong fractionation of LREE relative to HREE (Figure 2.25A). This is more pronounced for HWD (B remanence), with La/Sm (4.30), Gd/ErN (1.58) and Er/LuN (1.12). REE curves for HWA, HWB, HWF and HWH (C+/- remanence), and HWG (lightning affected) are less concave, with La/SmN (~3.91), Gd/Er (~1.37) and Er/LuN (~1.05) (Figure 2.25A). None of the samples display a significant Eu anomaly (Eu/Eu* = ~0.86), with HWD having the least significant anomaly (Eu/Eu* = ~0.80). Sample HWG (lightning affected) stands out from the other samples in having a slight Tb anomaly (Figure 2.25A), and may possibly be representative of another magmatic event than HWA, HWB, HWF, HWH (C+/- remanence) and HWD (B remanence).

Figure 2.25. Trace elements behaviour of the studied post-Transvaal intrusions. A. Chondrite-normalized (McDonough and Sun, 1995) REE profiles. B: Pyrolite-normalized (McDonough and Sun, 1995) incompatible trace elements patterns.
2.5.7. Multi-elemental plots (spidergrams)

All samples exhibit enriched multi-elemental levels with consistent, negative Nb, Ta, as well as P, Ce, and Ti anomalies. All samples display relatively steep light rare earth element (LREE), steep medium rare earth (MREE) patterns and flat heavy rare earth element (HREE) curves (Figure 2.25B). A slight negative Ba anomaly is present in the C+/- remanence sills and lightning affected HWG, and is generally more pronounced in the less evolved intrusions (HWA, HWB and HWF) (Figure 2.25B). The Ba anomaly is absent from sill HWD (B remanence), which otherwise mirrors the other intrusions, except for a slightly more pronounced Ti spike and slightly steeper HREE to MREE patterns. Rb, K, Th, and Nd, but most pronounced Pb display positive kinks (Figure 2.25B). The more evolved intrusions (HWH and HWD) are more light lithophile element (LILE) enriched and display markedly positive Pb spikes (Figure 2.25B).

2.5.8. Correlation to strata-bound igneous suites

In Figure 2.26A, the geochemical characteristics of samples HWA, B, D, F, G and H are compared with results from some well-documented Paleoproterozoic and younger igneous events in the KC, (i.e. the Dullstroom Lavas, the sills and marginal rocks of the basal contact of the eastern Bushveld Complex, the ~1.9 Ga post-Waterberg intrusions and Black Hills dykes, the ~1.1 Ga Umkondo sills, and the ~180 Ma Karoo intrusions). Details on these comparisons are given in Appendix 2, while a general summary is presented here.

2.5.8.1. HWA, HWB, HWF, HWH, and HWG

It can be observed that the chemistry of samples HWA, B, F, and H (C+ remanence) and HWG (lighting affected) do not generally correlate well with the younger units on KC (i.e. the ~1.1 Ga Umkondo sills and the ~180 Ma Karoo intrusions) (Figures 2.26G-J). A comparison of geochemical signatures of the studied units with the ~1.9 Ga post-Waterberg intrusions and the Black Hills dykes have also be done without observing much overlap (Figures 2.26E and F).
Samples HWA, B, F, H and G, however, bear some resemblance to the B2 and B3 Bushveld-related sills mostly in terms of REE profiles and spidergrams (Figures 2.26C and D).

To be continued on next page
Figure 2.26. Comparisons of trace elements geochemistry of studied samples with results from previously published Paleoproterozoic and younger units on KC. A, C, E, G and I: Rare earth elements (REE) plots normalized to chondrite of McDonough and Sun (1995). B, D, F, H and J: Multi-element plots (spidergram) normalized to pyrolite of McDonough and Sun (1995)
More importantly, samples HWA, B, D, F and G share remarkable geochemical similarities, in terms of major elements (Mg#, tholeiitic basaltic andesite), rare earth element profiles (similar levels of enrichment, similar La/Sm (4) and Er/Lu (~1.05) ratios) and multi-element plots (near identical shape and level of enrichment) with the B1, and in a lesser extent the B1 UM Bushveld-related sills of Barnes et al. (2010) (Figures 2.26C and D). This behaviour is in very good agreement with the interpreted age of the C+/- remanence (see Section 2.4.5.3). A partial overlap of the studied samples with the Dullstroom Lavas can also be observed (Figures 2.26A and B). This is not surprising since the Dullstroom Formation is generally believed to be related to an early Bushveld magma (Buchanan et al., 1999).

2.5.8.2. HWD

In contrast to C+/- remanence sites, sample HWD (B remanence) is more difficult to correlate in term of its geochemical fingerprint. When compared to known geochemical results from KC, this site shares most resemblance to the B1 Bushveld magma-related sills and in the lesser extent with the B1 UM and others Bushveld-related sills of Barnes et al. (2010), but less convincingly than the C+/- remanence samples (Figures 26C and D). Correlation of sample HWD to the low-Ti group of Karoo LIP rocks, the 1.1 Ga Umkondo sills or the 1.9 Ga magmatic events cannot be excluded (Figures 26I and J). This geochemical ambiguity is also reflected in the paleomagnetic signature of sample HWD (B remanence) which is either a magnetically overprinted Bushveld aged sill or a low-Ti Karoo aged sill.

2.5.9. Summary

Geochemical signatures revealed by sills HWB, HWD, HWF, HWH, and HWG, and dyke HWA sampled from the sill suite within the Pretoria Group in the eastern KC (Mpumalanga Province) generally indicate a tholeiitic affinity and basaltic andesite composition. Discrimination diagrams based on major element abundances, and REE profiles of trace elements generally suggested two magmatic events, which mirror the paleomagnetic distinction amongst sites (i.e. the B magmatism (HWD) and the C+/- magmatism (HWA, HWB, HWF, HWH and HWG)).
Comparisons of the chemistry of the samples with previously published geochemical data in the KC reveal that most samples bear remarkable similarities with the B1 Bushveld magma-related sills in the eastern KC, suggesting a genetic link. While sharing a common parental magma, it is possible to distinguish between the studied intrusions the less evolved units (HWA, HWB, HWD, and HWF) and the sills of more differentiated chemistry (HWG and HWH).

2.6. GEOCHRONOLOGY

2.6.1. Method

Here, new U-Pb baddeleyite ages obtained from two post-Transvaal sills are reported. Sills HWH and HWS, which revealed near antipodal (C+/-) magnetic directions during demagnetization and shared geochemical similarities with the B1 group of Bushveld magma-related sills of Barnes et al. (2010) were processed for baddeleyite following the Söderlund and Johansson (2002) water-based method using a Wifley® Table at Lund University (Sweden). After extraction, the best grains were chosen and combined into fractions of between 1 and 7 grains. Fractions were dissolved in 2 to 3 M HNO$_3$ on a hot plate and rinse in H$_2$O. After being dissolved under high pressure and temperature, samples were dried, re-dissolved in 3.1 M HCl and readied for analyses, which were performed on a Thermo Finnigan Triton thermal ionisation multicollector mass spectrometer at the Natural History Museum in Stockholm. As part of the process, intensities of $^{208}$Pb, $^{207}$Pb, $^{206}$Pb and $^{205}$Pb were monitored using Faraday collectors. An ETP SEM equipped with an RPQ filter was used to measure the intensity of $^{204}$Pb. Measurements of the Pb isotopic were achieved at filament temperatures in the 1200-1320°C range. Isotopes of uranium were measured subsequently in dynamic mode on the SEM. This was done at filament temperatures >1350°C. The obtained results were plotted following the Excel Add-in Isoplot of Ludwig (2003) and the decay constants for $^{238}$U and $^{235}$U were from Jaffey et al. (1971). All errors in age and isotopic ratios are reported at the 95% confidence level. Initial common Pb correction was done using the isotopic compositions according to the global common Pb evolution model by Stacey and Kramers (1975).
2.6.2. Results

2.6.2.1. HWH (C+ remanence)

The U-Pb data obtained for sample HWH are reported in the Table 2.5. Regression through three variably discordant analyses of three baddeleyite fractions yields an upper intercept age of 2058.4 ± 1.3 Ma (MSWD = 0.37) (Figure 2.27) using a forced lower intercept of 180 ± 50 Ma. Pb-loss is thus attributed to the Karoo magmatic event in accordance with an unforced regression with a lower intercept close to 180 Ma.

2.6.2.2. HWS (C- remanence)

The U-Pb data obtained for sample HWS are presented in the Table 2.6. Regression through four variably discordant analyses of four baddeleyite fractions yields an upper intercept of 2058.1 ± 6 Ma (MSWD = 1.06) (Figure 2.28) and a free regression of 0 ± 100 Ma.

2.6.3. Interpretation

The upper intercept U-Pb ages of 2058.4 ± 1.3 Ma and 2058.1 ± 6 Ma for sills HWH and HWS are near identical. The uncertainties associated to these ages indicate that at worst, sills HWH and HWS intruded in the interval of ~7 million years, and at the best at the same time. On the other hand, the influence of a Jurassic-aged event in the sampling area, as suggested by a Pb-loss and the lower intercept close to ~180 Ma of the concordia diagram of sample HWH (Figure 2.27), is consistent with the existence of paleomagnetic Karoo-like directions recorded by neighbour sites.

The U-Pb ages reported here are significant because they are the first precise ages ever to be determined on the post-Transvaal sill suite in the KC. The 2058.4 ± 1.3 Ma and 2058.1 ± 6 Ma values are indistinguishable from the emplacement age (U-Pb age of 2057.7 ± 1.6 Ma) recently reported by Olsson et al. (2010) for the Marginal Zone in the eastern limb of the RLS. This correlation will be further discussed in the next chapter.
Table 2.5. U-Pb TIMS data of sill sample HWH

<table>
<thead>
<tr>
<th>Analysis no.</th>
<th>U/ Pbc</th>
<th>Pbtot</th>
<th>206Pb/ 238U</th>
<th>207Pb/ 235U</th>
<th>206Pb</th>
<th>207Pb</th>
<th>± 2σ</th>
<th>± 2σ</th>
<th>207Pb/ 235U</th>
<th>206Pb/ 235U</th>
<th>207Pb/ 235U</th>
<th>± 2σ Concordance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bd-1 (6 grains)</td>
<td>2.2</td>
<td>0.009</td>
<td>6367.6</td>
<td>6.5175</td>
<td>0.18</td>
<td>0.37205</td>
<td>0.16</td>
<td>2048.3</td>
<td>2039.0</td>
<td>2057.6</td>
<td>1.5</td>
<td>0.991</td>
</tr>
<tr>
<td>Bd-2 (7 grains)</td>
<td>2.5</td>
<td>0.032</td>
<td>1670.3</td>
<td>6.2881</td>
<td>0.33</td>
<td>0.35952</td>
<td>0.28</td>
<td>2016.8</td>
<td>1979.9</td>
<td>2054.8</td>
<td>2.9</td>
<td>0.964</td>
</tr>
<tr>
<td>Bd-3 (1 grain)</td>
<td>49.2</td>
<td>0.011</td>
<td>5539.1</td>
<td>6.4580</td>
<td>0.23</td>
<td>0.36904</td>
<td>0.18</td>
<td>2040.2</td>
<td>2024.9</td>
<td>2055.7</td>
<td>2.7</td>
<td>0.985</td>
</tr>
</tbody>
</table>

1) Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).
2) measured ratio, corrected for fractionation and spike.
3) isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (1 pg Pb and 0.1 pg U), and initial common Pb. Initial common Pb corrected with isotopic compositions from the model of Stacey and Kramers (1975) at the age of the sample.

Figure 2.27. Concordia diagrams for sill sample HWH. All errors are reported at ± 2σ

Table 2.6. U-Pb TIMS data of sill sample HWS

<table>
<thead>
<tr>
<th>Analysis no.</th>
<th>U/ Pbc</th>
<th>Pbtot</th>
<th>206Pb/ 238U</th>
<th>207Pb/ 235U</th>
<th>206Pb</th>
<th>207Pb</th>
<th>± 2σ</th>
<th>± 2σ</th>
<th>207Pb/ 235U</th>
<th>206Pb/ 235U</th>
<th>207Pb/ 235U</th>
<th>± 2σ Concordance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bd-1 (4 grains)</td>
<td>17.8</td>
<td>0.172</td>
<td>344.2</td>
<td>6.5488</td>
<td>1.49</td>
<td>0.37321</td>
<td>1.48</td>
<td>2052.5</td>
<td>2044.5</td>
<td>2060.5</td>
<td>7.6</td>
<td>0.992</td>
</tr>
<tr>
<td>Bd-2 (1 grain)</td>
<td>42.6</td>
<td>0.253</td>
<td>250.8</td>
<td>6.5793</td>
<td>3.35</td>
<td>0.38045</td>
<td>2.93</td>
<td>2056.6</td>
<td>2078.4</td>
<td>2034.8</td>
<td>29.0</td>
<td>1.021</td>
</tr>
<tr>
<td>Bd-3 (3 grains)</td>
<td>4.9</td>
<td>0.162</td>
<td>37.1</td>
<td>6.5086</td>
<td>1.86</td>
<td>0.37178</td>
<td>1.84</td>
<td>2047.1</td>
<td>2037.8</td>
<td>2056.5</td>
<td>9.4</td>
<td>0.991</td>
</tr>
<tr>
<td>Bd-4 (3 grains)</td>
<td>20.2</td>
<td>0.224</td>
<td>268.1</td>
<td>6.5562</td>
<td>2.18</td>
<td>0.37403</td>
<td>2.16</td>
<td>2053.5</td>
<td>2048.3</td>
<td>2058.6</td>
<td>11.0</td>
<td>0.995</td>
</tr>
</tbody>
</table>

1) Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).
2) measured ratio, corrected for fractionation and spike.
3) isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (2 pg Pb and 0.2 pg U), and initial common Pb. Initial common Pb corrected with isotopic compositions from the model of Stacey and Kramers (1975) at the age of the sample.
Figure 2.28. Concordia diagram for sill sample HWS. All errors are reported at ± 2σ

2.7. RECONCILIATION OF DATA

In this section, B components and C+/− components (Section 2.4), together with geochemical signatures and the U-Pb precise ages obtained in Sections 2.5 and 2.6 are worked out in a meaningful way. Mean components as well as corresponding mean pole positions are calculated. Data from this chapter will be combined with results from the western KC in Chapter 3.

2.7.1. B component

B mean directions obtained from samples HWD, L, R, T, U, V, W and X bear some resemblance to the 180 Ma Karoo directions of Hargraves et al. (1997). However, geochemical results obtained from sample HWD do not convincingly correlate with the geochemistry of the Karoo LIP (see Figures 2.26I and J). Instead, sample HWD bears most resemblance to the B1 Bushveld sills of Barnes et al. (2010) (Figures 2.26C and D). It can also be observed that the B directions of site HWD clearly stand out from those of the other B remanence samples (i.e. HWL, R, T, U,
V, W and X) (Figure 2.12). Site HWD is also relatively separated, in term of geographic position, from the other B remanence sites. Also note that HWD is the only B remanence site from the farm Inyamazane. The neighbour sites (i.e. HWA, B, F, and E) yielded a C+ remanence which was found to be similar to the ~2.05 Ga Bushveld Complex directions (Letts et al., 2009) (Figure 2.20), and one site (HWG) was lightning affected. From what precedes, the B magnetization in sample HWD may represent a magnetic overprint acquired during the Karoo magmatic event ~180 Ma years ago, and which has totally reset the primary remanence (C+ remanence probably) of this sill. Although this idea seems logic, it should be kept in mind that the clear disturbance of baddeleyites near 180 Ma rather suggests that some Karoo-aged sill may be present in the sampling area. At this stage, no clear conclusion can be drawn regarding the nature (primary or secondary) of the B magnetization of sill HWD. Precise U-Pb dating of the sill in the future may clarify this question.

Although geochemical and radiometric results are not available for samples HWL, R, T, U, V, W and X, one can work from the premise that their B directions are of primary nature in regard of the positive baked contact test at HWW and a general backed contact in site HWK (see Sections 2.4.4.2.2. and 2.4.4.2.1). In situ site means of the eight sills yield a B component mean of declination = 120.7°, inclination = 53.3°, \( \alpha_{95} \) = 12.2°, k = 21.7 and N = 8 (corresponding pole position: Latitude = 38.5°N, Longitude = 273.4°E, A\( _{95} \) = 14.5, K = 15.6, and N = 8). This pole is significantly different from the majority of Karoo LIP paleopoles as reported by Hargraves et al. (1997), but it is very similar to VGP’s from the younger cape Peninsula dolerites and Bumberi Complex (Figure 2.29), as well as the Mbuluzi rhyolite. The Bumberi Complex is thought to be upper Jurassic (~145 Ma) in age (Allsopp et al., 1984).

2.7.2. C+/- component

The C+/- magnetization recorded in sites HWA, B, F, H, I, M, O, S and Y bears resemblance to the directions obtained from the 2058-2054 Ma RLS (Letts et al., 2009) (Figure 2.20). Geochemical results obtained from samples HWA, B, F and H are in good agreement with the paleomagnetic results (C+/- remanence), as major elements and REE profiles of these intrusions share remarkable similarities with the B1 Bushveld sills and marginal rocks (Barnes et al., 2010).
(Figures 2.26C and D). On the other hand, the U-Pb ages of sills HWH and HWS are in very good correspondence with the recent radiometric data obtained from the RLS. New U-Pb ages (i.e., $2058.4 \pm 1.3$ Ma and $2058.1 \pm 6$ Ma) from sills HWH and HWS, combined with geochemical constraints from sills HWA, B, F, and H tend to support the antipodal character of the C+ and C- remanences, which provide additional support of the primary nature of these magnetizations. The results also suggest that the Earth’s magnetic field experienced change in polarity during the formation of the RLS, an idea that was recently proposed by Letts et al. (2009).

Combination of tilt-corrected site means of both polarities (with exclusion of sites HWB, HWF, HWM and HWO that have associated large uncertainties) yields a component mean of declination = 23.8°, inclination = 70.8°, $\alpha_{95} = 10.2°$, $k = 57.5$ and $N = 5$ (corresponding pole position: Latitude = 06.5°S, Longitude = 44.2°E, $K = 26.8$, $A_{95} = 15.1$, and $N = 5$). The C+/- pole shares resemblances with similarly aged poles from the KC (Figure 2.30), particularly the pole for the Bushveld Complex of Letts et al. (2009).

**Figure 2.29.** Paleopole for the mean B remanence compared to VGP’s of the Karoo LIP after Hargraves et al. (1997). While the B pole is significantly different from the majority of Karoo LIP south poles, it is very similar to VGP’s of the Cape Peninsula dolerites (CP), the Bumberi Complex (BU) and the Mbuluzi rhyolite (MB).
Poles, however, only overlap partially and the C+/- remanence may be slightly biased by the B magnetic overprint. The result does, however, support the position of the Bushveld Complex pole and its spatial removal from the WUBS-I pole for the lower Waterberg Group pole of de Kock et al. (2006).

**Figure 2.30.** Paleopole for the ~2058 Ma C+/- remanence (100% tilt-corrected) compared to similar aged poles from the Phalaborwa Complex (PBC) (Letts et al., 2010); the Bushveld Complex (BVC) (Letts et al., 2009); the lower Waterberg Group (WUBS-I) (de Kock et al., 2006); and the Vredefort Impact Structure (VRED) (Salminen et al., 2009).

### 2.8. CONCLUSION

Primary magnetizations (B and C+/-) are recorded by most of the sills sampled from the Pretoria Group in the eastern KC. A notable exception is an extensively altered sill (HWQ), which recorded a different high temperature magnetization (named D).
Chapter 2

The B remanence is similar to that of the 180 Ma Karoo LIP and may be as younger as 145 Ma. Sills that recorded the B remanence are thus thought to represent the post-Transvaal sills of Sharpe (1982).

The D remanence is poorly constrained, but plots in a similar position to known ~2.1 to ~2.2 Ga known directions from the KC. Sill HWQ, which intrudes at a lower stratigraphic level compared to other sampled sills, may thus be a pre-Bushveld sill as envisaged by Sharpe (1982).

A large proportion of sills recorded near antipodal C+ or C- remanence directions. Individual components display best grouping upon a 100 per cent tilt-correction, suggesting that the C+/− remanence sills intruded prior to the tilting of the sediments of the Pretoria Group. Two of these sills (representative of both polarity groups) have here been shown to have near identical U-Pb ages of 2058.4 ± 1.3 Ma and 2058.1 ± 6 Ma. Geochemically, the C+/− remanence sills bear striking resemblance to the B1 parental magma composition of the Bushveld Complex. A new paleomagnetic pole calculated from five of these sills (Latitude = 06.5°N, Longitude = 44.2°E, K = 26.8 and A_{95} = 15.1) is similar to the mean paleomagnetic pole from the Bushveld Complex of Letts et al. (2009). This result confirms that many sills intruding the Pretoria Group are related to the Bushveld LIP and that the geomagnetic field reversed during the emplacement of the Bushveld Complex.

2.9. BIBLIOGRAPHIC REFERENCES


Olsson, J.R., Söderlund, U., Klausen, M.B. and Ernst, R.E., 2010. U-Pb baddeleyite ages linking major Archean dyke swarms to volcanic-rift forming events in the Kaapvaal craton (South Africa), and a precise age for the Bushveld Complex. Precambrian Research, (Special Issue), 183: 490-500.


CHAPTER 3

PALEOMAGNETISM OF POST-TRANSVAAL SILLS IN THE WESTERN KAAPVAAL CRATON AND CORRELATIONS TO THE EASTERN SILL COMPLEX

Like in the eastern KC, the post-Transvaal sills in the western limb have been previously subdivided into classes (i.e., pre, syn and post-Bushveld units). The syn-Bushveld class is believed to be genetically related to the RLS of the Bushveld Complex. In this chapter, paleomagnetic results obtained from more than 140 oriented cores in Bronkhorstpruit and Rustenburg areas are reported, in order to provide more information than previously available on the post-Transvaal sills to the west of the Bushveld Complex, and to add on the KC paleomagnetic database. With some exceptions, the high stability components obtained during demagnetization are generally in agreement with those recorded by the eastern sill samples (subject of Chapter 2). Combination of data from the two limbs allows for determining new pole positions for the KC. Comparisons of these newly defined poles with existing ones from the KC allow for correlations with known magmatic events as well as evaluation of the APWP of the KC during the intrusion of the Bushveld Complex.

3.1. INTRODUCTION

In the western KC, numerous ultramafic to mafic sills intrude the sediments of the Pretoria Group. The sills, which are generally intrusive stratigraphically below the Magaliesberg Quartzite (Figure 3.1), have been less well-studied, compared to their counterparts to the east of the Bushveld Complex. A review of literature on the post-Transvaal sills in the western KC only reveals one study by Cawthorn et al. (1981).

Cawthorn et al. (1981) studied the post-Transvaal sills in the areas of Pretoria, Johannesburg and Rustenburg. These authors suggested a common origin with the units that intrude the Pretoria Group in the eastern KC (subject of Chapter 2). Cawthorn et al. (1981) also grouped the post-Transvaal sills into pre, syn and post-Bushveld classes, similarly to the classification proposed for these units in the eastern KC by Sharpe (1982).
The pre-Bushveld group extents regionally and sills of this type are well-exposed to the south and southwest of Rustenburg (Cawthorn et al., 1981). This group, which is believed to predate the Bushveld Complex, consists of metadolerites. The rocks are characterized by the predominance of amphibole that pseudomorphed the primary clinopyroxene (Cawthorn et al., 1981). The syn-Bushveld group is regarded as being coeval with the RLS (Cawthorn et al., 1981). This is the most common type of sill in the western KC, and is mainly confined to the Magaliesberg Quartzite and the Silverton Formation (Cawthorn et al., 1981). According to Cawthorn et al. (1981), the rocks are characterized by the absence of chill margins, coarse-grained size and an extreme heterogeneity (norites, contaminated norites, microgabbros and micropyroxenites). Cawthorn et al. (1981) further arranged the syn-Bushveld sills into two types, (i.e. the norite sills and the microgabbro sills). These two groups are related to the early parental (B1), and the second major injection of magmas (B2 and B3) into the Bushveld Complex. The norite sills are very fresh and mostly occur in the immediate vicinity of the RLS as 5 to 80 m thick sills, while the microgabbro sills do not exceed 15 m in thickness (Cawthorn et al., 1981). The post-Bushveld sill class is less common and consists of fresh and non-metamorphosed gabbrororites and mostly dolerites that have no petrographical resemblance with the rocks of the Bushveld Complex (Cawthorn et al., 1981).

In this chapter, new paleomagnetic results from units that form part of post-Transvaal sill suites in the Bronkhorstspruit and Rustenburg areas are reported. This is aimed at providing more information on the timing of emplacement of these sills. This is the first paleomagnetic study of the post-Transvaal sills to the west of Bushveld Complex and an important goal is to add new paleomagnetic information to the KC database. Furthermore, the obtained results are compared to those of the eastern sill complex (subject of Chapter 2), in order to investigate the timing of magnetic remanence acquisition relative to the tilting of strata on a regional scale as was done recently for the Bushveld Complex proper (Letts et al., 2009), as well as to assist correlations of different thermo-magmatic events across the KC. Data of this study is also combined with that of Chapter 2 and the new pole positions generated are compared to previously published ones from the KC. This not only assists with correlations, but might also provide additional constraints on the KC position during the Paleoproterozoic.
3.2. SAMPLING

Post-Transvaal sills were sampled around Bronkhorstspruit and Rustenburg. Around Bronkhorstspruit, five sills of an extensive sill suite that intrudes the Silverton, Magaliesberg and Rayton formations of the Pretoria Group were sampled (Figures 3.1A and 3.2). To the south and west of Rustenburg, eleven sills were collected from various stratigraphic levels within the Timeball Hill, Silverton, Daspoort and Magaliesberg formations (Figures 3.1B and 3.2). The sampling sites are summarized in Table 3.1.

Like in the eastern KC (Chapter 2), the sampling was originally planned to be conducted outside of the thermal aureole of the Bushveld metamorphism (Cawthorn et al., 2006) in order to promote the chances of identifying primary magnetic directions. However, during various field trips, sills appeared to be poorly exposed (especially in the Rustenburg area) with possibilities of paleomagnetic sampling being limited. Most samples were thus collected within the contact metamorphic aureole of the Bushveld Complex.

Table 3.1 Summary of different sampling sites. N: number of oriented cores drilled per site.

<table>
<thead>
<tr>
<th>Site</th>
<th>GPS coord.</th>
<th>Nature</th>
<th>Thickness (m)</th>
<th>Strike</th>
<th>Dip</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRA</td>
<td>S 25°57'30.3&quot; E 028°41'25.4&quot;</td>
<td>sill</td>
<td>~ 80</td>
<td>130</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>BRB</td>
<td>S 25°50'30.9&quot; E 028°41'31.6&quot;</td>
<td>sill</td>
<td>~ 60</td>
<td>90</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>BRC</td>
<td>S 25°50'39.5&quot; E 028°41'32.1&quot;</td>
<td>sill</td>
<td>~ 60</td>
<td>90</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>BRD</td>
<td>S 25°55'17.3&quot; E 028°29'44.6&quot;</td>
<td>sill</td>
<td>~ 100</td>
<td>130</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>BRE</td>
<td>S 25°47'38.4&quot; E 028°37'24.1&quot;</td>
<td>sill</td>
<td>~ 200</td>
<td>120</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>RUA</td>
<td>S 25°48'24.15&quot; E 027°13'20.2&quot;</td>
<td>hornfels</td>
<td>135</td>
<td>12</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>RUB</td>
<td>S 25°52'54.5&quot; E 027°04'48.3&quot;</td>
<td>sill</td>
<td>~ 300</td>
<td>130</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>RUC</td>
<td>S 25°38'15.3&quot; E 027°07'04.8&quot;</td>
<td>sill</td>
<td>~ 40</td>
<td>170</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>RUD</td>
<td>S 25°38'12.9&quot; E 027°05'06.0&quot;</td>
<td>sill</td>
<td>~ 80</td>
<td>160</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>RUE</td>
<td>S 25°39'10.4&quot; E 026°42'44.5&quot;</td>
<td>sill</td>
<td>~ 50</td>
<td>160</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>RUF</td>
<td>S 25°39'29.1&quot; E 026°42'57.9&quot;</td>
<td>sill</td>
<td>~ 40</td>
<td>160</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>RUG</td>
<td>S 25°31'13.9&quot; E 026°57'17.8&quot;</td>
<td>sill</td>
<td>~ 35</td>
<td>160</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>RUH</td>
<td>S 25°37'37.2&quot; E 026°57'17.8&quot;</td>
<td>sill</td>
<td>~ 70</td>
<td>0</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>RUI</td>
<td>S 25°48'44.3&quot; E 026°54'40.4&quot;</td>
<td>sill</td>
<td>~ 80</td>
<td>130</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>RUI</td>
<td>S 25°43'07.3&quot; E 026°58'43.6&quot;</td>
<td>sill</td>
<td>~ 50</td>
<td>35</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>HKP</td>
<td>S 25°55'35.9&quot; E 027°32'44.4&quot;</td>
<td>sill</td>
<td>~ 50</td>
<td>85</td>
<td>20</td>
<td>9</td>
</tr>
</tbody>
</table>

Total = 16 sites (148 samples)
Figure 3.1. Summary geological maps of the Transvaal Supergroup and sills in the Bronkhorstpruit (A) and Rustenburg (B) areas showing the different sampling sites.
Samples include fine to medium-grained norite and dolerite that generally show a predominance of pyroxene and plagioclase minerals. In some samples, amphibole and quartz are present. The basic petrography of these rocks is presented in Appendix 3.

At each site 6 to 15 oriented cores were drilled using a portable, hand-held petrol drill. Orientation of the cores was achieved in all cases by magnetic compass and a sun compass when possible. It was planned to sample the country rock together with the sills in order to attempt baked-contact tests. Unfortunately, this could not be achieved, due to the intensive weathering of Pretoria Group and difficulties to find and access the contact between the intrusion and the country rocks. One hornfels was sampled near the top of the Silverton Formation in the Rustenburg area, but not in the context of a contact with a sill.

Figure 3.2: Stratigraphic setting of sampling sites within the Pretoria group. Legend is as for Figure 2.3.
3.3. PETROGRAPHY

Microscopic description of intrusions sampled in Bronkhorstspruit and Rustenburg areas are discussed in Appendix 3 in order to identify the textures of these units, as well as the mineral phases. The dominated lithologies found were dolerite and norite, followed by pyroxenite. Grain size of sample generally varied from fine to medium, and rarely coarse-grained. The rocks were variably altered and generally displayed similarities with the sills studied in the eastern KC (see Chapter 2). The mineralogy of sills was dominated by plagioclase and pyroxene. In norites and pyroxenites, orthopyroxene constitutes the most dominant pyroxene and occurs in very close association with clinopyroxene, and both minerals are generally intergrown with plagioclase to define subophitic textures. In general, the phenocrysts make up about twenty to thirty per cent by volume. Microscopic petrography indicates the presence of olivine, quartz and biotite as accessory mineral phases in some samples, and amphibole and clay minerals (chlorite, sericite) as secondary minerals. The matrix is dominated by fine-grained pyroxene, plagioclase, opaque minerals and other small sized mineral species. Individual descriptions of thin sections (15 in total) presented in Appendix 3 are in order of the stratigraphic heights of these sites in the Pretoria Group, from the base upwards.

Based on petrographic descriptions presented in Appendix 3, the studied intrusive units can be subdivided into three groups (Table 3.2): Group 1 (BRA, BRB, BRC, RUF, RUI, RUH, HKP, RUB and RUJ) with mineralogy essentially composed of clinopyroxene and plagioclase, Group 2 sills (BRE, RUG, RUD, and RUC) where orthopyroxene and plagioclase constitute the most abundant phases, and Group 3 sills (BRD, RUE) with mineralogy dominated by orthopyroxene.

If compared to the sill classification proposed in the sampling area, it is observed that Groups 2 and 3 correlate with the norites and pyroxenites sill class which is believed to be related to the Bushveld Complex (e.g., Cawthorn et al., 1981). Group 1 bears some resemblance to the dolerites sill class, which is regarded as postdating the Bushveld Complex (Cawthorn et al., 1981). Correlation between the sills in the western KC and those in Mpumalanga Province can also be made. The metadolerites, norites and pyroxenites, and dolerites described by Cawthorn et al. (1981) can be respectively correlated to the amphibolites, the pyroxenitic class (i.e. the micropyroxenites, the feldspathic pyroxenites and norites), and the post-Bushveld sill class of
Table 3.2. Summary of petrography of the post-Transvaal sills studied in the western KC

<table>
<thead>
<tr>
<th>Petrographic Group</th>
<th>Sites</th>
<th>Country rocks</th>
<th>Main minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>BRB and BRB, BRA, RUI, RUH, HKP</td>
<td>Rayton formation, Silverton Formation, Daspoort Formation, Timeball Hill Formation</td>
<td>Clinopyroxene and plagioclase</td>
</tr>
<tr>
<td>Group 2</td>
<td>RUJ, RUD, RUC, BRE, RUG, BRE, RUG, BRE, RUG, BRE, RUG, BRE, RUG, BRE, RUG, BRE, RUG, BRE, RUG</td>
<td>Silverton Formation, Daspoort Formation, Timeball Hill Formation</td>
<td>Orthopyroxene and plagioclase, Orthopyroxene</td>
</tr>
</tbody>
</table>

3.4. PALEOMAGNETISM

3.4.1. Method

Oriented samples were cut to standard specimens of ~2 cm. One specimen of each sample was subjected to demagnetization and measurements were completed using the new vertical 2G Enterprises DC-4K (liquid helium free) superconducting rock magnetometer housed at the University of Johannesburg. After measurements of natural remanent magnetization (NRM), samples were pretreated with low field strength alternating field (AF) demagnetization using a Molspin 2-axis tumbling AF-demagnetizer. This always consisted of four steps in increments of 2.5 mT from 2.5 to 10 mT. The specimens were then incrementally demagnetized in a shielded furnace from 100°C up to the temperature where sample’s magnetic intensity dropped below the noise level of the sample handler (typically up to 580°C). Magnetic components were obtained via least-squares principal component analysis (Kirchvink, 1980). The calculations, together with all subsequent statistical analyses utilized the Macintosh™ based software Paleomag 3 (Jones, 2002) and PaleoMac (Cogne, 2003).

3.4.2. Demagnetization results

Demagnetization results of individual intrusions appeared to be of relatively limited quality compared to the eastern sill complex (subject of Chapter 2). About 30 percent of sites appeared
to be weakly magnetized (BRC, RUE, and RUA) or lightning affected (HKP and RUD) and displayed unusable results. Fortunately, the other sites yielded interpretable results.

During AF and low temperature demagnetization steps, samples generally revealed scattered directions. However, some groupings, most commonly parallel to the Earth’s present dipole field (“PF”) (BRB, RUH, and RUC) could be noted. At higher levels of demagnetization the several following components were obtained:

- **B components** (BRB, RUF, RUI, and RUJ) are southeasterly downward directed components which were also present in some of the eastern sills (see Chapter 2)
- **C+/- components** (BRD, BRE and RUC) are northerly downward or southerly upward directed, and were also identified in the eastern sill complex (Chapter 2).
- **D components** (RUB) are poorly constrained easterly and shallow easterly, and not dissimilar to the remanence in site HWQ from the eastern sill complex (Chapter 2).
- **E+ components** (RUH and RUG) are southerly and shallow, and similar to the remanence of country rocks from site HWK east of the Bushveld Complex (Chapter 2).
- **F+ components** (BRA) are north westerly and downward, and were not seen in the eastern sill complex.

The demagnetization results (relatively high stability components) are summarized in Table 3.3 and are followed by a detailed description of the results from each sampling site from the base of the Pretoria Group upwards.

### Table 3.3: Summary of relatively high stability magnetic components obtained from the studied post-Transvaal sills in the western KC

<table>
<thead>
<tr>
<th>Component</th>
<th>Site</th>
<th>N/n</th>
<th>In</th>
<th>D</th>
<th>I</th>
<th>α95</th>
<th>α95</th>
<th>k</th>
<th>D</th>
<th>I</th>
<th>α95</th>
<th>α95</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Relatively high stability components</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>RUJ</td>
<td>10/10</td>
<td>99.9</td>
<td>59</td>
<td>2.51</td>
<td>334.32</td>
<td>92.1</td>
<td>70.5</td>
<td>2.51</td>
<td>334.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>RUI</td>
<td>10/16</td>
<td>142.4</td>
<td>35.1</td>
<td>18.35</td>
<td>7.1</td>
<td>134</td>
<td>40.5</td>
<td>18.35</td>
<td>7.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>BRB</td>
<td>9/9</td>
<td>156.6</td>
<td>70</td>
<td>5.41</td>
<td>92.5</td>
<td>150.5</td>
<td>81.9</td>
<td>5.41</td>
<td>92.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>RUF</td>
<td>5/10</td>
<td>140.7</td>
<td>51.2</td>
<td>16.37</td>
<td>18.23</td>
<td>122.5</td>
<td>47.2</td>
<td>16.37</td>
<td>18.23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C+</td>
<td>BRD</td>
<td>10/10</td>
<td>74.5</td>
<td>73.4</td>
<td>5.19</td>
<td>78.84</td>
<td>48.3</td>
<td>58.0</td>
<td>5.44</td>
<td>71.74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-</td>
<td>RUC</td>
<td>10/10</td>
<td>233.9</td>
<td>-42.7</td>
<td>10.45</td>
<td>20.08</td>
<td>235.5</td>
<td>-26.3</td>
<td>10.4</td>
<td>20.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-</td>
<td>BRE</td>
<td>8/10</td>
<td>250.7</td>
<td>-31.9</td>
<td>14.61</td>
<td>13.41</td>
<td>245.4</td>
<td>-24.9</td>
<td>14.62</td>
<td>13.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>RUB</td>
<td>9/10</td>
<td>103.9</td>
<td>14.6</td>
<td>13.68</td>
<td>13.44</td>
<td>99.8</td>
<td>11.2</td>
<td>13.68</td>
<td>13.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E+</td>
<td>RUH</td>
<td>6/10</td>
<td>185.4</td>
<td>4.1</td>
<td>7.33</td>
<td>70.45</td>
<td>183.7</td>
<td>9.7</td>
<td>7.33</td>
<td>70.45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F+</td>
<td>BRA</td>
<td>6/10</td>
<td>293.6</td>
<td>45.7</td>
<td>13.06</td>
<td>22.72</td>
<td>303.9</td>
<td>44.4</td>
<td>13.06</td>
<td>22.71</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.4.3. Sites in Bronkhorstspruit area

3.4.3.1. BRD

BRD is located about 35 km south of Bronkhorstspruit along the road R25 just outside of Babsfontein (Figure 3.1A). Here, oriented cores were collected from three distinct fresh blocks best judged to be in situ. All the samples (n = 10) exhibit two remanent magnetic components. The first of these was removed below 370°C as shallow north westerly components (Figures 3.3A and 3.4) (decl. = 288.1°, incl. = 1.7°, α₉⁵ = 9.99, k = 21.92, n = 10; stratigraphic correction: decl. = 289.2°, incl. = 3.6°, α₉⁵ = 9.91, k = 22.23, n = 10). Above 370°C, a high stability component unblocked (C+ component: decl. = 74.5°, incl. = 73.4°, α₉⁵ = 5.19, k = 78.84, n = 10; stratigraphic correction: decl. = 48.3°, incl. = 58.0°, α₉⁵ = 5.44, k = 71.74, n = 10). The C+ component, which is steeply downward inclined, has an east north easterly oriented declination that becomes more north easterly upon restoration of layering to horizontal (Figure 3.4). Sample behaviour became erratic between 540-565°C.

3.4.3.2. BRA

BRA is located about 20-25 km from Delmas along the R42 just south of the Bronkhorstspruit Dam (Figure 3.1A). During the demagnetization, randomly oriented components unblocked below 350°C (Figure 3.4). Between 350°C and 570°C, stable well-grouped north westerly and downward directed directions (F+ component) unblock in most samples (decl. = 293.6°, incl. = 45.7°, α₉⁵ = 13.06, k = 22.72, n = 6; stratigraphic correction: decl. = 303.9°, incl. = 44.4°, α₉⁵ = 13.06, k = 22.71, n = 6) (Figures 3.3B and 3.4). Exceptions are BRA 05 and 06 that show single linear components possibly due to lightning and BRA 01 and 02 that display steep easterly remanence above 350°C.
3.4.3.3. BRC

BRC occurs in the close vicinity of the sill BRB. Although the sill is poorly exposed and highly weathered, blocks best judged in situ were sampled. During the demagnetization, eight out of nine oriented samples unfortunately revealed a weak magnetization (Figure 3.3C) with unusable results. One sample (BRC09) collected halfway between BRC and BRD revealed a high stability magnetic component, oriented easterly and downward, as a stable endpoint of demagnetization.

Figure 3.3. Examples of demagnetization behaviour, in situ coordinates, of some samples in Bronkhorstpruit area A: BRD, B: BRA, C: BRC (stereonet plot), D: BRB and E: BRE. For Zijderveld diagrams, open symbols = vertical plane and close symbol = horizontal plane. For stereonet plot, open symbol = upper hemisphere and close symbol = lower hemisphere. NRM = natural remanence magnetization, mT = milli Tesla.
3.4.3.4. BRB

BRB occurs about 3 km south of Bronkhorstspruit. Here, nine oriented cores were drilled from blocks that were best judged in situ. Upon demagnetization, two coherent magnetic components were identified. The first of these is of low stability and was easily removed by AF pre-treatment (PF: decl. = 345.4°, incl. = -61.1°, k = 37.54, α95 = 16.58; stratigraphic correction: decl. = 345.4°, incl. = -61.1°, k = 37.54, α95 = 16.58.). Demagnetization steps above 200°C reveal the existence of a well-constrained, high-temperature magnetic component (B component) as origin seeking linear trajectories (Figure 3.3D). The B component which is oriented southerly with a steep downward-pointing inclination, (decl. = 156.6°, incl. =70.0°, α95 = 5.41, k = 92.52, n = 9; stratigraphic correction: decl. = 150.5, incl. = 81.9, α95 = 5.41, k = 92.52, n = 9) was generally stable up to the demagnetization temperature of 570°C (Figures 3.3D and 3.4).

**Figure 3.4.** Equal area plots of results from sites BRA, BRB, BRD and BRE. The left-hand panel depicts relatively low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts relatively high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.
3.4.3.5. BRE

BRE occurs about 15 km from Bronkhorstspruit along the road leading to Cullinan (Figure 3.1A). At this site, 10 oriented cores were drilled along the road from very fresh outcrops. Apart from randomly distributed directions observed at low demagnetization levels (below 200°C) in some sites, and interpreted as magnetization acquired during the sampling and/or during the preparation, a high stability south westerly magnetization (C-component: decl. = 250.7°, incl. = -31.9°, $\alpha_{95}$ = 14.61, k = 13.41, n = 8 ; stratigraphic correction: decl. = 245.4°, incl. = -24.9°, $\alpha_{95}$ = 14.62, k = 13.39, n = 8) was revealed in this site (Figures 3.3E and 3.4).

3.4.4. Sites in Rustenburg area

3.4.4.1. RUE

Immediately outside the town of Swartruggens on the road leading to Koster, a ~50 m thick sill intrudes the upper Timeball Hill Formation (Figure 3.1B). Eleven oriented cores were collected from this site. Demagnetization results revealed the samples to be weakly magnetized and no coherent magnetic components could be isolated from samples as they were completely demagnetized by 370°C (Figure 3.5A).

3.4.4.2. RUF

RUF occurs 700 m east of RUE. Samples are weakly magnetized and they generally displayed erratic behaviour before 350°C (Figure 3.5D). At this site, two magnetic components were developed at similar temperatures range but in different samples (Figure 3.5D). The first of these is developed in the specimens RUF 01 to 04 and exhibits a northeasterly oriented declination with a shallow inclination (decl. = 55.6°, incl. = 20.3°, $\alpha_{95}$ = 8.42, k = 89.99, n = 4) (Figure 3.6). Upon tilt-correction, this component becomes shallower (decl. = 55.6°, incl. = 4.3°, $\alpha_{95}$ = 8.42, k = 89.99, n = 4). Samples 06 to 10 on the other hand display south easterly downward magnetizations (B component: decl. = 140.7°, incl. = 51.2°, $\alpha_{95}$ = 16.37, k = 18.23, n = 5).
Chapter 3

(Figure 3.6). Upon tilt correction, this component becomes: decl. = 122.5°, incl. = 47.2°, α₉₅ = 16.37, k = 18.23, n = 5. Sample RUF 05 falls with neither of these components, but instead plots halfway between them.

3.4.4.3. RUG

At site RUG which occurs near the Lindley Dam about 10-12 km north of Swartruggens (Figure 3.1B), oriented specimens were taken from angular weathered in situ blocks. Demagnetization results from eight samples from this site, although noisy, reveal coherent (albeit slightly scattered) stable components that unblock as origin seeking linear trajectories (Figure 3.5B). These are shallow and directed down and to the south (E+ component: decl. = 214.8°, incl. = 26.4°, α₉₅ = 19.25, k = 9.24, n = 7) (Figure 3.6). Upon tilt-correction, this component becomes: decl. = 213.7°, incl. = 32.1°, α₉₅ = 19.25, k = 9.24, n = 7.

3.4.4.4. RUI

This site represents the so-called Koster sill and is exposed just outside of Koster on the northern side of the town, along the road to Swartruggens (Figure 3.1B). The sill is generally poorly exposed and outcrops are usually not in situ. Three spheroidally weathered core stones, believed to be in situ were sampled to yield eleven paleomagnetic samples. Five additional samples were collected some 700 m away closer to the margin of the sill. Apart from poorly developed and scattered components removed during the AF pre-treatment (Figure 3.5C), all samples displayed single linear seeking demagnetization trajectories during heating (Figure 3.5C). These were most commonly (10 out of 16) downward and southeasterly (i.e., B component) decl. = 142.4°, Incl. = 35.1°, α₉₅ = 18.35, k = 7.10, n = 10) (Figure 3.6). Upon tilt-correction, this becomes decl. = 134.0°, incl. = 40.5°, α₉₅ = 18.35, k = 7.10, n = 10. The remainder of samples is very poorly grouped southwesterly to westerly oriented and upwards with the exception of RUI 16 (decl. = 239.2°, incl. = -22.1°, α₉₅ = 31.79, k = 4.26, n = 6) (not showed).
### 3.4.4.5. RUH

Site RUH is located about 25 km south of Rustenburg along the road leading to Swartruggens (Figure 3.1B). Demagnetization results reveal that samples are weakly magnetized and completely demagnetized between 350 and 400°C (Figure 3.5E). Samples RUH 01 to 06 display univectorial behavior with components forming a tight cluster that is southerly down and shallow, (E Component : decl. = 185.4°, incl. = 4.1°, α₉₅ = 7.33, k = 70.45, n = 6; stratigraphic correction: decl. = 183.7°, incl. = 9.7°, α₉₅ = 7.33, k = 70.45, n = 6) (Figure 3.6). Samples 07 to 10 display components that are near parallel to the Earth’s present magnetic field (PF) (decl. = 2.2°, incl. = -31.7°, α₉₅ = 33.46, k = 6.38, n = 4; stratigraphic correction: decl. = 352.2°, incl. = -35.6°, α₉₅ = 33.45, k = 6.38, n = 4) (Figure 3.6). In addition, samples 07, 09 and 10 also reveal a less stable component that is removed during AF demagnetization steps. These are southerly and upward directed (decl. = 175.5°, incl. = -60.3°, α₉₅ = 19.07, k = 28.58, n = 3; stratigraphic correction: decl. = 197.1°, incl. = -54.1°, α₉₅ = 19.12, k = 28.41, n = 3) (Figure 3.6).

### 3.4.4.6. HKP

At site HKP, an east-west striking and northward dipping, relatively fresh, ~ 50 m thick dolerite sill crops out. All eight oriented cores from this site exhibit scattered univectorial demagnetization paths (Figure 3.7A). Samples remain stable up to 500°C (Figure 3.7A). Although some samples formed grouping (e.g., HKP 01 to 03 or HKP 06 to 08) there is no consistency amongst samples from this site, and no site means were calculated. Lightning may have had a detrimental effect on this site.

### 3.4.4.7. RUB

RUB which occurs north of Derby yielded ten paleomagnetic samples. Two magnetic components were isolated in each sample (Figure 3.7B). The first of these is a poorly developed low stability magnetization (B component) removed before 200°C. It is south easterly and downward directed (Figure 3.8) similar to components seen at some other sites (B Component: decl. = 147.6°, incl. = 26.2°, α₉₅ = 10.69, k = 33.53, n = 8; stratigraphic correction: decl. = 138.5°, incl. = 35.5°, α₉₅ = 10.65, k = 33.77, n = 8). Above 200°C, demagnetization of samples is
represented by linear trajectories towards the origin (Figure 3.7B). These stable components are shallow downward and easterly directed (D component: decl. = 103.9°, incl. = 14.6°, α95 = 13.68, k = 13.44, n = 9; stratigraphic correction: decl. = 99.8°, incl. = 11.2°, α95 = 13.68, k = 13.44, n = 9) (Figure 3.8).

Figure 3.5. Examples of demagnetization behaviour, in situ coordinates, of some studied post-Transvaal sill samples in Rustenburg area. A: RUE, B: RUG, C: RUI, D: RUF (stereonet plot), and E: RUH (stereonet plot). For Zijderveld diagrams, open symbols = vertical plane and close symbol = horizontal plane. For stereonet plot, open symbol = upper hemisphere and close symbol = lower hemisphere. NRM = natural remanence magnetization, mT = milli Tesla.
Figure 3.6. Equal area plots of results from sites RUF, RUG, RUI, RUH and HKP. The left-hand panel depicts relatively low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts relatively high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.
3.4.4.8. RUJ

RUJ is a poorly exposed sill along the Kosterfontein-Witfontein dirt road. Although outcrops of the sill are rare, five in situ fresh spheroidally weathered core stones were sampled in a gully along the road. Two magnetic components were revealed by stepwise demagnetization. The first was removed during AF pre-treatment and was directed easterly and downward (decl. = 94.2°, incl. = 9.9°, $a_{95} = 16.98$, $k = 13.77$; stratigraphic correction: decl. = 93°, incl. = 21.2°, $a_{95} = 16.98$, $k = 13.77$). During thermal demagnetization, linear origin seeking trajectories unblock (Figure 3.7D). These are all steep down and easterly directed (B Component: decl. = 99.9°, incl. = 59.0°, $a_{95} = 2.51$, $k = 334.32$, $n = 10$; stratigraphic correction: decl. = 92.1°, incl. = 70.5°, $a_{95} = 2.51$, $k = 334.32$, $n = 10$) (Figure 3.8).

3.4.4.9. RUA

A hornfels was sampled at the T-junction of the Rustenburg, Magaliesberg and Derby roads, but samples were extremely weakly magnetized and were completely demagnetized by 200°C (Figure 3.7F). Directional data from this site is unusable and are not further discussed.

3.4.3.10. RUD

At this sampling site, eight oriented cores were collected from a ~100 m thick sill. Samples 01 to 06 displayed two components during demagnetization (Figure 3.7C), but samples 05 and 06 plot removed from the other samples (Figure 3.8). Similar angular separation between the components of these groupings, however, suggests that samples may not be in situ. Samples 07 and 08 display univectorial south upward directed components reminiscent to B component.

3.4.3.11. RUC

Immediately below the Magaliesberg Quartzite, ten samples were taken from a sill that crops out along the highway N4 from Rustenburg to Swartruggens. During AF demagnetization low
stability and scattered components were removed while during low temperature demagnetization steps (below 400°C), components that are parallel to the Earth’s present dipole field can be defined albeit poorly (PF: decl. = 323.5°, incl. = -53.7°, α95 = 23.49, k = 7.5, n = 4; stratigraphic correction: decl. = 304.1°, incl. = -48.4°, α95 = 23.23, k = 7, n = 4) (Figure 3.7E). Above 400°C, and up to 540°C when samples start to display unstable behaviour, linear trajectories towards the origin define a fairly well-grouped cluster of components that are south westerly and upwards directed (C-component: decl. = 233.9°, incl. = -42.7°, α95 = 10.45, k = 20.08, n = 4; stratigraphic correction: decl. = 235.5°, incl. = -26.3°, α95 = 10.40, k = 20.28, n = 4) (Figures 3.7E and 3.8).

Figure 3.7. Examples of demagnetization behaviour, in situ coordinates of some studied post-Transvaal sill samples in Rustenburg area. A: HKP, B: RUB, C: RUD, D: RUJ, E: RUC and F: RUA (stereonet). For Zijderveld diagrams, open symbols = vertical plane and close symbol = horizontal plane. For stereonet plot, open symbol = upper hemisphere and close symbol = lower hemisphere. NRM = natural remanence magnetization, mT = milli Tesla.
Figure 3.8. Equal area plots of results from sites RUB, RUJ, RUD and RUC. The left-hand panel depicts relatively low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts relatively high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.

3.4.5. Summary

Several low stability components were revealed in sills from the Bronkhorstspruit and Rustenburg areas; generally these tended to be scattered within specific sites. But where grouping were evident they were most commonly parallel to the Earth’s present dipole field (BRB, RUH and RUC). For other grouping, there is no consistency amongst sites, making them
more difficult to interpret. Note that the prominent southerly and upward directed overprint (A component) that was present in the eastern sill complex is absent in the west.

High stability components (Figure 3.9) are most commonly south east and downward (like B component in Chapter 2) (BRB, RUF, RUI and RUJ). North down (C+ component of Chapter 2) and easterly and shallow components (D component of Chapter 2) were exclusive to site BRD and RUB respectively. C- like components were present in RUC and BRE. Other components were shallow southerly (E+ component) (RUH) or north westerly and upward directed (F+ component) (BRA). These inconsistencies amongst sites made data difficult to interpret but in comparison to data from the eastern sill complex, several observations can be made.

Figure 3.9. Summary of relatively high stability components and site means obtained from studied post-Transvaal sills in the western KC.
3.4.6. Interpretation

3.4.6.1. Low stability component (PF)

A coherent secondary component was revealed during AF pre-treatment and before 350°C of heating in sills BRB, RU, and RUC. This component generally consisted of poorly grouped northerly and upwards directions that were in most cases near parallel to the Earth’s present dipole field as defined by most current International Geomagnetic Reference Field (IGRF), indicating some recent remanence acquisition during weathering.

3.4.6.2. High stability components

3.4.6.2.1. B component

The most common high temperature component to unblock is oriented southeast downward (B component), and was revealed in sill samples BRB, RUF, RUI, and RUJ. Unfortunately, there were no field tests done to constrain the timing of this component, but it is nonetheless interpreted to represent a magnetization recorded by samples during the emplacement of sills. This interpretation is supported, albeit circumstantially, by the assumption that sills BRB, RUF, RUI, and RUJ are linked to their eastern counterparts, as suggested by good correlations between classifications of Cawthorn et al. (1981) and Sharpe (1982) from which similar B magnetizations were obtained and suggested to be of primary origin. Another argument for the B component’s primary origin is the difference to other high temperature directions obtained from the sampling area, and which argues against the presence of a pervasive magnetic overprint. Like in the eastern sill complex, the B directions here show a worse grouping upon tilt correction (Figure 3.9) and lead to the interpretation that this magnetization post-dates the tilting of the country rocks. If compared to known paleomagnetic directions from KC, the south east components of sills BRB, RUF, RUI, and RUJ, similarly to their counterparts to the east of Bushveld Complex, bear resemblance to the 180 Ma Karoo magmatic event, although the Karoo directions (Hargraves et al., 1997) are typically more south directed with a moderate inclination.
Sites RUJ and BRB are combined with data from the eastern sills in the next section for calculation of a component mean and pole. Sites RUF and RUI that have $\alpha_{95}$ values that are higher than 15° are excluded.

![Figure 3.10. Comparison of B components (southeasterly-down) from the present study with the site means for the ~180 Ma Karoo LIP after Hargraves et al. (1997)](image)

### 3.4.6.2.2. C+/- component

Between 370°C and 565°C of demagnetization, a north and downward oriented magnetization (C+ component) was revealed in site BRD. Opposing (south-west upward) directions (C- component) were revealed at similar temperature range in sites BRE and RUC. Despite the lack of field tests, these two magnetizations are interpreted as having been recorded by samples during the emplacement of sills. This interpretation is based upon the link, as suggested by Cawthorn et al. (1981), between the sills BRD, BRE and RUC to units in the eastern KC. The C+ magnetization shares similarities with the normally polarized primary directions of the Bushveld Complex (Letts et al., 2009) (Figure 3.11).

The C- directions are not antipodal to the C+ site means and are greatly offset of the Bushveld Complex reversed directions. These sites may be plagued by a non-removed magnetic component and are not included in the regional evaluation that follows in the next section.
In the next section, the BRD mean, which yields a virtual geomagnetic pole (VGP) at Latitude = 11.2 ° N, Longitude = 65 ° E, dp = 5.6, dm = 7.6, will be reconciled with paleomagnetic, geochemical and geochronological data from the C+ remanence sites in the eastern sill complex. A combined C+/- pole position will also be established.

**Figure 3.11.** Comparison of C+/- components (northerly-downward/southerly-upward) of sites BRD, BRE and RUC with site means of the 2058 Ma-2054 Ma RLS of the Bushveld Complex after Letts et al. (2009)

### 3.4.6.2.3. E+ component

Relatively stable southerly shallow directions (E+ component) were revealed in site RUH. Similar (but poorly grouped) components were also recorded in site RUG. There were no field tests to constrain the timing of these components, which were absent in the eastern sill complex. Although no mean was calculated for the E+ component, the different sites could be compared to known paleomagnetic directions from KC. It was observed that the E+ directions bear resemblance to the ~1.1 Ga Umkondo sills in South Africa and Botswana (Gose et al., 2006) (Figure 3.12). While the Umkondo-like character of E+ components of sills RUG and RUH may lead to the interpretation that these directions represent magnetic overprints, it can also signify that the sills are related to the Umkondo LIP. It is therefore difficult to come to any conclusion on the exact timing of the E+ component of sills RUG and RUH. Numerical ages and geochemical analyses of sills are needed to better investigate this question.
3.4.6.2.4. F+ component

Between 350° and 570°C of demagnetization, a northwesterly component was revealed in site BRA. Although no field test was done to constrain the timing of this component, it is interpreted as representative of a primary magnetization recorded at the time of sill emplacement. This interpretation, albeit circumstantial, is based on the difference between the high stability directions obtained from the sampling area which negate the presence of pervasive magnetic overprint. Another, perhaps stronger, argument for the northwesterly downward component’s primary origin is the resemblance to known paleomagnetic directions from the KC. In fact, the in situ F+ mean as well as the corresponding virtual geomagnetic pole (VGP) (Latitude = 7.2°N, Longitude = 333.6°E, dp = 10.6, dm =16.6) share similarities with some 1.9 Ga units on the KC such as the 1928 ± 4Ma Hartley lava (Evans et al., 2002) and the ~1.9 Ga northeast-trending dolerite dykes in the Archean Basement (Lubnina et al., 2010) (Figures 3.13 and 3.14).

Sharpe (1982) in his classification of post-Transvaal sills in the eastern KC defined a sill class of post-Waterberg age (i.e. 1.8 Ga -1.9 Ga). Cawthorn et al. (1981), who suggested that the sills in the western KC are genetically related to their counterparts in the eastern KC, also proposed a classification that included a post-Bushveld sill class. The age of ~1.9 Ga is therefore attributed to the F+ remanence of sill BRA. The magnetization is interpreted to postdate the tilting of the Pretoria Group sediments which is generally believed to have occurred just after the Bushveld event (i.e. at ~2.05 Ga).
Figure 3.13. Comparisons of the F+ component (northwest-downward) of site BRA with the 1928 Ma Hartley Lavas (Evans et al., 2002), 1900 Ma NE-trending dykes in the Archean Basement (Lubnina et al., 2010), the ~1.87 Ga post-Waterberg intrusions (Hanson et al., 2004) and the post-Bushveld dykes (Letts et al., 2005).

Figure 3.14. Comparison of the VGP of BRA with selected paleopoles from KC. All poles are plotted with their 95% error limits as per their A$_{95}$ or as dp and dm values (listed in Tables 3.4 and 3.5).
3.4.6.2.5. D component

Demagnetization above 200°C in site RUB revealed shallow down and easterly oriented magnetic directions. The easterly shallow component generally bears resemblance to the mean components obtained from the ~2.2 Ga units in the KC. These include the ~2.15 Ga dyke that intrudes the south-eastern Archean Basement (Lubnina et al., 2010) and the reversed MAM-1 directions obtained from the Mamatwan ore (2.2 Ga Hotazel Formation) (Evans et al., 2001), and to a lesser extent the 2200-2050 Ma Gamagara/Mapedi Formation (Evans et al., 2002) (Figure 3.15).

![Figure 3.15. Comparison of D component (easterly-downward) of site RUB with the 2200-2050 Ma Gamagara/Mapedi Formation (Evans et al., 2002), the MAM-1 components (2.2 Ga Hotazel Formation) (Evans et al., 2001) and the 2.15 Ga SE-trending dyke in the Archean Basement (Lubnina et al., 2010).](image-url)

Cawthorn et al. (1981) suggested the possibility of some sills in the sampling area to be of pre-Bushveld age. The ~2.15 Ga age of the south east dyke of Lubnina et al. (2010) is also interpreted to represent that of the easterly shallow component of sill RUB. Since this sill is interpreted to predate the Bushveld Complex, its tilt-corrected value is converted to give a VGP at Latitude = 15.3°S, Longitude = 117.8°E, dp = 7.2, dm = 14. In the next section, this is compared to data from sill HWQ to the east of the Bushveld Complex.
3.5. RECONCILIATION OF DATA FROM EASTERN AND WESTERN LIMBS AND COMBINED POLE CALCULATION

Individual intrusions and samples from country rocks in the western and eastern limbs of KC generally responded well to demagnetization. Several characteristic magnetic components (B, C+/−, D and F) were identified, with B and C+/− components being the most common (Table 3.4). For the magnetic components present in both western and eastern limbs, site means for separate sampling sites are combined (see Figure 3.16). New pole positions for the KC are also calculated.

Table 3.4. Summary of relatively high stability components obtained from studied post-Transvaal intrusions in the eastern and western limbs

<table>
<thead>
<tr>
<th>Component</th>
<th>Site</th>
<th>n/N</th>
<th>Present coordinates</th>
<th>Tilt-corrected coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>western limb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>RUJ</td>
<td>10/10</td>
<td>99.9 59 2.51 334.32</td>
<td>92.1 70.5 2.51 334.32</td>
</tr>
<tr>
<td>B</td>
<td>BRB</td>
<td>9/9</td>
<td>156.6 70 5.41 92.5</td>
<td>150.5 81.9 5.41 92.5</td>
</tr>
<tr>
<td>eastern limb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>HWR</td>
<td>6/6</td>
<td>114.5 51 6.27 95.93</td>
<td>125.6 60.9 8.88 48.2</td>
</tr>
<tr>
<td>B</td>
<td>HWD</td>
<td>4/8</td>
<td>144.1 29.1 11.04 52.67</td>
<td>139.8 66.2 4.98 50.57</td>
</tr>
</tbody>
</table>

B mean (in situ) at D = 120.9, I = 56.1, α₉₅ = 10.6, k = 21.6, N = 10 and Paleopole at 39.3°N, 89.3°E, A₉₅ = 13.2, N = 10

<table>
<thead>
<tr>
<th>Component</th>
<th>Site</th>
<th>n/N</th>
<th>Present coordinates</th>
<th>Tilt-corrected coordinates</th>
</tr>
</thead>
</table>

VGP recalculated from the tilt-corrected mean at 15.7°N, 117.8°E, dp = 7.2, dm = 14
The following conditions are required for inclusion in pole calculation: a) only the results from intrusions are used, b) the site mean is based on four or more samples, c) Fisher’s (1953) precision parameter \((k)\) for the site mean is above 7, and d) the \(\alpha_{95}\) cone of confidence about the mean is below fifty (see Table 3.4). The newly obtained pole positions are reconciled with geochemical and geochronological results generated in Chapter 2 and compared to previously published poles positions in the KC (listed in Table 3.5).

**Table 3.5.** Previously published pole positions for the KC

<table>
<thead>
<tr>
<th>Group/lithology</th>
<th>Label</th>
<th>Lat.(°N)</th>
<th>Long.(°E)</th>
<th>A95 (dp/dm)</th>
<th>Age (Ma)</th>
<th>References (for pole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ongeluk Lava</td>
<td>ONG</td>
<td>-0.5</td>
<td>100.7</td>
<td>5.3</td>
<td>2222 ± 13 (Pb/Pb)</td>
<td>Evans et al. (2002)</td>
</tr>
<tr>
<td>Mamatwan ore (Component 1)</td>
<td>MAM-1</td>
<td>-8.2</td>
<td>111.1</td>
<td>5.6/11.1</td>
<td>~ 2200</td>
<td>Evans et al. (2001)</td>
</tr>
<tr>
<td>Basal Gamagara / Mapedi Formation</td>
<td>BGM</td>
<td>2.2</td>
<td>81.9</td>
<td>7.2/11.5</td>
<td>2060-2200</td>
<td>Evans et al. (2002)</td>
</tr>
<tr>
<td>Phalaborwa Complex</td>
<td>PBC</td>
<td>27.7</td>
<td>35.8</td>
<td>6.6</td>
<td>2060.6 ± 0.5 (U-Pb zircon and baddeleyite)</td>
<td>Letts et al. (2010)</td>
</tr>
<tr>
<td>Bushveld (Critical Zone)</td>
<td>22.1</td>
<td>31</td>
<td>8.1/10.5</td>
<td>2054 ± 3.5 (SHRIMP U-Pb zircon)</td>
<td>Letts et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>Bushveld (northern Main Zone)</td>
<td>17.5</td>
<td>28.8</td>
<td>5.1/6.2</td>
<td>2023.0 ± 4.0 (U-Pb single zircon)</td>
<td>Salminen et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>Bushveld (eastern Main Zone)</td>
<td>18.3</td>
<td>40.5</td>
<td>2.7/5.2</td>
<td>2023.0 ± 4.0 (U-Pb single zircon)</td>
<td>Salminen et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>Bushveld (western Main Zone)</td>
<td>15.5</td>
<td>28.2</td>
<td>2.7/3.3</td>
<td>2023.0 ± 4.0 (U-Pb single zircon)</td>
<td>Salminen et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>Bushveld (upper Zone)</td>
<td>22.1</td>
<td>25.6</td>
<td>9.3/12</td>
<td>2023.0 ± 4.0 (U-Pb single zircon)</td>
<td>Salminen et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>Bushveld Complex (combined)</td>
<td>BVC</td>
<td>19.2</td>
<td>30.8</td>
<td>5.8</td>
<td>2057.7 ± 1.6 (U-Pb baddeleyite)</td>
<td>Letts et al. (2009)</td>
</tr>
<tr>
<td>Lower Waterberg Group</td>
<td>WUBS-I</td>
<td>36.5</td>
<td>51.3</td>
<td>10.9</td>
<td>2054 ± 3.5 (SHRIMP U-Pb zircon)</td>
<td>de Kock et al. (2006)</td>
</tr>
<tr>
<td>Vredfort Structure</td>
<td>VRED</td>
<td>22.8</td>
<td>41.6</td>
<td>10.5</td>
<td>2023.0 ± 4.0 (U-Pb single zircon)</td>
<td>Salminen et al. (2009)</td>
</tr>
<tr>
<td>NE trending dykes in the Archean Basement</td>
<td>BHD</td>
<td>9.4</td>
<td>352</td>
<td>4.3</td>
<td>~1900 (U-Pb baddeleyite)</td>
<td>Lubrina et al. (2010)</td>
</tr>
<tr>
<td>Sand river dykes</td>
<td>SRD</td>
<td>2.3</td>
<td>9.1</td>
<td>10.3</td>
<td>1876 ± 68 (Rb/Sr)</td>
<td>recalculated by Evans et al. (2002)</td>
</tr>
<tr>
<td>Post-Waterberg intrusions</td>
<td>WSD</td>
<td>15.6</td>
<td>17.1</td>
<td>8.9</td>
<td>1874.6 ± 3.9 (U-Pb baddeleyite)</td>
<td>Hanson et al. (2004)</td>
</tr>
<tr>
<td>Post-Bushveld dykes</td>
<td>PBD</td>
<td>12.6</td>
<td>24.1</td>
<td>10.8</td>
<td>1649 ± 10 ((^{40})Ar/(^{39})Ar)</td>
<td>Letts et al. (2005)</td>
</tr>
<tr>
<td>Rooirand dykes</td>
<td>RO</td>
<td>-77.3</td>
<td>116</td>
<td>18.8</td>
<td>200.8 ± 4.5</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Lesotho Lava</td>
<td>LS</td>
<td>-74.4</td>
<td>92.8</td>
<td>4.5</td>
<td>180 ± 4</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Dolerite dykes</td>
<td>DO</td>
<td>-68.3</td>
<td>93.7</td>
<td>7</td>
<td>Hargraves et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>Hooper sills</td>
<td>TRA</td>
<td>-64.8</td>
<td>97.9</td>
<td>8.9</td>
<td>Hargraves et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>Mashikiri and Letaba</td>
<td>MAL</td>
<td>-69</td>
<td>99.2</td>
<td>6.8</td>
<td>182</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Mbuluzi, Swaziland</td>
<td>MB</td>
<td>-45.6</td>
<td>98.6</td>
<td>10.2</td>
<td>Hargraves et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>Jozini, Natal</td>
<td>JR</td>
<td>-70.7</td>
<td>111.2</td>
<td>10.5</td>
<td>178</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Keetmanshoop sills</td>
<td>KEE</td>
<td>-69.8</td>
<td>96.2</td>
<td>18.1</td>
<td>Hargraves et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>Hardap basalts (Kalkrand)</td>
<td>HAR</td>
<td>-73.1</td>
<td>17.7</td>
<td>4.1</td>
<td>Hargraves et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>Bumberi Complex</td>
<td>BU</td>
<td>-30.2</td>
<td>105.9</td>
<td>8.1</td>
<td>145.8 ± 1.3</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Cape Peninsula dolerites</td>
<td>CP</td>
<td>-42.2</td>
<td>105.2</td>
<td>9.1</td>
<td>Hargraves et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>Swartruggens kimberlites</td>
<td>32</td>
<td>104</td>
<td>6.7</td>
<td>142 ± 4</td>
<td>Hargraves et al. (1989)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.16. Summary of relatively high temperature magnetic components present in both eastern and western limbs. Dashed circles are for site mean with $\alpha_{05} > 15^\circ$. 
3.5.1. B remanence

3.5.1.1. Regional bootstrap test

Southeast and downward directions (B component) were recorded by samples of a total of twelve sills (HWD, L, R, T, U, V, W and X in the eastern KC; BRB, RUF, RUI, and RUJ in the western limb). In each limb site mean directions generally show decrease in precision parameter K upon stepwise unfolding. In order to constrain the timing of B magnetization relative to the attitude of the country rocks on a regional scale, (i.e. in both eastern and western limbs), a regional bootstrap fold test (Tauxe et al., 1991) was achieved. During the test, different site means of B component displayed best grouping between -10 and 38 per cent of tilting restoration (Figure 3.17) and led to the interpretation that this magnetization was recorded by samples after the tilting of the country rocks. Since the B magnetization is of primary origin, it signifies that the sills HWL, R, T, U, V, W, and X, BRB, RUF, RUI, and RUJ were not intruded horizontally.

![Figure 3.17](image)

**Figure 3.17.** Regional Bootstrap fold test for B components. Note that the interval of tilt restoration (-9% - 38%) corresponding to the largest values of Y axis (tau_1) includes 0%.
3.5.1.2. B paleopole

After combination of data from both limbs, an in situ mean B component is calculated at declination = 120.9, inclination = 56.1, $\alpha_{95} = 10.6$, $k = 21.6$, $N = 10$. A pole position recalculated from the in situ B mean component is located at $-39.3^\circ S$, $89.3^\circ E$ ($K = 14.3$, $A_{95} = 13.2$, $N = 10$). On the Q-scale (Van der Voo, 1990), this newly defined B component pole scores a four out of seven. The criteria that are not met are the absence of magnetic reversals, no numerical age, and the limited number of sites ($N < 24$). Correlation of the B pole with the Karoo LIP poles listed by Hargraves et al. (1997) (Figure 3.18), suggests that some post-Transvaal sills intruded the tilted sediments of Pretoria Group in the eastern and western limbs during the Late Jurassic. The B pole is also similar to that of the Late Jurassic to Early Cretaceous Kimberlites (Hargraves, 1989) which include the Swartruggens Kimberlites of the Rustenburg area. Many of the post-Transvaal sills may thus be related to this magmatic event which would imply a much bigger extend than was previously recognized.

![Figure 3.18](image_url)

**Figure 3.18.** Paleopole for the in situ mean B remanence compared to VGP’s of the Karoo LIP after Hargraves et al. (1997). All poles are plotted with their 95% error limits as per their $A_{95}$ or as dp and dm values (listed in Tables 3.4 and 3.5).
3.5.2. C+/– Component

3.5.2.1. Regional bootstrap test

North and downward directions (C+ component) were recorded by samples of six sills (HWB, HWF, HWI, HWM and HWO) and one dyke (HWA) as well as country rocks (HWE and HWJ) in the eastern KC, and one sill (BRD) in the western limb. Inversely polarized (southwest and up) directions (C– component) were revealed in four sills (HWS and HWY in the eastern limb and sites BRE and RUC in the western limb). Unfortunately, the directions from sills BRE and RUC were believed to be mixed with younger components.

![Figure 3.19. Regional bootstrap fold test for C+/– component. Interval of tilt restoration (30-67) corresponding to the largest values of Y axis (τ1) includes 50%.](image)

The bootstrap fold test reveals that the different C+/– components from eastern sills are most tightly clustered upon a tilting restoration between 80 and 140 per cent (see Chapter 2). Results of site BRD were combined to directions previously used in the eastern KC and a new bootstrap fold test was achieved in order to constrain the timing of C+/– magnetization relative to the tilting
of strata on a regional scale. It was found that maximum cluster of directions, with 95 per of confidence, is obtained not near 100 percent like in the eastern sill complex, but between 30 to 67 per cent unfolding (Figure 3.19). Since inclusion of data from the western limb results in a statistically more powerful test than just using the eastern sills, a syn-folding C+/- remanence acquisition is given preference because the 95 percent confidence bounds on the degree of regional unfolding required for maximum clustering includes 50 percent. In others words, the C+/- directions were apparently locked in during the folding of the strata of the Pretoria Group.

3.5.2.2. C+/- pole and relation to the ~2.05 Ga Bushveld Complex

Combination of site means of both polarities (with exclusion of BRE and RUC that are suspected to be mixed with younger directions and in respect of early mentioned conditions required for inclusion in pole calculation) allows for calculation of a 50 percent tilt-corrected C+/- component mean of declination = 42.4 °, inclination = 67.1 °, α95 = 8.2 °, k = 67.7 and N = 6. The corresponding paleopole is located at Latitude = 04.9 ° N, Longitude = 056.1 ° E, K = 32, A95 = 12, and N = 6. A 100 percent tilt-corrected C+/- component mean can also be calculated (declination = 29.6°, inclination = 68.4 °, α95 = 9.6 °, k = 49.4 and N = 6) as well as the resulting pole position (Latitude = 07.3 ° N, Longitude = 47.6 ° E, K = 24.4, A95 = 13.8, and N = 6). The newly defined paleopole, regardless the amount of tilt correction, rates a six out of maximum of seven on the Q-scale of reliability (Van der Voo, 1990). The only criterion that is not met is that less than 24 sites were used to calculate the pole. Figures 3.20A and B represent the C+/- pole (50 and 100 per cent tilt-corrected) plotted along with similarly aged poles from the KC for comparison. In the remaining discussion, only the 50 per cent tilt-corrected pole will be considered. It can be observed that the newly defined ~2058 Ma C+/- pole is removed from the younger than 2054 Ma lower Waterberg Group pole (de Kock et al., 2006). The C+/- pole plots close to, but without overlapping with the poles and the mean pole of the 2058 Ma-2054 Ma RLS (Letts et al., 2009), the ~2060 Ma (Wu et al., 2011) Phalaborwa Complex pole (Letts et al., 2010), and the pole from the Vredefort Impact Structure (Salminen et al., 2009) (Figures 3.20A and B).
Figure 3.20. The ~2058 Ma C±- pole, from the present study, compared to similarly aged poles from the KC. A: different zones of the RLS. CZ: Critical Zone; WMZ: western Main Zone; EMZ: eastern Main Zone; NMZ: northern Main Zone; UZ: Upper Zone (Letts et al., 2009). B: PBC: the Phalaborwa Complex (Letts et al., 2010); BVC: the combined Bushveld Complex (Letts et al., 2009); WUBS-I: the lower Waterberg Group (de Kock et al., 2006); VRED: the Vredefort Impact Structure (Salminen et al., 2009). All poles are plotted with their 95% error limits as per their A95 or as dp and dm values (listed in Tables 3.4 and 3.5).

A U-Pb precise age of 2057.7±1.6 Ma has been recently obtained by Olsson et al. (2010) from the Marginal Zone of the RLS in the eastern KC. This age is generally, of few millions years, older than radiometric data reported from the upper layers of the suite (e.g. the 2054.4 ± 1.3 Ma of Scoates and Friedman (2008) obtained from the Merensky reef and the 2054.4 ± 1.8 Ma yielded by the Nebo granite (Walraven and Hattingh, 1993)). The upper intercept U-Pb ages of 2058.4 ± 1.3 Ma and 2058.1 ± 6 Ma obtained from sills HWH and HWS in the eastern sill complex (this study) are closer to the age of Olsson et al. (2010). Major and trace elements geochemical signatures obtained from the C remanence samples bear little resemblance to the B2 and B3 sills, but display considerable overlap with the B1 sills (see Chapter 2). The B2 and B3 sills are believed to respectively derive from the B2 and B3 Bushveld magmas (Barnes et al., 2010) which were also involved in the formation of the upper layers (i.e. the upper Critical Zone,
Main Zone and Upper Zone) of the RLS (Cawthorn, 2007; Kruger, 2005). The B1 sills are considered as related to the B1 magma, which is the parental magma of the lower part of the RLS (Cawthorn, 2007; Kruger, 2005). Thus the C+/- remanence intrusions were emplaced at about the same time as the Marginal Zone of the RLS. The C+/- pole therefore represents the KC position during the early stages of the RLS intrusion.

The mean Bushveld Complex pole of Letts et al. (2009) was based on samples that were not collected though the entire stratigraphy of the RLS, but mostly from the upper layers of the suite. Of a total of 101 sampling sites, only 10 sites originated from the Critical Zone, see Letts et al. (2009). The remaining ones (91) were stratigraphically located in the Main and Upper zones of the RLS, see Letts et al. (2009). The 101 sites generated a grand total of 915 oriented cores, with only 88 cores (i.e. less than 10 per cent) originating from the Critical Zone, see Letts et al. (2009). The mean Bushveld Complex pole of Letts et al. (2009) can therefore be considered as representative of the middle (if not final) stages of the RLS intrusion. Difference in position between the ~2058 Ma C+/- pole (this study) and the Bushveld Complex pole (Figure 3.20) could lead to the interpretation that the KC experienced movement during the formation of the RLS. On the other hand, spatial removal of the ~ 2058 Ma C+/- pole (this study) from the slightly younger WUSB-I pole from the lower Waterberg Group (de Kock et al., 2006) (Figure 3.20) suggests a probable shift in KC poles between 2058 Ma and 2054 Ma (the maximum age of the WUSB-I pole).

Another important finding of the present study is the existence of near dual polarities for C remanence in the sills. Baddeleyite grains from two of the sills that yielded opposite polarity directions (HWH (C+) and HWS (C-)) were U-Pb dated to give near identical ages (see chapter 2). Magnetic reversals have previously been reported from the RLS (e.g. Letts et al., (2009). Since the near dual polarities of the present study were observed in sills that have proved to derive from the Marginal Zone of the RLS (see Chapter 2), and since the reversals reported by Letts et al. (2009) were recorded by samples that originated from the Critical Zone, the Main Zone and the Upper Zone, it can be said that the Earth’s magnetic field underwent several magnetic reversals during the formation of the RLS.

The relative small size of the studied sills implies rapid cooling and each C remanence sill may only be represented by one polarity (either C+ or C-). However, two scenarios can be envisaged...
for the intrusion of these sills. The first hypothesis is that sills may have intruded due to a magma pulse that spanned several reversals of the Earth’s magnetic field. Another possibility is that sills may have intruded due to at least two separate magma pulses, one during reversed polarity period and one during the normal polarity period. The geochemical data suggest that the C+/−remanence sills share a common parental magma (the B1 Bushveld magma). The B1 magma thus either spanned a magnetic reversal or was protracted over time. In any of the two cases, the magma was injected probably in a near horizontal position and magnetic acquisition continued during the sagging of the country rocks.

3.5.3. D component and implications for > 2.05 Ga aged sills

Easterly shallow directions (D component) were exclusive to sill HWQ in the eastern limb and sill RUC in the western limb. Even though no field test could be done to constrain the timing of this component, it is believed to be of primary origin. Since the D directions in site HWQ are poorly constrained, no mean was calculated for the two sites. However, the two VGP’s previously recalculated for sites HWQ and RUC are plotted along with selected available KC paleopoles (listed in Table 3.5) for comparison. It can be observed that these VGP’s generally compare well with the existing ~2.2 Ga paleopoles (Figure 3.21). It is suggested that sills HWQ and RUB were intruded prior the emplacement of the 2058-2054 Ma RLS and also before the tilting of the sediments of the Pretoria Group. Sills that emplaced before the RLS have been discussed by previous authors in the eastern and western KC. Pre-Bushveld sills in the eastern KC were mapped by Sharpe (1982) in the Vermont Formation. Sill HWQ also occurs at this stratigraphic position (see Chapter 2). Pre-Bushveld sills in the western KC are abundant near Rustenburg (Cawthorn et al., 1981). Sample RUB originated from the same area. Sharpe (1982) and Cawthorn et al. (1981) further noted that the pre-Bushveld sills are generally highly altered and contain amphibole that pseudomorphed the orthopyroxene. These features were observed in sills HWQ and RUB. The amphibole is believed to have formed during the metamorphism subsequent to the RLS intrusion (Sharpe, 1982).

The exact age of pre-Bushveld sills described by Sharpe (1982) and Cawthorn et al. (1981) is unknown and these authors did not discuss a link to any known extensive igneous event on the
KC. However, paleomagnetic results for sills HWQ and RUB indicate a remanence of ~2.1 to ~2.2 Ga old, which makes these sills nearly coeval to the Bushy bend Lava member that occurs in the 2324 ± 17 Ma (zircon age) (Dorland et al., 2004) Timeball Hill and the 2224 ± 21 Ma (Rb/Sr age) (Walraven and Martini, 1995) Hekpoort Lavas.

Figure 3.21. Comparison of the VGP’s for sills HWQ and RUB with selected existing poles for the KC. All poles are plotted with their 95% error limits as per their A$_{95}$ or as dp and dm values (listed in Tables 3.4 and 3.5).

3.6. SUMMARY AND CONCLUSIONS

Various high stability magnetizations (B, C+/−, D, E+, and F+ components) were recorded by samples from post-Transvaal sills that occur in the areas of Bronkhorstspruit and Rustenburg (western KC). Some of these components (B, C+/− and D), which were previously revealed in the eastern intrusions, were believed to be of primary origin. It was more difficult to constrain the
timing of the E+ and F+ components, which bore resemblance to the ~1.1 Ga Umkondo LIP and the 1924 Ma Hartley Lavas respectively. Reconciliation of B, C+/- and D components from eastern and western limbs, with geochemical and geochronological data from the eastern limb allowed for calculating new pole positions of variable reliability for KC.

The paleopole recalculated from the in situ B remanence scored a reliability rating of four out of seven on the Q-scale ((Van der Voo, 1990) due to the absence of magnetic reversals, no numerical age and the limited number of sites (N < 24). This pole plotted close to the 180 Ma Karoo pole (Hargraves et al., 1997) and overlapped with the Late Jurassic intrusions.

The pole recalculated from the dual polarity C component, rates a six out of seven on the Q-scale of reliability (Van der Voo, 1990) due to the fact that it is only based on 8 sites. Agreement of the two U-Pb ages obtained from C+/- remanence sills with the age of the Marginal Zone of the RLS, and remarkable similarities between geochemical signatures obtained from the C remanence samples and the B1 sills and marginal rocks confirm the existence of post-Transvaal sills that are genetically related to the Marginal Zone of the RLS. Comparisons of the newly defined C+/- pole to some existing poles for KC suggest that the craton probably experienced movement during the RLS formation, and a possible loop between the RLS intrusion and the deposition of the sediments of the Waterberg Group. Presence of normally and reversely polarized directions in the studied sills, coupled to existence of magnetic reversals in the upper layers of the RLS (Letts et al., 2009) suggest that the Earth’s magnetic field underwent several changes in polarity during the RLS formation. Presence of magnetic reversals in sites of this study, which are generally of small size, coupled with the outcome of the regional bootstrap fold test for the C component strongly suggest that the Marginal Zone involved either a protracted magma pulse injected over a time period that spanned several changes in polarity, or injected at least two separate times. Intrusion is believed to have been at near horizontal position but magnetic acquisition may have occurred during slumping of the country rocks in response to boding by the Bushveld Complex.
The VGP’s recalculated from the D site mean of sills HWQ and RUB compared well with the ~2.1 Ga to ~2.2 Ga existing poles in KC, supporting the idea that some post-Transvaal sills predated the ~2.05 Ga Bushveld Complex as well as the folding of the country rocks (i.e. the Pretoria Group).

3.7. BIBLIOGRAPHIC REFERENCES


Chapter 3


Olsson, J.R., Söderlund, U., Klausen, M.B. and Ernst, R.E., 2010. U-Pb baddeleyite ages linking major Archean dyke swarms to volcanic-rift forming events in the Kaapvaal craton (South Africa), and a precise age for the Bushveld Complex. Precambrian Research, (Special Issue), 183: 490-500.


CHAPTER 4

PALEOMAGNETIC CONSTRAINTS FROM THE UITKOMST COMPLEX, SOUTH AFRICA: IMPLICATIONS FOR TIMING OF INTRUSION

The mineralized Uitkomst Complex, which has an age of ~2044 Ma, has previously been suggested to be coeval with and genetically related to the intrusion of the RLS of the Bushveld Complex. Here, first time paleomagnetic results from the Uitkomst Complex (Lower Pyroxenite and Chromatitic Peridotite units) and a younger north-south trending dyke at the Nkomati Mine are reported in order to provide additional clues regarding the timing of intrusion. Magnetic remanence for the Uitkomst Complex and that from a younger north-south trending dolerite dyke which crosscuts the Chromatitic Peridotite Unit in the Nkomati Mine are statistically indistinguishable. This, together with the dyke’s geochemical signature, suggests a late-magmatic link with the Uitkomst Complex. The pole position calculated for the Uitkomst Complex is in agreement with the current age constraints for the complex. The paleomagnetic data allows the evaluation of the APWP of during the Orosirian (i.e. between 2060 Ma and 2054 Ma).

4.1. INTRODUCTION

The layered ultramafic-mafic Uitkomst Complex (Figure 4.1) is a presumed satellite intrusion of the Bushveld Complex (de Waal et al., 2001), occurring 70 km to the southeast of the eastern limb of the Bushveld Complex in the escarpment area of Mpumalanga Province (South Africa). The complex is a tubular northwest-southeast trending, 850 m thick body that plunges approximately 4.5° to the northeast. It contains Ni-Cu-Co-PGE-Cr mineralization that was at the time of sampling exploited in both open cast and underground workings as the Nkomati Joint Venture between African Rainbow Minerals and Norilsk Nickel Africa.

The complex has been emplaced at the base of the Transvaal Supergroup between two northwest-southeast trending fracture systems (Gauert et al., 1995). The product is a long narrow complex with an anvil-shaped cross-section (Figure 4.1), with the lower part of the complex being tabular and the upper part of the complex cutting funnel-like over the Malmani dolomite,
the Bevets conglomerate, and into the Timeball Hill shale of the Transvaal Supergroup (Gauert et al., 1995).

Figure 4.1. A. Locality map, showing a simplified geology of Uitkomst Complex (after Gauert et al., 1995) and different sampling sites. B. Idealized cross-section of the Uitkomst Complex (modified after Theart and Du Nooy, 2001).
Igneous layering in the complex is divisible into two groups (Gauert et al., 1995; Kenyon et al., 1986; Theart and De Nooy, 2001). These are the Basal Group, which consists from bottom upwards of the Basal Gabbro, Lower Pyroxenite and Chromititic Peridotite units; and the Main Group that is made up from the bottom upwards of the Massive Chromitite, Peridotite, Upper Pyroxenite and Gabbronorite units (terminology of Theart and De Nooy, 2001). This layering, although consistent over a distance of 12 km, has been modified in places by thrusting and later mafic intrusions (Theart and De Nooy, 2001).

Numerous fine to medium-grained gabbroic sills intrude the Uitkomst Complex (Hulley, 2005). These sills are concordant to the Transvaal Supergroup sedimentary layering and are between 1 m to 30 m in thickness (Hulley, 2005) and have a considerable dilatational effect on the igneous layering (de Waal and Gauert, 1997). Some sill units contain sulphide mineralization as a result of contamination of material from the complex (Kenyon et al., 1986). Three sets of dykes have also been identified as crosscutting the Uitkomst Complex rocks in the Nkomati Mine area (Hornsey, 1999). These dyke swarm sets are north-south trending, northeast-southwest trending, and northwest-southeast trending (Uken and Watkeys, 1997). North-south and northeast-southwest trending dykes have been regarded as being representative of the Jurassic aged Karoo LIP related to the Olifants River swarm (Uken and Watkeys, 1997), but this swarm has been shown to contain much older dykes as well (Jourdan et al., 2006; Olsson et al., 2010).

The accepted age for the Uitkomst Complex intrusion is the 2044 ± 8 Ma \(^{207}\text{Pb}/^{206}\text{Pb}\) zircon age reported by de Waal et al. (2001), who suggested, based on this age and geochemistry, that there is a genetic link with the ultramafic to mafic layered sequence (RLS) of the Bushveld Complex.
Although the ~2044 Ma age represents a significant improvement on the ~2025 Ma Rb-Sr biotite model age of Kenyon et al. (1986) its associated uncertainty of 8 million years becomes problematic when it is compared with more recent geochronological constraints from the Bushveld Complex. The new U-Pb age of 2057.7 ± 1.6 Ma reported by Olsson et al. (2010) from the Marginal Zone in the eastern KC signifies that at worst the Uitkomst Complex intruded at least thirteen million years after the intrusion RLS, while the 2054.4 ± 1.3 Ma of Scoates and Friedman (2008) suggests that the Complex was intruded immediately after the emplacement of the RLS.

In order to add to the growing knowledgebase on the Uitkomst Complex, a paleomagnetic sampling of the Basal Group of the Complex was carried out. Despite limited possibilities for paleomagnetic drilling at the Nkomati Mine, these first paleomagnetic results for the Uitkomst Complex are reported and some light is shed on the timing of emplacement of this complex.

4.2. SAMPLING

The Basal Group of the Uitkomst Complex rocks was sampled within pit 2 of the Nkomati Mine (Figure 4.1). A total of 21 oriented specimens were drilled from the Lower Pyroxenite (sites NKC and NKD) and Chromititic Peridotite (site NKB) units. Six additional paleomagnetic oriented cores and one hand sample for geochemistry were collected from a north-south trending dolerite dyke of presumed Karoo age (site NKA) in the vicinity of NKB (Figure 4.1). Individually oriented core samples were collected using a portable, hand-held petrol drill and orientation was achieved in all cases by magnetic compass and a sun compass when possible.

The dyke (site NKA) is a fresh-looking dark colored coarse-grained rock. It has a well-developed subophitic texture involving olivine, pyroxene, plagioclase and opaque minerals. Site NKB was taken in the close vicinity of the dyke NKA. The sample from NKB also shows a well-developed subophitic texture and is made up of olivine, clinopyroxene and orthopyroxene. These minerals are associated with a consistent amount of sulphide-rich opaque minerals. Samples from sites NKC and NKD were taken from the Lower Harzburgite unit some 500-600 m away the previous sites. Thin sections reveal a predominance of pyroxene, which are associated with sulphide-rich minerals at site NKD. Detailed petrography of the Uitkomst Complex rocks is given by Gauert (1998).
4.3. PALEOMAGNETISM

4.3.1. Method

Core samples were cut to standard specimens of ~2 cm length. One specimen of each core was subjected to paleomagnetic measurements using a vertical 2G Enterprises DC-4K superconducting rock magnetometer housed at the University of Johannesburg. After measurement of natural remanent magnetization (NRM), specimens were treated with four steps of low-field-strength alternating field (AF) demagnetization up to 10 mT using a Molspin 2-axis tumbling AF-demagnetizer. The specimens were then thermally demagnetized in a shielded furnace from 100°C up to 585°C at decreasing intervals and analysed using a vertical automatic SQUID magnetometer. Magnetic components were obtained via and least-squares principal component analyses (Kirschvink, 1980). This, together with all subsequent statistical evaluation utilized Paleomag 3.1 (Jones, 2002) and PaleoMac (Cogne, 2003) software.

4.3.2. Demagnetization results

Individual samples from the Basal Group of the Uitkomst Complex generally responded well to demagnetization. Dyke samples displayed similar behaviour to the complex, but results here are a little bit noisier.

Apart from randomly directed low coercivity components, two low stability magnetic components were revealed during AF and low temperature demagnetization steps (below 400°C). The “PF” component (NKA, NKB, and NKC) is northerly and upward directed, and near parallel to the present geocentric axial dipole field of the Earth. The second component seen in samples from site NKD is easterly and upward oriented (E-up).

At high temperatures of demagnetization, all samples displayed northerly and downward components (C+ component).

The demagnetization results are summarized in Table 4.2 followed by a detailed description of the results from each sampling site.
Table 4.2. Summary of the different magnetic components obtained from the studied samples at Nkomati Mine

<table>
<thead>
<tr>
<th>Component</th>
<th>Site</th>
<th>n/N</th>
<th>D in deg.</th>
<th>I in deg.</th>
<th>a95</th>
<th>k</th>
<th>D in deg.</th>
<th>I in deg.</th>
<th>a95</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present coordinates</td>
<td>Tilt-corrected coordinates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low temperature magnetic components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF</td>
<td>NK</td>
<td>8/8</td>
<td>350.8</td>
<td>21.1</td>
<td>6.86</td>
<td>349.6</td>
<td>21.11</td>
<td>6.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-up</td>
<td>NKD</td>
<td>6/6</td>
<td>91.6</td>
<td>9.13</td>
<td>45.65</td>
<td>97.6</td>
<td>9.14</td>
<td>45.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature magnetic components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C+</td>
<td>NKA</td>
<td>6/6</td>
<td>3.7</td>
<td>54.4</td>
<td>8.95</td>
<td>357.8</td>
<td>56.4</td>
<td>8.95</td>
<td>59.24</td>
<td></td>
</tr>
<tr>
<td>C+</td>
<td>NKB</td>
<td>5/7</td>
<td>36.8</td>
<td>8.51</td>
<td>65.42</td>
<td>35.5</td>
<td>42.9</td>
<td>8.48</td>
<td>65.84</td>
<td></td>
</tr>
<tr>
<td>C+</td>
<td>NKC</td>
<td>8/8</td>
<td>18.8</td>
<td>10.10</td>
<td>27.15</td>
<td>18.9</td>
<td>46.2</td>
<td>10.1</td>
<td>27.14</td>
<td></td>
</tr>
<tr>
<td>C+</td>
<td>NKD</td>
<td>6/6</td>
<td>36.8</td>
<td>18.55</td>
<td>11.66</td>
<td>34.9</td>
<td>18.56</td>
<td>11.65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.2.1. Uitkomst Complex (Basal Group)

4.3.2.1.1. NKB

At this site, seven samples were collected from fresh blocks of the Chromititic Peridotite. During demagnetization, all samples displayed two magnetic components (Figure 4.2A.). The first one unblocked during AF pre-treatment and demagnetization temperature below 400°C (Figure 4.4) as extremely poor grouped northerly and upward pointed directions. During higher temperature steps up to 565°C, five samples revealed northerly and downward components as origin seeking straight line demagnetization trajectories (C+ Component: decl. = 36.8, incl. = 47.2, $\alpha_{95} = 8.51$, k = 65.42, n = 5; stratigraphic correction: decl. = 35.5, incl. = 42.9, $\alpha_{95} = 8.48$, k = 65.84, n= 5) (Figures 4.2A and 4.4). Samples NKA3 and 4 plotted removed from this grouping.

4.3.2.1.2. NKC

Some 400-600 m northwest of the previous site and stratigraphically below it, eight oriented cores were drilled from fresh portions of the Lower Pyroxenite. During the AF pre-treatment and low temperature demagnetization steps (below 350°C), a low stability component is revealed in all samples as poorly constrained upward northerly components (PF component: decl. = 350.8, incl. = -27.1, $\alpha_{95} = 21.10$, k = 6.86, n = 8; stratigraphic correction: decl. = 349.6, incl. = -31, $\alpha_{95} = 21.11$, k = 6.86, n = 8) (Figures 4.2B and 4.4.). At higher temperatures of heating and up to 565-580°C, well-defined northerly and downward directions unblocked as origin seeking linear trajectories in all samples (C+ component: decl. = 18.8, incl. = 50.7, $\alpha_{95} = 10.10$, k = 27.15, n = 8).
8; stratigraphic correction: decl. = 18.9, incl. = 46.2, α95 = 10.10, k = 27.14, n = 8) (Figures 4.2B and 4.4)

**Figure 4.2** Examples of demagnetization behaviour, in situ coordinates of selected samples from the Uitkomst Complex A: NKB, B: NKC, and C: NKD. Open symbols = vertical plane, closed symbols = horizontal plane, NRM = natural remanent magnetization, mT = milli Tesla.

### 4.3.2.1.3. NKD

Not far from site NKC and at similar stratigraphic height, six oriented samples were collected from fresh blocks of the Lower Pyroxenite. Demagnetization revealed the existence of two well
developed magnetic components (Figure 4.2C). The first one was revealed during the AF pre-
treatment and low temperatures of heating (below 400°C), and consisted of well-grouped
easterly and upward directions (decl. = 18.8, incl. = 50.7, α₉₅ = 10.10, k = 27.15, n = 8;
stratigraphic correction: decl. = 18.9, incl. = 46.2, α₉₅ = 10.10, k = 27.14, n = 8) (Figure 4.4.).
Above 400°C, all samples displayed reasonable grouped northerly and downward oriented
directions (C⁺ component: decl. = 36.8, incl. = 60, α₉₅ = 18.55, k = 11.66, n = 6; stratigraphic
correction: decl. = 34.9, incl. = 55.6, α₉₅ = 18.56, k = 11.65, n = 6) (Figure 4.4)

4.3.2.2. Uitkomst dyke

Six oriented samples were drilled from the dyke NKA that crosscuts the Chromititic Peridotite in
the vicinity of site NKB. During the AF pre-treatment and low temperature demagnetization,
samples displayed poorly grouped components some of which were identifiable as being parallel
to the present geomagnetic field (Figure 4.4). Between ~350°C and 585°C, all samples, with the
exception of sample NKA 01, demagnetized clearly towards the origin via linear
demagnetization trajectories and displayed northerly and downward directed (C⁺ component :
decl. = 3.7°, incl. = 54.4°, k = 59.23, α₉₅ = 8.95, n = 6; stratigraphic correction: decl. = 357.8°,
ingcl. = 56.4°, k = 59.24, α₉₅ = 8.95, n = 6) (Figures 4.3 and 4.4).

![Figure 4.3](image)

**Figure 4.3** Examples of demagnetization behaviour, in situ coordinates of the samples from the Uitkomst
dyke (NKA). Open symbols = vertical plane, closed symbols = horizontal plane, NRM = natural remanent
magnetization, mT = milli Tesla.
Figure 4.4. Equal area plots of results from all sites (NKA, NKB, NKC and NKD). The left-hand panel depicts low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts the high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.
4.3.3. Summary

One prolific (PF), one less well-developed (E-up), and some poorly developed low stability components were identified within samples from the Uitkomst Complex and a crosscutting dyke at Nkomati Mine. During high temperature demagnetization steps, both the Uitkomst Complex and dyke samples displayed C+ components. The different components means are summarized in Figure 4.5.

Figure 4.5. Summary of different components obtained from the Uitkomst Complex and a crosscutting dyke at Nkomati Mine
4.3.4. Interpretation

Absence of dual polarities in high stability directions obtained from separate sampling sites of the Uitkomst Complex and similarity between these directions and the high stability magnetization yielded by a crosscutting dyke (Figure 4.5) may raise concern about the possibility of a remagnetization in the sampling area. If the C+ component of the Uitkomst Complex samples represents a magnetic overprint, the source of the remagnetization may be related to the 180 Ma Karoo magmatic event (an age of 180 Ma has been previously assigned to dyke NKA, based on its north-south trend) or possibly to other events. Known tectono-thermal events that affected the KC are the ~1.1 Ga extensive Umkondo magmatic event and the ~1.87 Ga post-Waterberg magmatic intrusions. However, the C+ components plotted widely removed from the 180 Ma Karoo LIP directions (Hargraves et al., 1997) as well as from the ~1.1 Ga Umkondo LIP directions (Gose et al., 2006) (Figure 4.6.); the C+ components bear little resemblance to the primary directions obtained from 1.9 Ga-1.8 Ga units in the KC such as the ~1.87 Ga post-Waterberg intrusions (Hanson et al., 2004) and the ~1.6 or 1.9 Ga post-Bushveld northeast trending dykes (Letts et al., 2005) (Figure 4.6). Instead, the C+ directions of the Uitkomst Complex and crosscutting dyke samples are statistically indistinguishable from primary directions of some ~2.0 Ga units from the KC such as the 2054 Ma lower Waterberg Group (de Kock et al., 2006) and the 2023 Ma Vredefort Impact Structure (Salminen et al., 2009) (Figure 4.6). The lower Waterberg sedimentation was not associated with any notable thermal event that could reset the primary remanence of the Uitkomst Complex, and the Vredefort event is widely separated from the Nkomati Mine area (> 200 km) to be suspected as source of magnetic overprint. Based on the above arguments, the C+ magnetization of the Uitkomst Complex and the crosscutting dyke is interpreted to be of primary nature. This interpretation also signifies that the dyke NKA is probably not of Karoo age, an idea that will be geochemically explored.
Chapter 4

Figure 4.6 Comparison of the C+ directions, from the present study, with known directions from the KC (i.e. the 180 Ma Karoo magmatic province after Hargraves et al. (1997), the 1.1 Ga Umkondo LIP after Gose et al. (2006), the 1.87 Ga post-Waterberg intrusions after Hanson et al. (2004), the 1.6 or 1.9 Ga post-Bushveld dykes after Letts et al. (2005), the 2054 Ma lower Waterberg Group after de Kock et al. (2006) and the 2023 Ma Vredefort Impact Structure after Salminen et al. (2009).

4.4. GEOCHEMISTRY (UITKOMST DYKE)

4.4.1. Method

Major and trace element contents for the north-south trending dyke sample (NKA) was determined by X-ray fluorescent spectrometry at the ACME Labs, Canada, on glass beads prepared from powdered whole-rock samples with a sample-to-flux (lithium tetraborate) ratio of 1:10. Volatiles were determined by loss on ignition. Trace and rare earth elements (REEs) were
analyzed using inductively coupled plasma mass spectrometry (ICP-MS) also at the ACME Labs. Geochemical results are presented in Table 4.3.

### 4.4.2. Weathering and alteration

Degree of alteration of a rock can be recognized by observation of the hand sample and the description of the thin section. Hand sample of NKA is a fresh dark looking rock with no evidence of alteration. Thin section revealed a well-preserved subophitic texture made up of fresh olivine, pyroxene, plagioclase and opaque minerals. Alteration of minerals is limited and only occurs along some grains and cleavage planes.

Loss of ignition (LOI) is also an approach to recognizing alteration of a rock as high LOI content generally corresponds to more altered rocks. Dyke NKA has a relatively low LOI value (1.7). For comparison, the LOI values of sills studied in the eastern KC (subject of Chapter 2) ranged between 0.4 and 2.4. LOI values of the post-Transvaal dykes vary between 1.5 and 6.3 (see Chapter 5).

The alteration box plot of Large et al. (2001) can also help to evaluate the intensity and mode of alteration of a rock. In this diagram, dyke NKA falls in the least altered box of the hydrothermal chlorite-pyrite (sericite) alteration system (Figure 4.7).

From what precedes, it can be said that the dyke NKA has not been significantly affected by alteration. Thus the geochemical results are suitable for interpretation.

### 4.4.3. Major elements

Major element geochemistry (Table 4.3) reveals that dyke NKA is moderately enriched in SiO$_2$ (48.2 wt %) as well as in MgO (5.52 wt %), and also has a low MnO content (0.16 wt %). In contrast, the sample displays a relative high TiO$_2$ content (2.25 wt %), an enrichment in total FeO (14.49 wt %) and 14.32 wt% for Al$_2$O$_3$. Alkalis (Na$_2$O and K$_2$O) content of sample NKA is also relatively high (~5 wt %). These features make dyke NKA fall in the tholeiitic area of the AFM diagram (Irvine and Baragar, 1971) and plot as trachy-basalt in the bivariate diagram of total alkali vs. silica (Le Bas et al., 1986) (Figure 4.8). The relative low Mg# (~43) of dyke NKA suggests that it may originate from an evolved magma.
Table 4.3. Geochemical results of the Uitkomst dyke

<table>
<thead>
<tr>
<th>Element</th>
<th>NKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO %</td>
<td>5.52</td>
</tr>
<tr>
<td>SiO2</td>
<td>48.3</td>
</tr>
<tr>
<td>Al2O3</td>
<td>14.32</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>14.49</td>
</tr>
<tr>
<td>CaO</td>
<td>7.53</td>
</tr>
<tr>
<td>Na2O</td>
<td>3.55</td>
</tr>
<tr>
<td>K2O</td>
<td>1.43</td>
</tr>
<tr>
<td>TiO2</td>
<td>2.25</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.43</td>
</tr>
<tr>
<td>MnO</td>
<td>0.17</td>
</tr>
<tr>
<td>Cr2O3</td>
<td>0.013</td>
</tr>
<tr>
<td>LOI</td>
<td>1.7</td>
</tr>
<tr>
<td>Sum</td>
<td>99.7</td>
</tr>
<tr>
<td>Ni (ppm)</td>
<td>109</td>
</tr>
<tr>
<td>Sc</td>
<td>21</td>
</tr>
<tr>
<td>Ba</td>
<td>394</td>
</tr>
<tr>
<td>Be</td>
<td>1</td>
</tr>
<tr>
<td>Co</td>
<td>56.3</td>
</tr>
<tr>
<td>Cs</td>
<td>2</td>
</tr>
<tr>
<td>Ga</td>
<td>20.6</td>
</tr>
<tr>
<td>Hf</td>
<td>8</td>
</tr>
<tr>
<td>Nb</td>
<td>14.8</td>
</tr>
<tr>
<td>Rb</td>
<td>47.3</td>
</tr>
<tr>
<td>Sn</td>
<td>2</td>
</tr>
<tr>
<td>Sr</td>
<td>368.5</td>
</tr>
<tr>
<td>Ta</td>
<td>0.9</td>
</tr>
<tr>
<td>Th</td>
<td>3.4</td>
</tr>
<tr>
<td>U</td>
<td>1</td>
</tr>
<tr>
<td>V</td>
<td>287</td>
</tr>
<tr>
<td>W</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Zr</td>
<td>307.4</td>
</tr>
<tr>
<td>Y</td>
<td>40.2</td>
</tr>
<tr>
<td>La</td>
<td>32.2</td>
</tr>
<tr>
<td>Ce</td>
<td>74.1</td>
</tr>
<tr>
<td>Pr</td>
<td>9.44</td>
</tr>
<tr>
<td>Nd</td>
<td>38.8</td>
</tr>
<tr>
<td>Sm</td>
<td>8.55</td>
</tr>
<tr>
<td>Eu</td>
<td>2.56</td>
</tr>
<tr>
<td>Gd</td>
<td>8.57</td>
</tr>
<tr>
<td>Tb</td>
<td>1.37</td>
</tr>
<tr>
<td>Dy</td>
<td>7.46</td>
</tr>
<tr>
<td>Ho</td>
<td>1.44</td>
</tr>
<tr>
<td>Er</td>
<td>4.15</td>
</tr>
<tr>
<td>Tm</td>
<td>0.58</td>
</tr>
<tr>
<td>Yb</td>
<td>3.57</td>
</tr>
<tr>
<td>Lu</td>
<td>0.53</td>
</tr>
<tr>
<td>Cu</td>
<td>88</td>
</tr>
<tr>
<td>Pb</td>
<td>4</td>
</tr>
<tr>
<td>Zn</td>
<td>36</td>
</tr>
<tr>
<td>Ni</td>
<td>78.4</td>
</tr>
<tr>
<td>As</td>
<td>0.7</td>
</tr>
<tr>
<td>Cd</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Sb</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Bi</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Ag</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Au</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Hg</td>
<td>0.03</td>
</tr>
<tr>
<td>TI</td>
<td>0.1</td>
</tr>
<tr>
<td>Se</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>
4.4.5. Trace elements (Co, Ni, Sc, Cu, Zn, and V)

Dyke NKA is characterized by low Co and Ni, which generally exhibits a positive correlation with MgO (see Table 4.3). This trend can be attributed to the compatible nature of these three trace elements during the fractional crystallization and which allows them to be preferentially incorporated in the formation of the MgO-rich early minerals (olivine and pyroxene) noticed in thin section. In contrast, the sample is relatively enriched in Sc, Cu, Zn, and V (see Table 4.3). In fractionation process, Sc, Cu, Zn, and V are generally known as incompatible elements which tend to concentrate in residual liquids. Enrichment of NKA in incompatible elements may provide additional support of the evolved nature of this dyke.

4.4.6. Rare earth elements

Rare earth element (REE) geochemistry of dyke NKA is displayed on a chondrite normalized plot (McDonough and Sun, 1995) (Figure 4.9A). It can be observed that dyke NKA is enriched in REE by several orders of magnitude relative to chondritic values, and show a strong fractionation of light REE (100 to 135 times chondrite values), relative to medium REE and high
REE (20 to 40 times chondrite values) (Figure 4.9A), as attested by the La/Sm (2.35), Gd/Er (~1.66) and Er/Lu (~ 1.20) ratios.

**Figure 4.8.** Discrimination diagram for major elements showing the behaviour of the dyke NKA. A: AFM diagram (Irvine and Baragar, 1971). B: bivariate diagram of total alkali vs. silica (Le Bas et al., 1986)

### 4.4.7. Multi-element plot (spidergram)

Sample NKA is enriched in trace elements by several orders of magnitude relative to primitive mantle values. Although the profile is generally smoother, some anomalies can be observed (e.g. positive K, Pr, P, and negative Nb, Pb, Sr, Eu and Dy anomalies) (Figure 4.9B).

**Figure 4.9.** Trace elements behaviour of dyke NKA. A: Chondrite-normalized (McDonough and Sun, 1995) REE profile. B: Pyrolite-normalized (McDonough and Sun, 1995) incompatible trace elements pattern.
4.4.8. Comparison to strata-bound igneous suites

The dyke NKA has been suggested to be of Jurassic age, based on its N-S trend. Here, the geochemical signature of dyke NKA is compared not only to the 180 Ma Karoo intrusions, but also to results from other well-documented < 2044 Ma aged igneous events of the KC, (i.e. the 2044 Ma Uitkomst Complex, the ~1.9 Ga post-Waterberg intrusions and Black Hills dykes, and the ~1.1 Ga Umkondo sills). It can be said that the chemistry of dyke NKA does not correlate well with the ~1.9 Ga post-Waterberg intrusions and the Black Hills dykes, and the 1.1 Ga Umkondo sills) (not shown).

In terms of Mg# [100 x Mg/(Mg+Fe\(^{2+}\)); FeO = Fe\(_2\)O\(_3\)/1.15], the dyke NKA (~44) is in the range of Karoo LIP rocks (82-31) (Jourdan et al., 2007) but also falls at the high end of the Mg# range reported (~48-20) for different high-Ti Uitkomst Complex rocks (de Waal et al., 2001). Like the high-Ti Uitkomst Complex rocks, the dyke also has high Na\(_2\)O content (~3.55 wt. %), thereby falling in the trachybasalt field in the TAS plot (Le Bas et al., 1986).

This is in contrast to the Karoo intrusions that range from basalt to basaltic trachy-andesite in the same plot (Jourdan et al., 2007). The high Fe\(_2\)O\(_3\)t (~14.5 wt. %) content of the dyke NKA attests a tholeiitic affinity to this rock in the AFM plot (Irvine and Baragar, 1971) (Figure 4.8A). This is also similar to the high-Ti Uitkomst Complex rocks, which have a high Fe\(_2\)O\(_3\)t (~7-22 wt. %) content relative to the low-Ti Uitkomst Complex rocks (~2-13 wt. %).

In terms of REE, it can be said that the chondrite-normalized (McDonough and Sun, 1995) REE plot of the dyke NKA does not resemble the Karoo intrusions, but correlates very well with the high-Ti Uitkomst Complex rocks (Figure 4.10A) as attested by the following ratios: Low-Ti Karoo rocks: La/Sm= ~1.72-~2; Gd/Er= ~1.2; Er/Lu= ~ 0.98. High-Ti Karoo rocks: La/Sm= ~1.72-~2; Gd/Er= ~1.58 - ~3.67; Er/Lu= ~ 1.42- ~ 1.75. Dyke NKA: La/Sm= ~2.35; Gd/Er= ~1.66; Er/Lu= ~ 1.20. High-Ti Uitkomst Complex rocks: La/Sm= ~2.3-~3.4; Gd/Er= ~1.54-~1.778; Er/Lu= ~ 1.035-~1.20.

In terms of multi-element plot (spidergram), dyke NKA generally contrasts with the low-Ti group of Karoo LIP rocks, but bears some resemblance to the high-Ti group (Figure 4.10B). However, the most remarkable similarities in both shape and enrichment are shared by dyke NKA and high-Ti Uitkomst Complex rocks (see Figure 4.10B).
Chapter 4

Figure 4.10. Chondrite-normalized (McDonough and Sun, 1995) rare earth elements (panel A) and spidergram plots (panel B) comparing the composition of dyke NKA (this study) with respect to the representative composition of the 180 Ma Karoo intrusions and Uitkomst Complex magmas from Jourdan et al. (2007) and Gomwe (2002).

4.4.9. Summary

The geochemical results of dyke NKA that intrudes within the Basal Group of the Uitkomst Complex indicate a tholeiitic affinity and trachy-basaltic composition. Both major and trace elements suggest that the dyke is of an evolved nature. When compared to known geochemical data on KC, dyke NKA does not convincingly correlate with the 180 Ma Karoo LIP. Instead, the dyke shares consistent similarities (major elements, REE profile and spidergram) with the high Ti group of the Uitkomst Complex rocks. This correlation is in very good agreement with the
paleomagnetic signature (C+ remanence). Dyke NKA is probably not related to the Jurassic aged Karoo LIP, but may rather represent the late stage of the Uitkomst magmatism.

4.5. RECONCILIATION OF DATA AND DISCUSSION

In this section, paleomagnetic data and geochemical analysis generated in the chapter are reconciled. A mean component is calculated and a pole position for the Uitkomst Complex is established. This newly defined pole will be discussed by comparison to existing paleopoles from the KC (listed in Table 4.4 below).

Table 4.4. Selected pole positions for the KC

<table>
<thead>
<tr>
<th>Group/lithology</th>
<th>Label</th>
<th>Lat.(°N)</th>
<th>Long.(°E)</th>
<th>A_{dp/dm}</th>
<th>Age (Ma)</th>
<th>References (for pole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uitkomst Complex</td>
<td></td>
<td>28.7</td>
<td>58.5</td>
<td>6.2/9.4</td>
<td>2044 ± 8 (\text{Pb}/\text{Pb})</td>
<td>This study</td>
</tr>
<tr>
<td>Ongeluk Lava</td>
<td>ONG</td>
<td>-0.5</td>
<td>100.7</td>
<td>5.3</td>
<td>2222 ± 13 (Pb/Pb)</td>
<td>Evans et al. (2002)</td>
</tr>
<tr>
<td>Mamatwan ore</td>
<td>MAM-I</td>
<td>-8.2</td>
<td>111.1</td>
<td>5.6/11.1</td>
<td>~ 2200</td>
<td>Evans et al. (2001)</td>
</tr>
<tr>
<td>Basal Gamagara / Mapedi Formation</td>
<td>BGM</td>
<td>2.2</td>
<td>81.9</td>
<td>7.2/11.5</td>
<td>2060-2200</td>
<td>Evans et al. (2002)</td>
</tr>
<tr>
<td>Phalaborwa Complex</td>
<td>PBC</td>
<td>27.7</td>
<td>35.8</td>
<td>6.6</td>
<td>2060.6 ± 0.5 (U-Pb zircon and baddeleyite)</td>
<td>Letts et al. (2010)</td>
</tr>
<tr>
<td>Bushveld Complex</td>
<td>BVC</td>
<td>19.2</td>
<td>30.8</td>
<td>5.8</td>
<td>2057.7 ± 1.6 (U-Pb baddeleyite)</td>
<td>Letts et al. (2009)</td>
</tr>
<tr>
<td>Lower Waterberg Group</td>
<td>WUBS-I</td>
<td>36.5</td>
<td>51.3</td>
<td>10.9</td>
<td>2054 ± 3.5 (SHRIMP U-Pb zircon)</td>
<td>de Kock et al. (2006)</td>
</tr>
<tr>
<td>Vredefont Impact Structure upper Swaershoek Formation</td>
<td>VRED</td>
<td>22.8</td>
<td>41.6</td>
<td>10.5</td>
<td>2023.0 ± 4.0 (U-Pb single zircon)</td>
<td>Salminen et al. (2009)</td>
</tr>
<tr>
<td>NE trending dykes in the Archean Basement</td>
<td>BHD</td>
<td>9.4</td>
<td>352</td>
<td>4.3</td>
<td>~1900 (U-Pb baddeleyite)</td>
<td>Lubnina et al. (2010)</td>
</tr>
<tr>
<td>Sand river Dykes</td>
<td>SRD</td>
<td>2.3</td>
<td>9.1</td>
<td>10.3</td>
<td>1876 ± 68 (Rb/Sr)</td>
<td>recalculated by Evans et al. (2002)</td>
</tr>
<tr>
<td>Post-Waterberg intrusions</td>
<td>WSD</td>
<td>15.6</td>
<td>17.1</td>
<td>8.9</td>
<td>1874.6 ± 3.9 (U-Pb baddeleyite)</td>
<td>Hanson et al. (2004)</td>
</tr>
<tr>
<td>Post-Bushveld dykes</td>
<td>PBD</td>
<td>12.6</td>
<td>24.1</td>
<td>10.8</td>
<td>1649 ± 10 (^{40}\text{Ar}/^{39}\text{Ar})</td>
<td>Letts et al. (2005)</td>
</tr>
<tr>
<td>Umkondo Intrusions</td>
<td>UMK</td>
<td>64</td>
<td>38.8</td>
<td>3.7</td>
<td>~1100</td>
<td>Gose et al. (2006)</td>
</tr>
</tbody>
</table>

4.5.1. Calculation of Uitkomst Complex pole position

Since the dyke NKA has been proved to represent a late magmatic phase of the Uitkomst Complex, it seems logic to combine the paleomagnetic data of the two units in the calculation of the mean component and pole position for the complex. However, one should kept in mind that dyke NKA is by definition younger than the Uitkomst Complex, and it is unknown by how
much, since there is no numerical age for this dyke (during the present study, sample NKA failed to provide viable baddeleyite grains for U-Pb dating). For these reasons, results of dyke NKA are excluded in the calculation of the mean direction and pole position for the Uitkomst Complex. Since the Uitkomst Complex sites (NKB, NKC and NKD) are of limited number and revealed magnetic directions of single polarity, it is likely that the palaeosecular variation has not been adequately averaged out by the sampling. All data can therefore be combined and treated as one site. The mean direction for C+ component has a declination of 28.8° and an inclination of 53.0° (n = 19, k = 37.3, α95 = 6.3). The tilt-correction of igneous layering results in a small change to a declination of 28.1° and an inclination of 48.5°. The corresponding tilt-corrected pole position is located at 28.7˚N and 58.5˚E (dp = 6.2, dm = 9.4). The stratigraphic correction is based upon the assumption that the intrusion of the Uitkomst Complex predated the tilting of regional sedimentary layering as suggested in de Waal et al. (2001). The newly defined Uitkomst Complex pole is a VGP.

4.5.2. Uitkomst Complex VGP and implication for the timing of intrusion

In Figure 4.11, the newly defined VGP for the Uitkomst Complex is plotted along with selected existing primary paleopoles on KC (listed in Table 4.4) for comparison. It can be observed that the VGP is widely separated from the youngest paleopoles (i.e. the 180 Ma mean Karoo LIP pole (Hargraves et al., 1997), and the 1.1 Ga Umkondo LIP mean pole (Gose et al., 2006)), and also clearly stands out from the 1.9 Ga-1.8 Ga paleopoles (i.e. the pole for 1879 to 1872 Ma post-Waterberg intrusions (Hanson et al., 2004) and that of the 1.6 or 1.9 Ga post-Bushveld northeast trending dykes (Letts et al., 2010) (Figure 4.11). This provides further support for the primary nature of the Uitkomst Complex VGP, which falls in the area of the ~2.0 Ga aged paleopoles for the KC. It is important to note that the Uitkomst Complex VGP does not overlap with the pole from the 2058 Ma to 2054 Ma RLS of the Bushveld Complex (Letts et al., 2009) or the ~ 2060 Ma (Wu et al., 2011) Phalaborwa Complex pole (Letts et al., 2010), but does with the < 2054 ± 3.5 Ma (Dorland et al., 2006) lower Waterberg Group pole (de Kock et al., 2006) (Figure 4.11). While the disagreement in position between the Uitkomst Complex VGP (this study) and the Bushveld Complex pole of Letts et al., (2009) may be due to the inadequate averaging of palaeosecular variation (e.g. the dispersion angle between a VGP
position and that of a “standard” paleomagnetic pole can be as much as 15-20° (Buchan and Halls, 1990)), it does not appear problematic in regard of the current age constraints from the Uitkomst Complex (2044 ± 8 Ma $^{207}$Pb/$^{206}$Pb zircon age (de Waal et al., 2001)) and the recent age obtained from the RLS (e.g. an U-Pb age 2057.7±1.6 Ma has been reported by Olsson et al. (2010) from the Marginal Zone of the RLS). It is suggested that the Uitkomst Complex postdates the 2058 Ma to 2054 Ma RLS of the Bushveld Complex, but predates the ~1.93 Ga to ~1.87 Ga events on the KC. It is important to note that a genetic link between the Uitkomst Complex and the RLS is not being questioned here.

Figure 4.11. Comparison of the Uitkomst Complex VGP (this study) with selected existing poles from the KC. All poles are plotted with their 95% error limits as per their A$_{95}$ or as dp and dm values (listed in Table 4.4).
According to Rajesh et al. (2013), the two entities are members of the 2.06 Ma-2.04 Ga Bushveld LIP. The Bushveld magmatism is believed to have involved at least three separated major events in the time intervals 2061 Ma-2060 Ma, 2059 Ma-2054 Ma and 2046 Ma-2042 Ma (Rajesh et al., 2013). The RLS, as well as the Rashaop Granophyre and the Lebowa Granite Suite belong to the 2059-2054 Ma group, while the Uitkomst Complex is member of the 2046 Ma-2042 Ma group, together with the 2041 ± 41 Ma (Coetzee and Kruger, 1989) Losberg Complex, 2046 ± 3.4 (Rajesh et al., 2013) Thabazimbi sills, 2044 ± 24 Ma Molopo farms Complex, 2040 ± 18 Ma (Zeh et al., 2007) diorite and 2037 ± 12 Ma (Millonig et al., 2010) granitoids from the Mahalaye Complex and the 2038 ± 15 Ma (Majaule et al., 2001) Kubu Island granites. The three group ages Bushveld-LIP events are believed to be genetically related one another (asthenosphere-derived Bushveld magma) as they have all produced high-Ti and low-Ti group rocks (Rajesh et al., 2013). Both the RLS and the Uitkomst Complex display this feature and share many other geochemical similarities that place them in the context of the same LIP (e.g. de Waal et al., 2001). Thus although not coeval (as supported by the paleomagnetic results of this study), a genetic link between the Uitkomst Complex and the RLS as advocated by de Waal et al. (2001) cannot be discarded. The question is how to bring this seeming dichotomy together in a meaningful way. The answer probably lies in a modified concept, which differs from previous suggestions in terms of the timing of the final closure of the Uitkomst Complex.

One potential complication to the paleomagnetic results of the present study is the recent suggestion that the lower Waterberg Group pole is significantly affected by inclination shallowing (Letts et al., 2010). Sedimentary rocks with remanence carried by detrital magnetic minerals commonly show directions that are biased to shallow because of deposition and later compaction (Tauxe, 2005). The lower Waterberg Group data, however, do not come solely from sedimentary rocks as portrayed by Letts et al. (2010). Some of the data also originate from 2054 ± 3.5 Ma quartz porphyry (de Kock et al., 2006), which is immune to inclination shallowing. A separation of igneous and sedimentary data allows for estimating the shallowing bias as recorded by the clastic sedimentary rocks of the lower Waterberg Group. Formal comparison (Tauxe et al., 2009) shows that porphyry and sedimentary rocks share a common mean, and therefore common inclination, at the 95% level of confidence (Figure 4.12). The relatively large amount of shallowing suggested by Letts et al. (2010) is rather unsatisfactory when it comes in
explaining the difference between their Bushveld Complex pole and the lower Waterberg Group pole. Here it is proposed that the 2054 ± 3.5 Ma age of the porphyry should be regarded as the maximum age of the lower Waterberg Group pole, and that the minimum age of the pole is given by the timing of deformation of the lower Waterberg Group. The data thus suggests that there is a possible shift in poles of the Orosirian APWP in the interval between the RLS intrusion, deposition and deformation of the lower Waterberg Group, and Uitkomst Complex intrusion.

Figure 4.12. A comparison of directions obtained from the 2054 Ma lower Waterberg Group quartz porphyry and interbedded shale and siltstone of the Swaershoek Formation (data from de Kock et al., 2006) illustrates that directions share a common mean, and therefore inclination, at the 95% confidence level. A large degree of inclination shallowing as suggested by Letts et al. (2010) is therefore unlikely.

4.6. CONCLUSION

Paleomagnetic data from Nkomati Mine provide new constraints on the timing of intrusion of the Uitkomst Complex. The VGP for the Uitkomst Complex suggests that the intrusion post-dated
the 2058 Ma-2054 Ma RLS, but predated the ~1.93 Ga to ~1.87 Ga events on the KC. This observation is in line with current $^{207}\text{Pb}/^{206}\text{Pb}$ zircon constraints and the recent age obtained from the RLS, and suggests a possible shift between 2060 and 2054 Ma poles in the Orosirian APWP of the KC. Paleomagnetism and geochemistry data from a younger north-south trending dyke that crosscuts the complex suggest that this dyke represents a late-magmatic phase of the Uitkomst Complex. This is a surprising result, given that the dyke was previously believed to be Jurassic in age.

4.7. BIBLIOGRAPHIC REFERENCES


Chapter 4


Olsson, J.R., Söderlund, U., Klausen, M.B. and Ernst, R.E., 2010. U-Pb baddeleyite ages linking major Archean dyke swarms to volcanic-rift forming events in the Kaapvaal craton (South Africa), and a precise age for the Bushveld Complex. Precambrian Research, (Special Issue), 183: 490-500.


CHAPTER 5
CHARACTERIZATION OF A POST-TRANSVAAL DYKE SWARM IN THE MPUMALANGA PROVINCE

The exact timing of intrusion of mafic dykes within the Pretoria Group in the eastern KC is unclear. Post-Bushveld dykes which cut though the sediments of the Pretoria Group have been dated to be either 1.6 Ga or 1.9 Ga. However, the large majority of post-Transvaal dykes are assigned to the ~180 Ma Karoo magmatism based on their N to NNE trend. In this chapter, geochemical and paleomagnetic results from a north northeast-trending dyke swarm near Lydenburg are reported. The study provides the first analytical data for these units. Demagnetization results indicate a very complex magnetic history with existence of several poorly defined magnetizations. The VGP’s recalculated from these remanences correlate well with previously published poles for the KC; but geochemical constraints suggest that most of these VGP’s may be related to magnetic overprints. However, two remanences are strongly believed to represent the primary magnetization of the Lydenburg dykes. Further investigation is needed to refine these results.

5.1. INTRODUCTION

Dyke swarms are widely spread over the KC and intrude the Archean Basement as well as the cover sequences and younger igneous units of the craton. Integrated studies (geochemistry, geochronology, paleomagnetism) on the KC dykes have so far revealed about five major dyking events between ~2.95 Ga and ~0.18 Ga across the craton. These are: 1) the ~2.95 Ga SE-trending dykes, 2) the ~2.87 Ga NW-trending dykes, 3) the ~2.65 Ga E-trending dykes, 4) the ~1.90 Ga NE-trending dykes, and 5) the ~180 Ma dyking event (Gumsley et al., 2012; Hanson et al., 2004; Hargraves et al., 1997; Letts et al., 2005; Letts et al., 2010; Lubnina et al., 2010; Olsson et al., 2010).

A review of literature on the KC dykes also reveals that few data is available for the dyke swarms that intrude the sediments of the upper Transvaal Supergroup (i.e. the Pretoria Group). The studies of Letts et al. (2005) and Olsson (2012) who respectively dated the dykes that
crosscut the Transvaal Supergroup and the Bushveld Complex with $^{40}$Ar-$^{39}$Ar at 1.6 Ga and U-Pb on baddeleyite at 1.9 Ga are exceptions. A large majority of post-Transvaal dykes remains to be investigated and these dykes are believed to be of 180 Ma age based upon trend analysis (Uken and Watkeys, 1997). On the available geological maps, the north-northeast-trending dyke swarms that intrude the Pretoria Group are generally mapped as “diabases of Jurassic age”, implying that they represent a single magmatic event (i.e. the ~180 Ma Karoo magmatism).

In this chapter, paleomagnetic results, coupled with geochemical analyses from dykes that form part of a dyke swarm in the area of Lydenburg (Mpumalanga province), eastern KC are reported. This study offers the first analytical data for the Lydenburg dykes and adds to the growing knowledgebase on dyke swarms of the KC.

### 5.2. SAMPLING AND METHOD

East of the eastern limb of the Bushveld Complex and in proximity to the sill complex studied in Chapter 2, a prominent north-northeast-trending dyke swarm cuts through the Silverton shales of the Pretoria Group (Figure 5.1.). Individual dykes have multi-kilometric strike lengths, range between 25 m and 100 m in thickness, and consist of fine to medium and rarely coarse-grained dolerite. Hand samples are generally altered (Figures 5.2D-F) and are mainly composed of pyroxene and plagioclase. During field work in the area, paleomagnetic samples were collected from ten dykes to the northeast (LDD, E, F, G, I and J) and southeast (LDA, B, C and H) of Lydenburg (Table 5.1. and Figures 5.2 A-F). All sampling sites are localized outside of the outer limit of the contact metamorphism of the Bushveld Complex (Cawthorn et al., 2006), but fall within the distribution areas of the 1.9 Ga magmatism (Hanson et al., 2004) as well as the ~1.1 Ga Umkondo magmatism (Gose et al., 2006) and the ~180 Ma Karoo magmatism (Jourdan et al., 2007).

Oriented core samples were collected from individual dyke using a portable, hand-held petrol drill and orientation was achieved in all cases by magnetic compass and with a sun compass when possible. Together with the paleomagnetic sampling, hand samples were taken from seven of the ten dykes for major and trace element geochemistry. During field work it was not possible to collect the country rocks for field tests of paleomagnetic stability, due to the weathered
character of the Pretoria Group rocks and/or difficulty in finding the contact between the dyke and the host rocks.

**Figure 5.1.** Geological map of the Transvaal Supergroup in the area of Lydenburg showing the different sampling sites. Dykes are mapped as Jurassic units.
The oriented cores were cut to standard specimens of ~2 cm length. One specimen of each core was paleomagnetically analysed using the new vertical 2G Enterprises DC-4K (liquid helium free) superconducting rock magnetometer housed at the University of Johannesburg. The natural remanent magnetizations (NRM) were first measured, followed by low-field-strength alternating field (AF) demagnetization in four 2.5 mT steps up to 10 mT, which was achieved using a Molspin 2-axis tumbling AF-demagnetizer. Thermal demagnetization was then conducted on the samples in a shielded furnace from 100°C up to 550°C - 585°C depending on the site, at decreasing intervals. Magnetic components were obtained via least-squares principal component analysis (Kirchvink, 1980). The calculations, together with all subsequent statistical analyses utilized the Macintosh ™ based software Paleomag 3 (Jones, 2002) and PaleoMac (Cogne, 2003).

### Table 5.1. Characteristics of the different sampling sites. N: number of paleomagnetic oriented cores drilled per site. (*) sample with geochemistry.

<table>
<thead>
<tr>
<th>Dyke site</th>
<th>GPS coordinates</th>
<th>thickness</th>
<th>N</th>
<th>strike</th>
<th>dip (country rocks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDA*</td>
<td>S 25°07’03.2’’ E 030°29’22.3’’</td>
<td>~25m</td>
<td>8</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>LDB*</td>
<td>S 25°07’52.0’’ E 030°30’43.0’’</td>
<td>~100m</td>
<td>10</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>LDC*</td>
<td>S 25°08’23.6’’ E 030°30’50.9’’</td>
<td>~50m</td>
<td>8</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>LD*</td>
<td>S 25°02’13.1’’ E 030°29’08.4’’</td>
<td>~70m</td>
<td>11</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>LDE*</td>
<td>S 25°02’19.1’’ E 030°29’31.8’’</td>
<td>~20m</td>
<td>7</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>LDF*</td>
<td>S 25°02’21.40’’ E 030°29’48.1’’</td>
<td>~50m</td>
<td>11</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>LDG*</td>
<td>S 25°02’33.5’’ E 030°30’17.8’’</td>
<td>~80m</td>
<td>9</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>LDH*</td>
<td>S 25°08’39.7’’ E 030°31’05.9’’</td>
<td>~50m</td>
<td>6</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>LD*</td>
<td>S 25°03’31.3’’ E 030°31’18.0’’</td>
<td>~60m</td>
<td>8</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>LDJ*</td>
<td>S 25°03’06.8’’ E 030°31’30.0’’</td>
<td>~60m</td>
<td>5</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

Total = 10 sites (83 oriented cores)

### 5.3. PETROGRAPHY

General petrography of sampled dykes is described in this section with aims of identifying the textures of these units, as well as the different mineral phases. The rocks are variably altered with the igneous textures being obliterated in most cases. Grain size generally varies from fine to medium-grained and rarely coarse-grained. The mineralogy is dominated by plagioclase and orthopyroxene. Intergrowth of these phenocrysts is very common and generally defines a subophitic texture. Some samples also display a granular texture. In most thin sections, the phenocrysts make up about twenty to thirty per cent by volume.
The microscopic petrography also indicates the presence of quartz and biotite as accessory mineral phases in some samples, and amphibole and clay minerals (chlorite, sericite) as secondary minerals. The matrix is generally composed of fine-grained pyroxene, plagioclase,
opaque minerals and other small sized mineral species. Petrography descriptions of individual dykes are presented in Appendix 4.

5.4. DEMAGNETIZATION RESULTS

Demagnetization behaviour of the dykes was highly variable and not easy to interpret. Despite this, an attempt is made here to summarize the results in a meaningful way. Although some samples were only weakly magnetized (specifically the most altered ones like LDG and LDD), most samples yielded interpretable results. Each sample was generally characterized by two magnetic components, but never more than three. This apparently simple picture is complicated by the variation of these components (see Figure 5.3)

During low field strength AF and low temperature demagnetization steps, samples displayed one of the three possible components (within any specific dyke behavior was uniform, unless otherwise stated). These components are 1) “PF” components, northerly and upward directed components that are parallel to the Earth’s present dipole field (identified in LDI, LDE, LDB and LDC) always as first component to unblock, 2) “A1 +/-” components, westerly downward and easterly upward components (identified in LDH as the first component to unblock, and in LDB, it unblocked after PF components were removed, and 3) “A2 +/-” components generally poorly grouped shallow northerly or shallow southerly components (identified in LDJ and LDF as the first components to unblock, and in LDE as unblocking after PF components were removed) (Figure 5.3).

A1 +/- components and A2 +/- components were also identified at higher levels of demagnetization as being characteristic components in samples from dykes LDC and LDD (A1+) and dykes LDG and LDA (A2 +/-). In samples from LDC, A1+ components were revealed after PF components were removed, while in samples from LDD, A2- components had to be removed first. In samples from LDA and LDG, A2 +/- components were present as single components.

In addition to these high stability components, samples from dykes LDB, LDH, LDF, LDI and LDJ displayed east southeast downward components (LDB, LDF, LDI and LDJ) or south westerly upward directed components (LDH). The components from these dykes, LDB, LDF, LDI and LDJ, however, cluster into three general ways.
Components from dykes LDI and LDJ cluster east southeasterly and named “B” (Figure 5.3). The upward directed components from dyke LDH is named “C-“(Figure 5.3), while the north easterly downward directed components of dyke is named “C+”. Components from dyke LDF cluster easterly and are shallow downward, and are thus named “D”. The various components can be arranged according to relative stability (i.e. in order of unblocking). Such a sorting starting from least stable to most stable would look as follows: PF, A2+/-, A1+/-, (B, D and C-). B, D and C- components are grouped in brackets as they cannot be sorted according to relative stability. PF and A2+/ directions are probable magnetic overprints while A1+/-, B, C and D components may be primary.

Demagnetization results are summarized in Table 5.2. In the next section, the demagnetization results from each sampling site are described in detail. Dykes southeast of Lydenburg are generally better exposed and less altered than those to the northeast of Lydenburg, something that should be kept in mind during the interpretation of the data.

Table 5.2. Summary of the different magnetic components obtained from the Lydenburg dykes

<table>
<thead>
<tr>
<th>Component</th>
<th>Site</th>
<th>n/N</th>
<th>Present coordinates</th>
<th>Tilt-corrected coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF (low stability)</td>
<td>LDB</td>
<td>7/10</td>
<td>21.0 -31.8 19.91 8.69</td>
<td>28.6 -25.7 19.9 8.7</td>
</tr>
<tr>
<td>PF (low stability)</td>
<td>LDC</td>
<td>8/8</td>
<td>2.5 -57.8 17.28 9.83</td>
<td>27.7 -60.5 17.25 9.85</td>
</tr>
<tr>
<td>PF (low stability)</td>
<td>LDH</td>
<td>7/8</td>
<td>340.5 -45.2 14.33 16.02</td>
<td>355.6 -44.3 14.4 15.88</td>
</tr>
<tr>
<td>A1- (low stability)</td>
<td>LDH</td>
<td>6/6</td>
<td>119.1 -33.4 24.98 6.79</td>
<td>117.6 -18.7 25 6.78</td>
</tr>
<tr>
<td>A1+ (low stability)</td>
<td>LDB</td>
<td>10/10</td>
<td>275.6 37.9 12.4 14.53</td>
<td>274.9 23 12.4 14.52</td>
</tr>
<tr>
<td>A1+ (high stability)</td>
<td>LDC</td>
<td>8/8</td>
<td>284.9 24.1 4.5 136.32</td>
<td>285.6 9.4 4.46 136.01</td>
</tr>
<tr>
<td>A1+ (high stability)</td>
<td>LDD</td>
<td>3/11</td>
<td>232.4 62.8 27.75 13.87</td>
<td>254.7 55.5 27.73 13.88</td>
</tr>
<tr>
<td>A2- (low stability)</td>
<td>LDD</td>
<td>8/11</td>
<td>162.9 3.2 55.74 1.66</td>
<td>164.4 15 55.71 1.66</td>
</tr>
<tr>
<td>A2- (low stability)</td>
<td>LDF</td>
<td>4/6</td>
<td>133.6 -17.1 17.6 21.06</td>
<td>131.9 -5.3 17.62 21.11</td>
</tr>
<tr>
<td>A2- (low stability)</td>
<td>LDE</td>
<td>5/7</td>
<td>212.9 19.3 26.32 7.52</td>
<td>218.2 19.2 26.32 7.22</td>
</tr>
<tr>
<td>A2- (low stability)</td>
<td>LDJ</td>
<td>5/5</td>
<td>324.6 -0.7 30.09 5.93</td>
<td>325.6 -12.5 30.43 5.82</td>
</tr>
<tr>
<td>A2- (low stability)</td>
<td>LDK</td>
<td>5/5</td>
<td>94.3 -0.7 30.67 5.74</td>
<td>94.5 14 30.63 5.75</td>
</tr>
<tr>
<td>A2- (high stability)</td>
<td>LDA</td>
<td>8/8</td>
<td>198.6 -7.7 4.7 122.31</td>
<td>197.1 -4.5 4.69 122.8</td>
</tr>
<tr>
<td>A2+ (high stability)</td>
<td>LDD</td>
<td>3/9</td>
<td>358.8 37.4 22.90 20.03</td>
<td>20.1 64.8 22.93 19.97</td>
</tr>
<tr>
<td>B (high stability)</td>
<td>LDI</td>
<td>8/8</td>
<td>113.7 44.1 7.97 49.99</td>
<td>124.8 56 7.97 50.05</td>
</tr>
<tr>
<td>B (high stability)</td>
<td>LDJ</td>
<td>5/5</td>
<td>113.6 28.0 6.80 101.96</td>
<td>119.3 40.6 6.84 100.81</td>
</tr>
<tr>
<td>C+ (high stability)</td>
<td>LDB</td>
<td>10/10</td>
<td>101.2 72.4 9.95 22.08</td>
<td>149.3 85.7 9.95 22.08</td>
</tr>
<tr>
<td>C- (high stability)</td>
<td>LDH</td>
<td>6/6</td>
<td>248.4 -55.3 5.2 139.13</td>
<td>232.2 -67.6 5.2 139.44</td>
</tr>
<tr>
<td>D (high stability)</td>
<td>LDF</td>
<td>5/6</td>
<td>94.6 10.6 14.07 24.42</td>
<td>94.7 25.6 14.07 24.41</td>
</tr>
</tbody>
</table>
**Figure 5.3.** Summary of different site means obtained from the post-Transvaal dykes in Lydenburg area
5.4.1. Dykes southeast of Lydenburg

5.4.1.1. Site LDH

All samples collected at this site displayed two well-developed magnetic components. The first generally unblocked during AF pre-treatment and demagnetization temperature up to 250°C (Figure 5.4A), but persists in one sample (LDH 04) up to 450°C. These are upward and easterly oriented (A- Component: decl. = 119.1°, incl. = -33.4°, α95 = 24.98, k = 6.79, n = 6; stratigraphic correction: decl. = 117.6°, incl. = -18.7°, α95 = 25, k = 6.78, n = 6) (Figure 5.5). During higher temperature steps up to 565°C (Figure 5.4A), well-grouped high stability westerly and downward oriented components unblocked (C- Component: decl. = 248.4°, incl. = -55.3°, α95 = 5.20, k = 139.13, n = 6; stratigraphic correction: decl. = 232.2°, incl. = -67.6°, α95 = 5.19, k = 139.44, n = 6) (Figure 5.5).

5.4.1.2. Site LDB

At this site, oriented cores (ten in total) were collected from a fairly fresh dolerite. All samples displayed three well-developed magnetic components (Figure 5.4B). During AF pre-treatment and thermal demagnetization steps up to 250°C, northerly and upward oriented components unblocked in all samples (PF component: decl. = 21°, incl. = -31.8°, α95 = 19.91, k = 8.69, n = 7; stratigraphic correction: decl. = 28.6°, incl. = -25.7°, α95 = 19.90, k = 8.70, n = 7) (Figure 5.5). The second component was revealed between 250°C and 450°C of demagnetization temperatures, as well-grouped and stable westerly and downward oriented components (A1+ component: decl. = 275.6°, incl. = 37.9°, α95 = 12.40, k = 14.53, n = 10; stratigraphic correction: decl. = 274.9°, incl. = 23°, α95 = 12.40, k = 14.52, n = 10) (Figure 5.5). At higher temperature steps until demagnetization response becomes unstable (above 550°C), north easterly and downward oriented components unblocked in all samples as origin seeking straight demagnetization trajectories (C+ component: decl. = 103.2°, incl. = 72.4°, α95 = 9.95, k = 22.08, n = 10; stratigraphic correction: decl. = 149.3°, incl. = 85.7°, α95 = 9.95, k = 22.08, n = 10) (Figures 5.4B and 5.5).
Figure 5.4. Examples of demagnetization behaviour, in situ field coordinates, of some post-Transvaal dykes samples A: LDH, B: LDB, C: LDC, D: LDA. Open symbols = vertical; close symbols = horizontal. Open symbols = vertical plane, closed symbols = horizontal plane, NRM = natural remanent magnetization, mT = milli Tesla.
Figure 5.5. Equal area plots of results from sites LDH, LDB, LDC and LDA. The left-hand panel depicts relatively low-stability components in geographic and tilt-corrected coordinates, while the right-hand panel depicts the relatively high-stability components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.
5.4.1.3. Site LDC

Eight paleomagnetic samples were collected at this site. During AF pre-treatment, samples displayed poorly grouped northerly and upward oriented directions (PF component: decl. = 2.5°, incl. = -57.8°, $\alpha_{95} = 17.28$, $k = 9.83$, $n = 8$; stratigraphic correction: decl. = 27.7°, incl. = -60.5°, $\alpha_{95} = 17.25$, $k = 9.85$, $n = 8$) (Figure 5.5). Further thermal demagnetization up to 570°C revealed zero seeking straight line trajectories that defined a well-grouped shallowly downward pointing and westerly oriented cluster (A1+ component) at decl. = 284.8°, incl. = 24.1°, $\alpha_{95} = 4.45$, $k = 136.32$, $n = 8$; stratigraphic correction: decl. = 285.6°, incl. = 9.4°, $\alpha_{95} = 4.46$, $k = 136.01$, $n = 8$) (Figures 5.4C and 5.5).

5.4.1.4. Site LDA

At this site, eight paleomagnetic samples were collected from fresher core stones of a weathered dolerite. Sample behaviour during the demagnetization was consistent and one well-defined magnetic component was revealed. All samples demagnetize along straight line trajectories towards the origin and stable endpoints of demagnetization that are oriented southerly and upward (A2- component) (Figure 5.4D). The site mean calculated for the A2- component has a declination of 198.6°, an inclination of -7.7°, with $\alpha_{95} = 4.70$, $k = 122.31$, $n = 8$ (stratigraphic correction: decl. = 197.1°, incl. = -4.5°; $\alpha_{95} = 4.69$, $k = 122.80$, $n = 8$) (Figure 5.5).

5.4.2. Dykes northeast of Lydenburg

5.4.2.1. Site LDI

At this site, which exposes a weathered sill, eight paleomagnetic samples were collected from fresher core stones best judged to be in situ. During AF pre-treatment and thermal demagnetization up to 250-300°C (Figure 5.6A), well-grouped northerly and upward directed directions unblocked (PF: decl. = 340.5°, incl. = -45.2°, $\alpha_{95} = 14.33$, $k = 16.02$, $n = 7$; stratigraphic correction: decl. = 355.6°, incl. = -44.3°, $\alpha_{95} = 14.40$, $k = 15.88$, $n = 7$), together with other poorly defined and very scattered low stability components (Figure 5.7). At high
temperature demagnetization steps up to 560-570°C, all but one sample displayed a high stability component that was located south easterly and downward (Figure 5.7). Sample LDI 07 stands out from this cluster and was excluded in the calculation of the site mean (B component: decl. = 113.7°, incl. = 44.1°, α₉⁵ = 7.97, k = 49.99, n = 8; stratigraphic correction: decl. = 124.8°, incl. = 56°, α₉⁵ = 7.97, k = 50.05, n = 8)

5.4.2.2. Site LDJ

At this site, five oriented samples were drilled from fresher core stones of a weathered dolerite. During the AF pre-treatment, a low stability component is revealed in all samples as poorly constrained shallow northerly directions (A₂+? component: decl. = 324.6°, incl. = -0.7°, α₉⁵ = 30.09, k = 5.93, n = 5; stratigraphic correction: decl. = 325.6°, incl. = -12.5°, α₉⁵ = 30.43, k = 5.82, n = 5) (Figure 5.7). During thermal demagnetization up to 300-400°C, a second magnetic overprint (A₂-? component: decl. = 110.3°, incl. = -11.6°, α₉⁵ = 31.97, k = 10.62, n = 3; stratigraphic correction: decl. = 109.5°, incl. = 1.7°, α₉⁵ = 32.07, k = 10.56, n = 3) is recorded in samples 01, 03 and 04 as poorly grouped easterly and upward directions (Figure 5.7). Above 400°C, well-defined south easterly and downward directions (B component) unblocked as origin seeking linear trajectories in all samples (decl. = 113.1°, incl. = 28°, α₉⁵ = 6.80, k = 101.96, n = 5; stratigraphic correction: decl. = 119.3°, incl. = 40.6°, α₉⁵ = 6.84, k = 100.81, n = 5) (Figures 5.6C and 5.7).

5.4.2.3. Site LDG

A total of nine paleomagnetic samples were taken at this site. During the heating, most of these samples were completely demagnetized before 500°C (Figure 5.6B). Apart from incoherent low stability components revealed in some samples during the AF pre-treatment, all samples displayed poorly resolved northerly and downward directions. In samples LDG 04, 06 and 09 shallow stable end points of demagnetization were reached. In the remainder of samples, demagnetization behaviour is constrained by great circles generally towards the shallow northerly and downward cluster. The site mean calculated for samples 04, 06 and 09 has a
declination of 358.8°, inclination of 37.4°, $\alpha_{95} = 22.90$, $k = 20.03$, $n = 3$; stratigraphic correction: decl. = 20.1°, incl. = 64.8°, $\alpha_{95} = 22.93$, $k = 19.97$, $n = 3$) (Figure 5.7).

Figure 5.6. Examples of demagnetization behaviour, insitu field coordinates, of some post-Transvaal dykes samples A: LDI, B: LDG, and C: LDJ. Open symbols = vertical plane, closed symbols = horizontal plane, NRM = natural remanent magnetization, mT = milli Tesla.
**Figure 5.7.** Equal area plots of results from sites LDI, LDJ and LDG. The left-hand panel depicts low-temperature components in geographic and tilt-corrected coordinates, while the right-hand panel depicts the high-temperature components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits. Squares = pole to the plane of best-fit great circle arcs.
5.4.2.4. Site LDD

At this site, eleven paleomagnetic samples were drilled from fresher core stones of a weathered dyke. The samples are weakly magnetized and showed rather erratic behaviour at temperature steps below 500°C (Figure 5.8A). After the removal of extremely poorly grouped southerly and shallow low stability components during the AF pre-treatment, a westerly and downward oriented component was isolated from samples 02, 03 and 05 (Figure 5.8A). Samples 05, 06 and 10 displayed demagnetization along great circle arc paths towards a westerly downward direction without reaching stable end points. The A1+ component mean for this site has decl. = 232.4°, incl. = 62.8°, α95 = 27.75, k = 13.87, n = 3; stratigraphic correction: decl. = 254.7°, incl. = 55.5°, α95 = 27.73, k = 13.88, n = 3 (Figure 5.9).

5.4.2.5. Site LDE

At this site, eleven long paleomagnetic cores were drilled from a weathered dyke to ensure the freshness of the samples. Despite this precaution, the samples appeared to be weakly magnetized as they showed rather erratic behaviour at demagnetization temperature steps below 500°C (Figure 5.8B). However, two components could be identified. The first one consists of poorly grouped directions (PF) identified in samples 01 to 03 (Figure 5.9). The second component was revealed in samples 04 to 07 as poorly grouped shallow downward and southerly directions (A2-component: decl. = 212.9°, incl. = 19.3°, α95 = 26.32, k = 7.52, n = 5; stratigraphic correction: decl. = 218.3°, incl. = 19.2°, α95 = 26.32, k = 7.22, n = 5) (Figure 5.9).

5.4.2.6. Site LDF

Site LDF is a weathered dolerite. In order to ensure sample freshness, long oriented cores (six in total) were drilled. During AF pre-treatment and temperatures steps up to 250°C (Figure 5.8C), all samples with exception of LDF 04 and LDF 03 display low stability southerly and upward components (A2-component: decl. = 133.6°, incl. = -17.1°, α95 = 17.64, k = 21.06, n = 4; stratigraphic correction: decl. = 131.9°, incl. = -5.3°, α95 = 17.62, k = 21.11, n = 4) (Figure 5.8C). At demagnetization steps above 250°C, all samples with exception of LDF 01, display well
constrained, south easterly and shallow upward pointing directions (D Component : decl.: = 94.6°, incl. = 10.6°, $\alpha_{95} = 14.07$, $k = 24.42$, $n = 5$; stratigraphic correction: decl. = 94.7°, incl. = 25.6°, $\alpha_{95} = 14.07$, $k = 24.41$, $n = 5$) (Figure 5.9).

Figure 5.8. Examples of demagnetization behaviour, in situ field coordinates, of some post-Transvaal dykes samples A: LDD, B: LDE, and C: LDF. Open symbols = vertical plane, closed symbols = horizontal plane, NRM = natural remanent magnetization, mT = milli Tesla.
Figure 5.9. Equal area plots of results from sites LDD, LDE and LDF. The left-hand panel depicts low-temperature components including in geographic and tilt-corrected coordinates, while the right-hand panel depicts the high-temperature components in geographic and tilt-corrected coordinates. Open symbols indicate negative inclinations (upward directed components) and closed symbols are positive inclinations or downward directed components. Circles = direction obtained from best line fits.
5.4.3. Interpretation

In this section, paleomagnetic components obtained from individual dykes are interpreted. New pole positions (listed in Table 5.3) are established and compared to previously published poles from the KC (listed in Table 5.4). Interpretation of magnetic components is presented from the least stable to the most stable components.

5.4.3.1. PF component

PF components were revealed during AF pre-treatment and thermal demagnetization steps up to 350°C in dykes LDB, LDC, LDE and LDI. PF component means form a northerly upward clustering near parallel to the Earth’s present dipole field in South Africa. This component is interpreted as the product of recent weathering.

5.4.3.2. A2 +/- component

A2- directions were identified in dyke LDA as stable southerly and shallow directions and a site mean with $\alpha_{95} < 15^\circ$ could be calculated. This was not possible for any of the other A2 +/- remanence sites (LDD, E, F, G and J,) (see Table 5.2). A VGP for the A2- component from dyke LDA was calculated (Table 5.3). Because no field test could be completed, it is difficult to determine the relative age of the A2- component. The shallow southerly nature of the component does, however, bears resemblance to components assigned to the 1.1 Ga Umkondo LIP. The VGP calculated from the in situ site mean of dyke LDA (Table 5.3) also corresponds well with the pole from the 1.1 Ga Umkondo LIP of Gose et al. (2006) (Figure 5.10). The presence of Umkondo-like component in the sampling area would not be surprising given the extent of this LIP. Dyke LDA may thus be a member of the Umkondo LIP. However, it should be kept in mind that up to date, no Umkondo-related dyke has been recognized on KC. It is therefore difficult to draw any clear conclusion regarding the timing (primary magnetization or magnetic overprint) the 1.1 Ga remanence of dyke LDA.

Geochemistry of the dyke is presented in Section 5.5 and results are expected to provide additional constraints on the interpreted timing of the A2- remanence.
### Table 5.3. Summary of the virtual geomagnetic poles calculated from the different components identified in the Lydenburg dykes*

<table>
<thead>
<tr>
<th>Component</th>
<th>Site</th>
<th>n</th>
<th>Lat.(*N)</th>
<th>Long.(*E)</th>
<th>dp</th>
<th>dm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2-</td>
<td>LDA</td>
<td>8</td>
<td>55.8</td>
<td>65.0</td>
<td>2.4</td>
<td>4.7</td>
</tr>
<tr>
<td>A1+</td>
<td>LDB</td>
<td>10</td>
<td>4.1</td>
<td>142.1</td>
<td>8.6</td>
<td>14.6</td>
</tr>
<tr>
<td>A1+</td>
<td>LDC</td>
<td>8</td>
<td>-7.7</td>
<td>138.4</td>
<td>2.6</td>
<td>4.8</td>
</tr>
<tr>
<td>B</td>
<td>LDI</td>
<td>8</td>
<td>30.8</td>
<td>284.2</td>
<td>6.3</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>LDJ</td>
<td>5</td>
<td>27.3</td>
<td>296.1</td>
<td>4.1</td>
<td>7.4</td>
</tr>
<tr>
<td>C+</td>
<td>LDB</td>
<td>10</td>
<td>28.0</td>
<td>246.7</td>
<td>15.6</td>
<td>17.6</td>
</tr>
<tr>
<td>C-</td>
<td>LDH</td>
<td>6</td>
<td>1.2</td>
<td>79.5</td>
<td>5.3</td>
<td>7.4</td>
</tr>
<tr>
<td>D</td>
<td>LDF</td>
<td>5</td>
<td>6.4</td>
<td>297.6</td>
<td>7.2</td>
<td>14.3</td>
</tr>
</tbody>
</table>

*VGP’s calculated with $\alpha_{95}<15^\circ$

### Table 5.4. Selected published paleomagnetic and virtual geomagnetic poles for the KC

<table>
<thead>
<tr>
<th>Group/lithology</th>
<th>Label</th>
<th>Lat.(*N)</th>
<th>Long.(*E)</th>
<th>A95 (dp/dm)</th>
<th>Age (Ma)</th>
<th>References (for pole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ongeluk Lava</td>
<td>ONG</td>
<td>-0.5</td>
<td>100.7</td>
<td>5.3</td>
<td>2222±13 (Pb/Pb)</td>
<td>Evans et al. (2002)</td>
</tr>
<tr>
<td>Mamatwan ore (Component 1)</td>
<td>MAM-1</td>
<td>-8.2</td>
<td>111.1</td>
<td>5.6/11.1</td>
<td>~2200</td>
<td>Evans et al. (2001)</td>
</tr>
<tr>
<td>Dyke in the SE Archean Basement</td>
<td>NSA</td>
<td>5.9</td>
<td>93.4</td>
<td>12/20.4</td>
<td>~2150</td>
<td>Lubnina et al. (2010)</td>
</tr>
<tr>
<td>Basal Gamagara / Mapedi Formation</td>
<td>BGM</td>
<td>2.2</td>
<td>81.9</td>
<td>7.2/11.5</td>
<td>2060-2200</td>
<td>Evans et al. (2002)</td>
</tr>
<tr>
<td>Phalaborwa Complex</td>
<td>PBC</td>
<td>27.7</td>
<td>35.8</td>
<td>6.6</td>
<td>2060.6 ± 0.5 (U-Pb zircon and baddeleyite)</td>
<td>Letts et al. (2010)</td>
</tr>
<tr>
<td>Bushveld Complex (combined)</td>
<td>BVC</td>
<td>19.2</td>
<td>30.8</td>
<td>5.8</td>
<td>2057.7 ± 1.6 (U-Pb baddeleyite)</td>
<td>Letts et al. (2009)</td>
</tr>
<tr>
<td>Lower Waterberg Group</td>
<td>WUBS-I</td>
<td>36.5</td>
<td>51.3</td>
<td>10.9</td>
<td>2054 ± 3.5 (SHRIMP U-Pb zircon)</td>
<td>de Kock et al. (2006)</td>
</tr>
<tr>
<td>Vredefort Structure</td>
<td>VRED</td>
<td>22.8</td>
<td>41.6</td>
<td>10.5</td>
<td>2023.0 ± 4.0 (U-Pb single zircon)</td>
<td>Salminen et al. (2009)</td>
</tr>
<tr>
<td>upper Swaershoek Formation</td>
<td>WUBS-II</td>
<td>-10.5</td>
<td>330.4</td>
<td>9.8</td>
<td>2054-1930</td>
<td>de Kock et al. (2006)</td>
</tr>
<tr>
<td>Hartley Lava</td>
<td>HAR</td>
<td>12.5</td>
<td>332.8</td>
<td>18.6</td>
<td>1928 ± 4 (U-Pb zircon)</td>
<td>Evans et al. (2002)</td>
</tr>
<tr>
<td>NE trending dykes in the Archean Basement</td>
<td>BHD</td>
<td>9.4</td>
<td>352</td>
<td>4.3</td>
<td>~1900 (U/Pb baddeleyite)</td>
<td>Lubnina et al. (2010)</td>
</tr>
<tr>
<td>Sand river Dykes</td>
<td>SRD</td>
<td>2.3</td>
<td>9.1</td>
<td>10.3</td>
<td>1876 ± 68 (Rb/Sr)</td>
<td>recalculated by Evans et al. (2002)</td>
</tr>
<tr>
<td>Post-Wateberg intrusions</td>
<td>WSD</td>
<td>15.6</td>
<td>17.1</td>
<td>8.9</td>
<td>1874.6 ± 3.9 (U-Pb baddeleyite)</td>
<td>Hanson et al. (2004)</td>
</tr>
<tr>
<td>Post-Bushveld dykes</td>
<td>PBD</td>
<td>12.6</td>
<td>24.1</td>
<td>10.8</td>
<td>1649 ± 10 (20Ar/39Ar)</td>
<td>Letts et al. (2005)</td>
</tr>
<tr>
<td>Umkondo Intrusions</td>
<td>UMK</td>
<td>64</td>
<td>38.8</td>
<td>3.7</td>
<td>~1100</td>
<td>Gose et al. (2006)</td>
</tr>
<tr>
<td>Lesotho Lavas</td>
<td>LS</td>
<td>-74.4</td>
<td>92.8</td>
<td>4.5</td>
<td>180 ± 4</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Dolerite dykes</td>
<td>DD</td>
<td>-68.3</td>
<td>93.7</td>
<td>7</td>
<td></td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Hooper sills</td>
<td>TRA</td>
<td>-64.8</td>
<td>97.9</td>
<td>8.9</td>
<td></td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Mashikini and Letaba</td>
<td>MAL</td>
<td>-69</td>
<td>99.2</td>
<td>6.8</td>
<td>182</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Mbuluzi, Swaziland</td>
<td>MB</td>
<td>-45.6</td>
<td>98.6</td>
<td>10.2</td>
<td></td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Rooirand dykes</td>
<td>RO</td>
<td>-77.3</td>
<td>116</td>
<td>18.8</td>
<td>200.8 ± 4.5</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Jozini, Natal</td>
<td>JR</td>
<td>-70.7</td>
<td>111.2</td>
<td>10.5</td>
<td>178</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Keetmanshoop sills</td>
<td>KEE</td>
<td>-69.8</td>
<td>96.2</td>
<td>18.1</td>
<td></td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Hardap basaltks (Kalkrand)</td>
<td>HAR</td>
<td>-73.1</td>
<td>17.7</td>
<td>4.1</td>
<td></td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Bumberi Complex</td>
<td>BU</td>
<td>-30.2</td>
<td>105.9</td>
<td>8.1</td>
<td>145.8 ± 1.3</td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Cape Peninsula dolerites</td>
<td>CP</td>
<td>-42.2</td>
<td>105.2</td>
<td>9.1</td>
<td></td>
<td>Hargraves et al. (1997)</td>
</tr>
<tr>
<td>Swartruggens kimberlites</td>
<td></td>
<td>32</td>
<td>104</td>
<td>6.7</td>
<td>142 ± 4</td>
<td>Hargraves et al. (1989)</td>
</tr>
</tbody>
</table>
5.4.3.3. A1+- component

A1+ component was revealed in dykes LDB, LDC and LDD as westerly and downward oriented directions either as low stability components (LDB) or high stability components (LDC and LDD). Near antipodal components (A1-) were revealed as low stability components from dyke LDH. No field tests could be done to constrain the timing of this magnetization. Thus it is unknown whether the A1+/- component is of primary nature or represents a magnetic overprint. However, the fact that it is developed as non-characteristic remanence in some dykes (LDH and LDB) may indicate that it is related to a remagnetization event.

A comparison to existing poles from the KC reveals that the VGP’s calculated from the A1+ components of dykes LDB and LDC share similarities with poles from 1.9 Ga aged units such as the pole from the 2054-1930 Ma upper Swaershoek Formation (de Kock et al., 2006), the pole from the 1928 Ma Hartley Lavas (Evans et al., 2002) and in a lesser extent the pole from the 1.9
Ga dykes that intrude the Archean Basement in the eastern KC (Lubnina et al., 2010), see Figure 5.11.

In Section 5.5, geochemical results of dykes LDC and LDD are presented. This may help to refine the interpreted timing of the A1+ component.

**Figure 5.11.** Comparisons of the A1+ components VGP’s of dykes LDB and LDC with selected existing poles for the KC. All poles are plotted with their 95% error limits as per their $A_{95}$ or as $dp$ and $dm$ values (listed in Tables 5.3 and 5.4).

### 5.4.3.4. Exclusively characteristic components (B, C+/- and D)

Components B, C+/- and D were identified in dykes LDI and LDJ (B components), dyke LDH (C-), dyke (LDB (C+) and dykes LDF (D) as characteristic remanent magnetizations. Unlike the PF, A1+- and A2+- components, they are not identified as low stability components in any of the samples. Unfortunately, no field tests could be done to evaluate the timing of these components. Instead, VGP’s were calculated for each of the dykes and these were compared to existing pole positions from the KC, see Figure 5.12.

The VGP’s recalculated from B components share similarities with the Late Jurassic poles of the KC (Figure 5.12), as was already illustrated for similar components identified in post-Transvaal
Supergroup sills (Chapters 2 and 3). These VGP’s also, however, do not plot very far removed from the ~2.2 Ga paleopoles of the KC (Figure 5.12).

Components C+/− VGP’s plot close to the ~2.2 Ga poles, with the C- VGP sharing significant overlap with the pole from the Basal Gamagara/Mapedi Formation of Evans et al. (2002) (Figure 5.12). The C+ pole plots more distinct and may in fact shares most similarities with the VGP’s from dykes LDI and LDJ and the Late Jurassic poles of the KC (Figure 5.12). It is important to note that dyke LDH was found to be the least altered of all the dykes sampled and if any of the dykes are likely to record a primary magnetization, this would be it.

The VGP for component D also shares significant similarities with the ~2.2 Ga paleopoles of the KC, in particular with the MAM-1 (Mamatwan ore component 1) pole of Evans et al. (2001) (Figure 5.12).

Geochemical results of samples LDB and LDF are reported in Section 5.5. This may help to better constrain the timing of C+ and D magnetizations.

Figure 5.12. Comparisons of the B, C+/− and D components VGP’s of dykes LDB, LDF, LDH, LDI and LDJ with selected existing poles for the KC. All poles are plotted with their 95% error limits as per their $A_{05}$ or as dp and dm values (listed in Tables 5.3 and 5.4).
5.5. GEOCHEMISTRY

5.5.1. Method

Seven dyke samples (LDA, B, C, D, E, F, and G) were sent to Canada for geochemical analyses. Results are summarized in Table 5.5 and described in this section. Major and trace element contents were determined by X-ray fluorescent spectrometry at ACME Labs, Canada, on glass beads prepared from powdered whole-rock samples with a sample-to-flux (lithium tetra borate) ratio of 1:10. Volatiles were determined by loss on ignition. Trace and rare earth element (REEs) were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) also at ACME Labs.

5.5.2. Weathering and alteration

The degree of alteration of rocks can be recognized by studying hand samples and thin sections. Individual dykes sampled for this study were variably altered. Samples were taken from least weathered sections of outcrops. However, thin sections generally revealed alteration features characterized by obliterated igneous textures, with pyroxenes being altered and plagioclases being variably saussuritized.

Loss of ignition (LOI) content of rocks can also be taken as a proxy for recognizing alteration as high LOI content generally corresponds to more altered rocks. The sampled dykes have relatively high LOI values that vary between 1.5 and 6.3 (Table 5.5). For comparison, the LOI values of sills studied in the eastern KC (subject of Chapter 2) ranged between 0.4-2.4. This may signify that alteration has affected the chemistry of the sampled dykes.

The intensity and mode of alteration of the rock can also be evaluated by using the alteration box plot of Large et al. (2001). In this diagram, samples LDB (C+ remanence) and LDC (A+ remanence) fall in the area of strong hydrothermal chlorite-pyrite-(sericite) alteration (Figure 5.13). These samples are thus believed to be significantly affected by alteration.
## Table 5.5. Geochemical results of the dyke samples (7 sites)

<table>
<thead>
<tr>
<th>element</th>
<th>LDA</th>
<th>LDB</th>
<th>LDC</th>
<th>LDD</th>
<th>LDE</th>
<th>LDF</th>
<th>LDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2 (%)</td>
<td>51.58</td>
<td>48.56</td>
<td>47.08</td>
<td>53.2</td>
<td>53.44</td>
<td>52.45</td>
<td>53.84</td>
</tr>
<tr>
<td>AI2O3</td>
<td>14.97</td>
<td>7.57</td>
<td>8.21</td>
<td>14.57</td>
<td>13.72</td>
<td>15.01</td>
<td>9.08</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>8.88</td>
<td>10.3</td>
<td>10.61</td>
<td>8.83</td>
<td>9.76</td>
<td>9.19</td>
<td>12.61</td>
</tr>
<tr>
<td>MgO</td>
<td>7.79</td>
<td>20.58</td>
<td>20.61</td>
<td>7.14</td>
<td>8.45</td>
<td>6.73</td>
<td>9.68</td>
</tr>
<tr>
<td>CaO</td>
<td>9.56</td>
<td>5.58</td>
<td>5.5</td>
<td>7.19</td>
<td>7.06</td>
<td>8.35</td>
<td>9.14</td>
</tr>
<tr>
<td>Na2O</td>
<td>1.68</td>
<td>0.12</td>
<td>0.13</td>
<td>4.05</td>
<td>3.02</td>
<td>3.82</td>
<td>1.42</td>
</tr>
<tr>
<td>K2O</td>
<td>1.56</td>
<td>0.02</td>
<td>0.05</td>
<td>0.93</td>
<td>0.47</td>
<td>0.45</td>
<td>1.04</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.65</td>
<td>0.29</td>
<td>0.31</td>
<td>0.66</td>
<td>0.75</td>
<td>0.71</td>
<td>0.91</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
<td>0.07</td>
<td>0.08</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>MnO</td>
<td>0.14</td>
<td>0.14</td>
<td>0.16</td>
<td>0.15</td>
<td>0.18</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>Cr2O3</td>
<td>0.058</td>
<td>0.495</td>
<td>0.478</td>
<td>0.056</td>
<td>0.077</td>
<td>0.05</td>
<td>0.145</td>
</tr>
<tr>
<td>Ni (ppm)</td>
<td>120</td>
<td>85</td>
<td>879</td>
<td>93</td>
<td>111</td>
<td>96</td>
<td>202</td>
</tr>
<tr>
<td>Sc (ppm)</td>
<td>34</td>
<td>22</td>
<td>22</td>
<td>35</td>
<td>38</td>
<td>36</td>
<td>27</td>
</tr>
<tr>
<td>LOI</td>
<td>2.8</td>
<td>5.8</td>
<td>6.3</td>
<td>2.9</td>
<td>2.7</td>
<td>2.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Ba (ppm)</td>
<td>461</td>
<td>7</td>
<td>21</td>
<td>916</td>
<td>553</td>
<td>289</td>
<td>324</td>
</tr>
<tr>
<td>Be</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>Co</td>
<td>32.4</td>
<td>89.1</td>
<td>87.4</td>
<td>28.7</td>
<td>26.1</td>
<td>38</td>
<td>63.6</td>
</tr>
<tr>
<td>Cs</td>
<td>1.2</td>
<td>0.3</td>
<td>0.9</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>Ga</td>
<td>15.1</td>
<td>7.7</td>
<td>8.2</td>
<td>13.7</td>
<td>14.3</td>
<td>15.4</td>
<td>13.8</td>
</tr>
<tr>
<td>Hf</td>
<td>1.9</td>
<td>1.1</td>
<td>1.1</td>
<td>2.1</td>
<td>2.2</td>
<td>1.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Nb</td>
<td>4.4</td>
<td>2.1</td>
<td>2.1</td>
<td>4.6</td>
<td>5</td>
<td>4.6</td>
<td>8.4</td>
</tr>
<tr>
<td>Rb</td>
<td>48.8</td>
<td>0.7</td>
<td>3.7</td>
<td>23.9</td>
<td>13.1</td>
<td>11.6</td>
<td>38.7</td>
</tr>
<tr>
<td>Sn</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>2</td>
<td>3</td>
<td>&lt;1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Sr</td>
<td>118</td>
<td>33.6</td>
<td>33.6</td>
<td>116</td>
<td>184.1</td>
<td>100.8</td>
<td>124.4</td>
</tr>
<tr>
<td>Ta</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Th</td>
<td>3.5</td>
<td>1.8</td>
<td>2.2</td>
<td>3.5</td>
<td>4.3</td>
<td>3.6</td>
<td>6.7</td>
</tr>
<tr>
<td>U</td>
<td>0.9</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1.2</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>V</td>
<td>233</td>
<td>135</td>
<td>147</td>
<td>246</td>
<td>268</td>
<td>251</td>
<td>221</td>
</tr>
<tr>
<td>W</td>
<td>0.7</td>
<td>&lt;0.5</td>
<td>0.5</td>
<td>1</td>
<td>1.1</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Zr</td>
<td>68.6</td>
<td>45.7</td>
<td>42.9</td>
<td>70.3</td>
<td>81.2</td>
<td>70.2</td>
<td>121.4</td>
</tr>
<tr>
<td>Y</td>
<td>19.1</td>
<td>8</td>
<td>7.1</td>
<td>18.1</td>
<td>22.8</td>
<td>23.6</td>
<td>23.3</td>
</tr>
<tr>
<td>La</td>
<td>10.1</td>
<td>7.6</td>
<td>6.9</td>
<td>10.1</td>
<td>14</td>
<td>15.2</td>
<td>20.6</td>
</tr>
<tr>
<td>Ce</td>
<td>19</td>
<td>13.2</td>
<td>11.2</td>
<td>15.9</td>
<td>23.8</td>
<td>15.4</td>
<td>42.8</td>
</tr>
<tr>
<td>Pr</td>
<td>2.5</td>
<td>1.68</td>
<td>1.4</td>
<td>2.52</td>
<td>3.16</td>
<td>3.48</td>
<td>4.85</td>
</tr>
<tr>
<td>Nd</td>
<td>10</td>
<td>6.9</td>
<td>5.3</td>
<td>9.5</td>
<td>12.6</td>
<td>14.1</td>
<td>18.9</td>
</tr>
<tr>
<td>Sm</td>
<td>2.42</td>
<td>1.48</td>
<td>1.14</td>
<td>2.3</td>
<td>2.86</td>
<td>3.14</td>
<td>4.15</td>
</tr>
<tr>
<td>Eu</td>
<td>0.76</td>
<td>0.36</td>
<td>0.35</td>
<td>0.75</td>
<td>0.84</td>
<td>1.01</td>
<td>1.11</td>
</tr>
<tr>
<td>Gd</td>
<td>2.8</td>
<td>1.48</td>
<td>1.16</td>
<td>2.8</td>
<td>3.49</td>
<td>3.71</td>
<td>4.23</td>
</tr>
<tr>
<td>Tb</td>
<td>0.51</td>
<td>0.23</td>
<td>0.2</td>
<td>0.5</td>
<td>0.61</td>
<td>0.66</td>
<td>0.73</td>
</tr>
<tr>
<td>Dy</td>
<td>3.08</td>
<td>1.29</td>
<td>1.23</td>
<td>2.97</td>
<td>3.61</td>
<td>3.87</td>
<td>4.05</td>
</tr>
<tr>
<td>Ho</td>
<td>0.66</td>
<td>0.27</td>
<td>0.25</td>
<td>0.63</td>
<td>0.78</td>
<td>0.8</td>
<td>0.78</td>
</tr>
<tr>
<td>Er</td>
<td>1.93</td>
<td>0.81</td>
<td>0.82</td>
<td>1.87</td>
<td>2.15</td>
<td>2.46</td>
<td>2.24</td>
</tr>
<tr>
<td>Tm</td>
<td>0.29</td>
<td>0.11</td>
<td>0.11</td>
<td>0.27</td>
<td>0.32</td>
<td>0.35</td>
<td>0.33</td>
</tr>
<tr>
<td>Yb</td>
<td>1.73</td>
<td>0.75</td>
<td>0.76</td>
<td>1.74</td>
<td>1.94</td>
<td>2.27</td>
<td>2.12</td>
</tr>
<tr>
<td>Lu</td>
<td>0.27</td>
<td>0.11</td>
<td>0.12</td>
<td>0.26</td>
<td>0.31</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td>Mo</td>
<td>3.1</td>
<td>1.2</td>
<td>1.3</td>
<td>3.7</td>
<td>3.8</td>
<td>2.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Cu</td>
<td>73.7</td>
<td>58.1</td>
<td>38.5</td>
<td>63.2</td>
<td>57.3</td>
<td>101</td>
<td>112.7</td>
</tr>
<tr>
<td>Pb</td>
<td>2.8</td>
<td>0.6</td>
<td>3.2</td>
<td>1.5</td>
<td>1.8</td>
<td>1.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Zn</td>
<td>29</td>
<td>39</td>
<td>40</td>
<td>28</td>
<td>43</td>
<td>24</td>
<td>28</td>
</tr>
<tr>
<td>Ni</td>
<td>64.4</td>
<td>465.8</td>
<td>530.7</td>
<td>63.7</td>
<td>85.6</td>
<td>77.2</td>
<td>102.5</td>
</tr>
<tr>
<td>As</td>
<td>11.2</td>
<td>11</td>
<td>13.8</td>
<td>16.6</td>
<td>46.7</td>
<td>14.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Cd</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Sb</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>&lt;0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Bi</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Ag</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Au</td>
<td>&lt;0.5</td>
<td>0.7</td>
<td>0.5</td>
<td>0.7</td>
<td>0.5</td>
<td>0.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Hg</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Tl</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Se</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>
Figure 5.13. Post-Transvaal dyke samples, from the present study, in the alteration box plot of Large et al. (2001).

Samples LDB and LDC also have the highest LOI values. Sample LDG (A2+ remanence) also plots as hydrothermally altered but relatively removed from LDB and LDC (Figure 5.13). The remaining samples LDA (A2- remanence), LDD (A1+ magnetization), LDE (A2-magnetization), and LDF (D remanence) generally fall in the upper area of the least altered box (i.e., close to the boundary with the altered area) (Figure 5.13). These three dykes are therefore considered as less altered, relative to samples LDB, LDC, and LDG, which are excluded from the remaining discussion.

5.5.3. Major element geochemistry

The sampled dykes generally display relative differences in terms of major element contents (see Table 5.5). SiO$_2$ varies between ~ 51.5 and ~ 53.4 wt %. Samples LDD and LDE are richer in SiO$_2$ (53.4 wt %). In terms of MgO, sample LDE is the most enriched. For the remainder, MgO content ranges between 6.73 wt % and 7.79 wt %. The samples generally display a relative enrichment in alkalis (Na$_2$O and K$_2$O) (>2 wt). The studied dykes also display some separation in terms of TiO$_2$ contents, which range between 0.65 and 0.75 wt % (Table 5.5). These differences may indicate the existence of different intrusion events. In terms of Mg# (= Mg$^{2+}$/Mg$^{2+}$ + Fe$^{2+}$),
the samples show a range of values between ~ 60 and ~ 64 (Table 5.5). This suggests that none of the dykes is entirely primitive. All samples, with exception of LDA display CaO and Na$_2$O values that decrease with increasing of MgO content and total FeO. In contrast, there is no clear correlation for K$_2$O, P$_2$O$_5$, and MnO.

### 5.5.4. Magma types

In the total alkali, FeO and MgO (AFM) ternary system of Irvine and Baranger (1971), the samples fall in the calco-alkaline field (Figure 5.14A). Following the IUGS total alkalis versus silica (TAS) system (Le Bas et al., 1986), all but one sample were classified as basaltic andesite (Figure 5.14B). Dyke LDA plotted as basaltic.

![Discrimination diagrams for major elements showing the behaviour of the dyke samples. A: AFM diagram (Irvine and Baragar, 1971). B: bivariate diagram of total alkali vs. silica (Le Bas et al., 1986)](image)

**Figure 5.14.** Discrimination diagrams for major elements showing the behaviour of the dyke samples. A: AFM diagram (Irvine and Baragar, 1971). B: bivariate diagram of total alkali vs. silica (Le Bas et al., 1986)

### 5.5.5. Trace elements (Co, Ni, Sc, Cu, Zn and V)

The composition of studied dykes varies in terms of trace elements. Samples show a general positive correlation between Co and Ni and MgO. This trend can be explained by the compatible character of these three trace elements during fractional crystallization, which allows them to be preferentially incorporated in the formation of MgO-rich early minerals such as pyroxene. On the
other hand, there is a negative correlation between Sc, Cu, Zn, and Vn and MgO content. In fractionation process, Co and Ni are known to be incompatible elements, which tend to concentrate in residuals liquids.

5.5.6. Rare earth elements

REE geochemistry of sampled dykes are displayed on a chondrite-normalized plot (McDonough and Sun, 1995) (Figure 5.15A). All samples exhibit REE enriched levels relative to chondrite values. Samples LDA, LDD, LDE, and LDF are enriched up to ~90 times chondritic values. All samples generally display steep light rare earth element (LREE) and medium rare earth element (MREE) patterns (Figure 5.15A). (Table 5.6 summarizes important REE ratios and characteristics). The heavy rare earth element HREE curves are generally flat for all samples with Er/Lu varying from ~1.05 to ~1.18 (see Table 5.5). All samples exhibit a negative Ce anomaly, with LDD and LDF having the most pronounced anomalies (Figure 5.15A). A Eu anomaly (Eu/Eu* = ~0.24 - ~0.30; with Eu* = (Sm x Gd)^1/2) is also observed in all samples. Samples LDA and LDF display most significant Eu anomalies.

5.5.7. Multi-elements plots (spidergrams)

All dykes are enriched in trace elements by several orders of magnitude relative to primitive mantle values (McDonough and Sun, 1995) (Figure 5.15B). Samples LDA, LDD, LDE, and LDF generally plot at similar levels of enrichment (Figure 5.15B). Although the profiles generally differ from one another, some similarities can be observed. Samples LDA (A2- remanence) display a steep profile with pronounced negative Ta, Nb, Ce, Pr, and Sr, and positive K, Pb and Nd anomalies (Figure 5.15B). Slight negative Zr, Sm, Eu and positive Ti anomalies are also present. Multi-element plots of samples LDD, LDE and LDF are characterized by positive Ba and K spikes (Figure 5.15B). These samples are also similar in terms of Nb, Ce, Sr, Zr, and Eu. But samples LDD, LDE and LDF generally differ in terms of HREEs (Figure 5.15B).
Figure 5.15. Trace elements behaviour of studied Lydenburg dykes. A Chondrite-normalized (McDonough and Sun, 1995) REE profiles. B: Pyrolite-normalized (McDonough and Sun, 1995) multi-elements (spider) patterns.

Table 5.6. Summary of major and trace elements characteristics of the studied post-Transvaal dykes in the eastern KC

<table>
<thead>
<tr>
<th>Site</th>
<th>Major elements</th>
<th>AFM diagram</th>
<th>SiO2 Vs Alkalis</th>
<th>Rare earth elements (REE)</th>
<th>Trace elements</th>
<th>Multi-elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg#</td>
<td></td>
<td></td>
<td>La/Sm</td>
<td>Gd/Er</td>
<td>Er/Lu</td>
</tr>
<tr>
<td>LDA</td>
<td>64.25 calco-alkaline</td>
<td>basalt</td>
<td></td>
<td>2.6</td>
<td>1.16</td>
<td>1.09</td>
</tr>
<tr>
<td>LDD</td>
<td>62.52 calco-alkaline</td>
<td>basaltic andesite</td>
<td>2.74</td>
<td>1.2</td>
<td>1.1</td>
<td>1.31</td>
</tr>
<tr>
<td>LDE</td>
<td>63.94 calco-alkaline</td>
<td>basaltic andesite</td>
<td>3.05</td>
<td>1.3</td>
<td>1.06</td>
<td>1.34</td>
</tr>
<tr>
<td>LDF</td>
<td>60.08 calco-alkaline</td>
<td>basaltic andesite</td>
<td>3.02</td>
<td>1.21</td>
<td>1.18</td>
<td>1.4</td>
</tr>
</tbody>
</table>

5.5.8. Correlation to strata-bound igneous suites

In Figures 5.16A-N, geochemical signatures of dykes LDA, LDD, LDE and LDF are compared to results from some well-documented Paleoproterozoic and younger igneous events in the KC, (i.e., the Hekpoort Lavas, the Machadodorp Member, the Dullstroom Lavas, the sills and marginal rocks of the basal contact of the eastern Bushveld Complex, the ~1.9 Ga post-Waterberg intrusions and Black Hills dykes, the ~1.1 Ga Umkondo LIP, and the 180 Ma Karoo LIP). Detailed on these correlations are given in Appendix 4, while a general summary is presented here.

It can be observed that the samples do not generally resemble the younger igneous units on KC (i.e. 1.1 Ga Umkondo sills (Bullen et al., 2012) and the 180 Ma Karoo dolerites (Jourdan et al., 2007)) (Figures 5.16A-D). A comparison of dykes LDA, LDD, LDE and LDF to the ~1.9 Ga
post-Waterberg intrusions and the Black Hills dykes (Hanson et al., 2004; Klausen et al., 2010) as well as the different groups (B1, B2 and B3) of the Bushveld marginal rocks (Barnes et al., 2010) can also be done without observing much overlap (see Figures 5.16E-H).
There is a poor match between dykes LDA, LDD, LDE and LDF and the >2.05 Ga Machadodorp Member (Crow and Condie, 1990) (see Figures 5.16K and L). Partial overlap can be observed (e.g. similar Tb/Lu, negative Nb, La, Ce, Sr kinks) when comparing the geochemical signatures of the dyke samples (this study) to the ~2.2 Ga Hekpoort Lavas (Crow and Condie, 1990) (see...
Figures 5.16I and J). More consistent similarities are found between the samples from Lydenburg dykes and the Dullstroom Lavas (Crow and Condie, 1990), in terms of major elements (basaltic andesite), rare earth elements profiles (similar levels of enrichment, similar La/Sm and Tb/Lu ratios), and multi-elements plots (near identical shape and level of enrichment) (see Figures 5.16M and N).

Figure 5.16. Comparisons of trace elements geochemistry of studied dykes with previously published results from Paleopreterozoic and younger units on KC. A, C, E, G, I, K, and M: REE plots normalized to chondrite (McDonough and Sun, 1995). B, D, F, H, J, L, and N: Multi-element plots (spidergram) normalized to pyrolite(McDonough and Sun, 1995)
5.5.9. Summary

Major element geochemistry of dykes LDA, LDD, LDE, and LDF sampled from the north-northeast-trending swarm that intrudes the Pretoria Group near Lydenburg (Mpumalanga Province) generally indicate a basaltic andesite composition with a calco-alkaline affinity. Spidergrams of the samples display consistent negative Nb and Ta anomalies which are very common in mafic rocks on the KC. Comparisons of studied dykes with existing geochemical results from the KC generally do not display clear correlations. This can be ascribed to the relative similarities of the geochemical signatures of mafic igneous rocks on KC and the altered character of the dykes. However, some similarities were identified between samples LDA, LDD, LDE, and LDF and the Dullstroom Lavas.

5.6. RECONCILIATION OF DATA AND DISCUSSION

In this section, paleomagnetic data obtained from studied dykes are interpreted in the light of the geochemical results obtained from sites LDA, LDD, LDE and LDF.

5.6.1. A2- Component

The A2- component was identified as low stability (LDE) and relatively high stability (LDA) components. This remanence shares similarities to the magnetization of the 1.1 Ga Umkondo magmatic units. Geochemical results obtained from samples LDA and LDE did not convincingly correlate with the 1.1 Ga old units, but rather displayed similarities with the Dullstroom Lavas. This is taken as support for the overprint nature of the A2- remanence in dykes LDA and LDE. This magnetization is believed to have totally overprinted the primary magnetization of these dykes.

5.6.2. A1+ component

The A1+ component was identified as high stability components in dyke LDD. This magnetization was interpreted to be of a ~1.9 Ga age. Geochemical results once again do not
support this age assignment for dyke LDD and the A1+ component is interpreted to represent a magnetic overprint.

5.6.3. **B Component**

B characteristic components were found at high temperature demagnetization steps in dykes LDI and LDJ. These magnetizations and the corresponding VGP’s were found to best resemble the Late Jurassic poles reported from the KC (Hargraves et al., 1997). No geochemical analyses were undertaken for dykes LDI and LDJ. Most other dykes, however, displayed consistent similarities with the Dullstroom Lavas. This may suggest that the B remanence might be primary (i.e. ~2.2 Ga old). More likely, however, it represents a Late Jurassic magnetic overprint.

5.6.4. **C+/- Component**

The C+/- characteristic magnetization was identified in dykes LDB and LDH. Dyke LDB turned out to be highly altered, while no geochemical data is available for LDH. The C+ components from dyke LDB translated into a VGP position that was not very different from B components VGP’s. Given the altered nature of this dyke, the C+ remanence is also interpreted to represent a Late Jurassic magnetic overprint. Dyke LDH on the other hand was unaltered (as attested by petrography), and the C- components identified within the samples from this dyke gave a VGP that was very similar to the ~2.2 Ga paleopoles of the KC. The C- component is most likely to represent the primary magnetization of the Lydenburg dykes. However, this assignment should be regarded as preliminary at this stage and requires future testing. A more detailed integrated study (paleomagnetism, geochemistry, and U-Pb geochronology) of Lydenburg dykes is needed.

5.6.5. **D component**

The D component was identified only in dyke LDF, of which the geochemistry suggests a possible relationship to the Dullstroom Lavas. The calculated VGP shares similarities with the
~2.2 Ga paleopoles of the KC. The D remanence may thus represent a primary magnetization possibly related to the C- remanence.

5.7. CONCLUSION

Paleomagnetic results from dykes that form a north-northeast-trending dyke swarm near Lydenburg (eastern KC) reveal a complicated magnetic history with several magnetic components that can be interpreted as magnetic overprints (PF, A1+/-, A2+/-, B and C+) and two components that may be primary (C- and D). Geochemical signatures of these dykes were generally of limited quality because of high degrees of alteration of samples. However, the chemistry of fresher material was generally similar to the pre-RLS Dullstroom Lavas. The VGP’s of the C- and D components shared similarities with the ~2.2 Ga paleopoles of the KC, but such an age assignment to the Lydenburg dykes requires further exploration in the future.

5.8. BIBLIOGRAPHIC REFERENCES


Evans, D.A.D., Beukes, N.J. and Kirschvink, J.L., 2002. Paleomagnetism of a lateritic paleoweathering horizon and overlying Paleoproterozoic red beds from South Africa: implications for the Kaapvaal apparent polar wander path and a confirmation of


Olsson, J.R., Söderlund, U., Klausen, M.B. and Ernst, R.E., 2010. U-Pb baddeleyite ages linking major Archean dyke swarms to volcanic-rift forming events in the Kaapvaal craton (South Africa), and a precise age for the Bushveld Complex. Precambrian Research, (Special Issue), 183: 490-500.


CHAPTER 6
CONCLUDING REMARKS - IMPLICATIONS OF RESULTS

This study aimed to evaluate the APWP of the KC during the Paleoproterozoic. Bushveld LIP-related units were paleomagnetically studied. In this chapter, the results obtained are summarized and their implications in the understanding of the magnetic history, timing and duration of the RLS are examined. This is done in the context of the Bushveld LIP model recently proposed. Newly obtained pole positions are used in conjunction with the existing ones to define a new APWP for the Paleoproterozoic KC with some striking features.

6.1. INTRODUCTION

The main objective of this study was to evaluate the APWP of the KC during the Paleoproterozoic (i.e. 2500 Ma to 1600 Ma). Sill complexes east and west of the Bushveld Complex, post-Transvaal dykes near Lydenburg, and the Uitkomst Complex at the Nkomati Mine were paleomagnetically studied. The results, which are summarized below, allowed deciphering the timing of emplacement of these mafic units and establishment of new paleopoles for the Paleoproterozoic KC (see Table 6.1 below). In this chapter, implications of results in the understanding of the chronology of formation, and the magnetic history of the RLS are examined. The significance of the timing of emplacement of the studied units in the context of the Bushveld LIP described by Rajesh et al. (2013) is also addressed. Finally, the paleomagnetic database for the Paleoproterozoic KC (including data generated in the present study) is used to propose a new APWP for this craton.

6.2. SUMMARY OF RESULTS

Study of sill complexes east and west of the Bushveld Complex yielded data of excellent quality. Two sills to the east of the KC were U-Pb dated to give the ages of 2058.4 ± 1.3 Ma and 2058.1 ± 6 Ma which constitute the first precise numerical ages ever obtained from post-Transvaal sills. Together with these new ages, geochemical data and three distinct primary magnetic components
were obtained from the sills. This dataset allowed the establishment of new paleopoles. A sill class older than the RLS and the tilting of the sediments of Pretoria Group, and a sill class that postdates the emplacement of the RLS and the tilting of strata could be distinguished. There was also a sill class that was emplaced about the same time as the RLS.

Southeast of the eastern post-Transvaal sills, the 2044 Ma Uitkomst Complex was investigated at the Nkomati Mine to provide the first paleomagnetic dataset for this complex. The obtained results were of good quality and allowed for the identification of a magnetic remanence from the complex and a crosscutting north-northeast-trending dyke. This timing of this remanence, constrained by existing geochemical data, revealed that the Uitkomst dyke, which was previously believed to be of Karoo age, rather represents a late-Uitkomst magmatic phase. A VGP was established for the Uitkomst Complex and suggested that the complex intruded after the 2058 Ma-2054 Ma RLS, but predated the ~1.93 Ga to ~1.87 Ga events on the KC.

North of the eastern sills and the Uitkomst Complex, a post-Transvaal dyke swarm near Lydenburg (eastern KC) was also studied. Paleomagnetic and geochemical results obtained, although of limited quality compared to the other studied units, were of significant interest as they were the first analytical dataset for the Lydenburg dykes. It was found that the Lydenburg dykes experienced a complex magnetic history with existence of several poorly constrained characteristic magnetic components. Two of these remanences were believed to be of primary nature and were used to constrain the timing of emplacement of the dykes. The corresponding VGP’s, constrained by geochemical data, did not support the Karoo age previously assigned to the Lydenburg dykes, but rather suggest a possible link with the 2061 Ma Dullstroom Lavas.

### Table 6.1. Summary of primary paleomagnetic and virtual geomagnetic poles obtained from studied mafic units.

<table>
<thead>
<tr>
<th>Units</th>
<th>Paleopole</th>
<th>Latitude</th>
<th>Longitude</th>
<th>$A_{95}$ (dp/dm)</th>
<th>K</th>
<th>N (n)</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Transvaal sills to the east and west of the KC</td>
<td>B pole</td>
<td>-39.3°</td>
<td>89.3°</td>
<td>13.2</td>
<td>14.3</td>
<td>10</td>
<td>180 Ma?</td>
</tr>
<tr>
<td></td>
<td>C+/- pole</td>
<td>04.9°</td>
<td>56.1°</td>
<td>12</td>
<td>32</td>
<td>6</td>
<td>2058 Ma</td>
</tr>
<tr>
<td></td>
<td>D VGP (HWQ)</td>
<td>05.1°</td>
<td>102.1°</td>
<td>16.5/30.4</td>
<td>3</td>
<td>&gt;2058 Ma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D VGP (RUB)</td>
<td>15.7°</td>
<td>117.8°</td>
<td>7.2/14</td>
<td>9</td>
<td>&gt;2058 Ma</td>
<td></td>
</tr>
<tr>
<td>Uitkomst Complex</td>
<td>Uitkomst VGP</td>
<td>28.7</td>
<td>58.5°</td>
<td>6.2/9.4</td>
<td>19</td>
<td>2044 Ma</td>
<td></td>
</tr>
<tr>
<td>Lydenburg dykes</td>
<td>C- VGP (LDH)</td>
<td>1.4</td>
<td>60.7°</td>
<td>7.7/8.7</td>
<td>6</td>
<td>&gt;2058 Ma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D VGP (LDF)</td>
<td>9.8</td>
<td>290.1°</td>
<td>8.2/15.2</td>
<td>5</td>
<td>&gt;2058 Ma</td>
<td></td>
</tr>
</tbody>
</table>
6.3. IMPLICATION OF RESULTS

In this section, the results obtained from sills east and west of the KC and Lydenburg dykes are used to provide constraints on the chronology of occurrence (duration of formation and cooling) and magnetic history (remanence acquisition) of the RLS and the Bushveld LIP described by Rajesh et al. (2013).

6.3.1. Timing and duration of the RLS

Rajesh et al. (2013) have recently proposed that the Bushveld LIP consisted of at least three separate, but genetically related pulses (i.e. 2060-2060 Ma, 2059-2054 Ma, and 2046-2042 Ma), with the RLS being part of the 2059-2054 Ma pulse. The U-Pb ages of 2058.4 ± 1.3 Ma and 2058.1 ± 6 Ma obtained from the present study clearly place the sampled post-Transvaal sills in the same group with the RLS.

It is generally believed that the formation of the RLS involved at least three magma pulses (B1, B2 and B3), but what remains unclear is the timing of emplacement of these magmas. Paleomagnetic poles obtained by Hattingh (1986a; 1986b; 1986c; 1989) from the upper layers of the RLS suggested an emplacement time span of ~50 million years for the Bushveld Complex. Cawthorn and Walwaren (1998) estimated that the emplacement period of the Bushveld Complex was as little as 75 000 years. Recent paleomagnetic work of Letts et al. (2009) suggested an emplacement period of 1.4 million year for the RLS, based on reversal rates. The precise U-Pb ages of 2058.4 ± 1.3 Ma and 2058.1 ± 6 Ma obtained from sills that intrude the sediments of the Pretoria Group in the vicinity of the RLS (this study) are near identical to the U-Pb age of 2057.7 ± 1.6 Ma obtained by Olsson et al. (2010) from the Marginal Zone of the RLS. The upper layers of the RLS (B2 and B3 magmas) are geochemically characterized by high-TiO$_2$ contents (> 1 wt %), while the lower levels (B1 magma) of this suite display low-TiO$_2$ contents (< 1 wt %) (Rajesh et al., 2013). The 2058 Ma sills of the present study revealed low TiO$_2$ contents. Furthermore these sills displayed many other characteristics (e.g. major elements as well as REE profiles) that clearly place them in the same parental context (B1 Bushveld magma) with the Marginal Zone of the RLS. The 2058.4 ± 1.3 Ma and 2058.1 ± 6 Ma ages from the sills,
while broadly similar, are older than the ages obtained from the upper layers of the Bushveld Complex such as the $2054.4 \pm 1.3$ Ma age obtained from the Merensky reef (upper Critical Zone) by Scoates and Friedman (2008) and the $2054.4 \pm 1.8$ Ma age obtained by Walwaren and Hattingh (1993) from the Nebo Granite. Thus it can be said that the B1 B2 and B3 magma pulses that were involved in the formation of the RLS, occurred over a period of at least 4 million years.

6.3.2. Magnetic reversals in the RLS and the Bushveld LIP

An important objective of this study was to clarify the existence and nature of magnetic reversals in the RLS of the Bushveld LIP. Paleomagnetic results obtained by Letts et al. (2009) revealed that the Earth’s magnetic field reversed at least seven times during the formation of the upper layers (B2 and B3 Bushveld magmas) of the RLS. The rapid nature of these magnetic reversals as interpreted by Letts et al. (2009) was based on the emplacement period of 1.4 million year for the RLS proposed by these authors. The paleomagnetic results from the B1 Bushveld magma-related sills (this study), which occur stratigraphically below the sampling sites of Letts et al. (2009), have revealed the existence of normal and reversed polarity directions (Figure 6.1). Thus there was also a change in polarity of the Earth’s magnetic field during the early stages (Marginal Zone) of the formation of the RLS.

From the present study and that of Letts et al. (2009), it can be said that the Earth’s magnetic field reversed at least eight times throughout the formation of the entire RLS. However, taking in account that the emplacement period for the RLS is probably longer (at least 4 million years) than 1.4 million years as suggested by the geochronological and paleomagnetic data from this study, it is likely that these magnetic reversals did not occur as rapidly as suggested by Letts et al. (2009).
Figure 6.1. Stratigraphic setting of B1 sills sampling sites in the Pretoria Group in the western and eastern limbs indicating the magnetic polarity of sampling sites. Black color represents a normal polarity while red color indicates a reversed polarity.

Paleomagnetic and geochemical results of Lydenburg dykes (this study) suggested a genetic relationship with the Dullstroom Lavas. The Dullstroom Formation (~1500 m thick) occurs stratigraphically at the base of the Rooiberg Group and constitutes a mafic to intermediate volcanic phase (rocks essentially range from basalt to dacite) that is believed to predate the RLS by a few million years (an age of 2061 ± 2 Ma has been reported by Walvaren (1997) for the Dullstroom Lavas rocks). Rajesh et al. (2013) have recently proposed a unifying model for the
Chapter 6

Bushveld magmatism that considers the Dullstroom Formation as part (of the 2061-2060 Ma group) of the Bushveld LIP. This places the Lydenburg dykes in the context of the Bushveld LIP and potentially makes them the first recognized Bushveld LIP-related dykes on the KC. The characteristic magnetic components of the dykes included reversely and normally polarized directions. Thus collectively, the data (from the present study and previous one from Letts et al. (2009)) probably indicate the presence of at least nine magnetic reversals in the Bushveld LIP throughout a time period of 7 million years (i.e. from 2061 Ma to 2054 Ma). Note that the paleomagnetic results from the Uitkomst Complex (this study) which are the first ones for the 2045-2042 Ma group of the Bushveld LIP (Rajesh et al., 2013) have revealed no magnetic reversals.

6.3.3. Remanence acquisition of the RLS

Results from the present study and data from Letts et al. (2009) indicate that at least one magnetic reversal occurred during the emplacement of the Marginal Zone (B1 magma) and seven others were recorded by the B2 and B3 magmas of the upper layers of the suite. The change in polarity recorded by the RLS rocks signifies that the cooling of the B1, B2 or B3 magma pulse was protracted over time so as to span at least eight magnetic reversals or that each magma type involved more than one pulse that intruded during normal and reversed polarity periods. The relative small size of the studied sills supposes a rapid cooling and each sill may have only recorded one magnetic polarity. In this context, the presence of polarity change in the Marginal Zone (B1 magma) may indicate that the formation of this zone involved at least two magma pulses. In Sharpe (1981), it is proposed that the Marginal Zone and related sills derived from a B1 magma that was differentiated in a magmatic chamber and injected along the fracture surface and floor bedding planes as multiple pulses. Cawthorn (2007) studied the Cr and Sr contents of the RLS rocks and found evidence of magma addition of similar as well as of different compositions throughout the entire sequence.

Regarding the timing of remanence acquisition of the RLS relative of the tilting of the country rocks, Letts et al. (2009) suggested that the magnetic directions in the suite were locked-in before the sagging of the country rocks. However, it was found during the present study that maximum
clustering of primary directions of eastern and western B1 Bushveld sills was obtained between 30 to 67 per cent unfolding (regional bootstrap test) and led to the interpretation that the magnetic history of the Marginal Zone started when the sediments of Pretoria Group were horizontal, but continued during the sagging of the country rocks.

6.3.4. The APWP for the Paleoproterozoic KC

One of the aims of this study was to expand the paleomagnetic database for the Paleoproterozoic KC though the establishment of new paleopoles. These poles could also help in evaluating and strengthening the interpreted ages of some existing KC poles (i.e. the WUBS-I (lower Waterberg Group) pole of de Kock et al. (2006) and the Bushveld Complex pole of Letts et al. (2009)) proposed in previous studies. It could be observed that the pole obtained from the 2058 Ma post-Transvaal sills to the east and west of the KC compared well with the Bushveld Complex pole of Letts et al. (2009) (see Chapter 3) and support the pole position in the north-east of Africa during the formation of the RLS. Another observation was that the pole obtained from the 2044 Ma Uitkomst Complex at the Nkomati Mine (this study) overlapped with the pole from the > 2054 Ma lower Waterberg Formation (de Kock et al., 2006) (see Chapter 4) and negated the argument of Letts et al.(2010) regarding the inaccuracy of the latter.

Taking the above observations in account, the reliable paleopoles of the paleomagnetic database for the Paleoproterozoic KC (including those generated in the present study) are used to propose a new Paleoproterozoic (for the period 2200 Ma to 1800 Ma) APWP for the craton (Figure 6.2.). This newly defined APWP is, for the period 2200 Ma (Ongeluk and MAM-I poles) to 2060 Ma (Phalaborwa pole), consistent with previous suggestions (see Chapter 1). But it differs from the proposed APWPs in the existence of previously unrecognized complexities in the time interval between the formation of the Phalaborwa Complex at 2061 Ma, the formation of the RLS between 2058 and 2054 Ma, deposition and deformation of the lower Waterberg Group at >2054 Ma, and the intrusion of the Uitkomst Complex at 2044 Ma. Significant apparent polar wander occurs between the intrusion of the Phalaborwa Complex at 2061 Ma (PBC pole of Letts et al.(2010)), the early stages of the RLS at 2058 Ma (the pole for the B1 Bushveld magma-related sills (this study)), and the formation of the upper layers of the RLS at 2054 Ma (the BVC pole of
Figure 6.2. Paleoproterozoic APWP for the KC, with new paleopoles of the 2058 Ma B1 sills and the 2044 Ma Uitkomst Complex. Outlines of the continents are showed for reference. Red shaded swath shows APWP for the time interval 2200 Ma to 1900 Ma. MAM-1: Mamatwan type manganese ore component 1, ONG: Ongeluk Lavas, BGM: basal Gamagara/Mapedi Formation, BVC: Bushveld Complex, WUBS-I: lower Waterberg Formation, PBC: Phalaborwa Complex, VRED: Vredefort VGP, PBD: post-Bushveld dykes, WSD: post-Waterberg intrusions, SRB: Sand River dikes, BHD: dykes intruding the Archean Basement, WUBS-II: upper part of the Swaershoek Formation and Alma Formation, HAR: Hartley Lavas. Poles color represents their reliability (Van der Voo, 1990). Yellow = Q value of 3, 4 or 5 Green = Q value of 6 or 7.
Letts et al. (2009)). During this time interval, the KC experienced fairly rapid, but small scale movements (see Figure 6.2.).

A second loop in the APWP occurs between the formation of the upper layers of the RLS, the deposition of the lower Waterberg, the intrusion of the Uitkomst Complex and the Vredefort Impact Structure (see Figure 6.2). During this time interval, the pole migrated from the northeast of Africa (BVC pole of Letts et al. (2009)) towards a position in the Arabic peninsula (< 2054 Ma WUBS-I pole of de Kock et al. (2006) and the 2044 Ma Uitkomst Complex VGP (this study)). After this shift, the pole came back to the position in northeast Africa (VRED pole of Salminen et al. (2009) (see Figure 6.2) before continuing along the swath of longer scale movement proposed by de Kock et al. (2006).

6.4. BIBLIOGRAPHIC REFERENCES

(South Africa), and a precise age for the Bushveld Complex. Precambrian Research, (Special Issue), 183: 490-500.


APPENDIX 1

1. SUMMARY OF PREVIOUS WORK ON MARGINAL ROCKS AND SILLS THAT INTRUDE THE ~2.2 Ga PRETORIA GROUP IN THE EASTERN KC

Mafic-ultramafic sills that intrude the ~2.2 Ga upper Transvaal Supergroup (i.e. the Pretoria Group) in the eastern KC (Mpumalanga Province) (Figure 1.1) are highly concentrated above the Magaliesberg Quartzite Formation and towards the contact zone with the RLS.

![Diagram showing the distribution of post-Transvaal sills in the Pretoria Group and rocks of Marginal Zone between the country rocks and the RLS near the eastern limb of the Bushveld Complex.](image)

**Figure 1.1.** Diagrammatic outlines of post-Transvaal sill’s distribution in the Pretoria Group and rocks of Marginal Zone between the country rocks and the RLS near the eastern limb of the Bushveld Complex, after Sharpe (1982) and Sharpe and Hubert (1985).
The more thorough studies on the post-Transvaal sills are those of Sharpe and Hulbert (1985), Sharpe (1982), and more recently Barnes et al. (2010). Sharpe (1982) subdivided the marginal rocks that occur along the basal contact of the RLS in the eastern KC into two major groupings (i.e. pre-Bushveld and syn-Bushveld sills), based on field relationships, petrography (mostly) and geochemistry. The pre-Bushveld sills were believed to occur before the RLS while the syn-Bushveld units were emplaced about the same time as the RLS (Sharpe, 1982). Following the early studies of Sharpe and Hulbert, (1985) and Sharpe (1982), an extensive geochemical study was recently carried out by Barnes et al. (2010) on marginal rocks and sills that occur at the contact with the RLS in the eastern KC. These previous studies are reviewed here, with a summary in Table 1.1.

Table 1.1. Summary of classification of post-Transvaal mafic sills in the Mpumalanga province as proposed by Sharpe (1982)

<table>
<thead>
<tr>
<th>SILL GROUPS AND TIMING OF INTRUSION</th>
<th>PETROGRAPHY TYPES</th>
<th>STRATIGRAPHICAL LOCATION</th>
<th>MINERALOGY</th>
<th>GEOCHEMICAL CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Bushveld (i.e. pre-dated the formation of RLS)</td>
<td>Hornblende-rich amphibolites</td>
<td>Occur in the entire Pretoria group with abundance above the Vermont Fm</td>
<td>Dominant hornblende, tremolite, altered plagioclase, Quartz, carbonate,</td>
<td>Tholeiitic Mg-rich basaltic andesite (Mg#71) with strong negative Ta, Nb, P, Ti, and positive Pb anomalies ([La/Sm (4); Gd/Er (1.9); Er/Lu (0.9); and Eu/Eu* (0.85 - 1.15)] similar to Lower Zone and lower Critical Zone of RLS</td>
</tr>
<tr>
<td></td>
<td>tremolite-rich amphibolites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dunites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyroxenitic subgroup (B1, B1 UM sills)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Micropyrroxenites</td>
<td>Vermont Formation</td>
<td>Dominant orthopyroxene (En 75-94), clinopyroxene, plagioclase (An 65-80)</td>
<td>Tholeiitic Mg-rich basaltic andesite (Mg#71) with strong negative Ta, Nb, P, Ti, and positive Pb anomalies ([La/Sm (4); Gd/Er (1.9); Er/Lu (0.9); and Eu/Eu* (0.85 - 1.15)] similar to Lower Zone and lower Critical Zone of RLS</td>
</tr>
<tr>
<td></td>
<td>Peridotites and harzburgites</td>
<td>Contact between L2 and lower CZ, and floor rocks</td>
<td>Accessories: Olivine, magnetite, ilmenite</td>
<td></td>
</tr>
<tr>
<td>Syn-Bushveld (intruded during the formation of RLS)</td>
<td>Pyroxenites, feldspathic pyroxenites and norites</td>
<td>Between Silverton Fm and Lavenkalei Fm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gabbroic subgroup (B2 and B3 sills)</td>
<td>Microgabros</td>
<td>Steenkampsberg Fm</td>
<td>Dominant orthopyroxene (En 62-80), clinopyroxene,</td>
<td>Tholeiitic basalts (Mg#55) with strong positive Ba and Pb and negative P, Ti, Hf, and Zr anomalies ([La/Sm (2.5), Gd/Lu (1.6) and Eu/Eu* (0.85 - 1.15)] similar to the upper Critical Zone</td>
</tr>
<tr>
<td></td>
<td>Gabbronorites and norites (B2 sills)</td>
<td>Steenkampsberg Fm, Lavenkalei Fm, and Nederhorst Fm</td>
<td>Accessories: Olivine (Fo 72-84)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gabbros (B3 sills)</td>
<td>Houtenbek Fm</td>
<td>Accessories: Ilmenite and magnetite</td>
<td>Tholeiitic basalts (Mg#62) with large positive Ba, Pb, Eu, and negative Nb, Ta, Hf and Zr anomalies ([La/Sm (2.3), Gd/Lu (1.3) and Eu/Eu* (&gt; 1.4)] similar to the Main Zone of RLS</td>
</tr>
</tbody>
</table>
1.1. PRE-BUSHVELD SILLS

The pre-Bushveld sills occur in the entire Pretoria Group with abundance above the Vermont Formation. Sills of presumed pre-Bushveld age studied by Sharpe (1982) generally consisted of amphibolite and contained no orthopyroxene (Sharpe, 1982). The mineralogy was dominated by amphibole, plagioclase, and quartz (Sharpe, 1982). These sills were similar to the “Lydenburg type” units and the “diorite sills” early described by Willemse (1959) and Frick (1973) respectively. Sharpe (1982) further arranged these sills into ones that are hornblende-rich (more hornblende than tremolite), tremolite-rich (more tremolite than hornblende), and those that are ultramafic.

1.1.1. Hornblende-rich pre-Bushveld sills

This group of pre-Bushveld sills included lithologies that range from pure amphibolites to leucoamphibolites (DIH sills) and tremolite-rich rocks (Sharpe, 1982). DIH sills occur above the Magaliesberg Quartzite Formation (Figure 1.1). The rocks are dark green to green, with equigranular and ophitic textures (Sharpe, 1982). The mineral assemblage of DIH sills is dominated by euhedral zoned amphibole grains displaying cleavages. Sharpe (1982) also noted that the plagioclase when present is mostly fresh. Clinopyroxene, quartz, calcite, clinozoisite, and zeolite constitute the accessory minerals. The mineral assemblage of the tremolite-rich type is comprised out of 20 to 50 per cent of tremolite, which generally pseudomorphosed the orthopyroxene (Sharpe, 1982). Hornblende is of variable size, reflecting the evidence of two phases of growing of this mineral (Sharpe, 1982). Plagioclase mostly appears replaced by fibrous amphibole, mica or quartz (Sharpe, 1982).

1.1.2. Tremolite-rich pre-Bushveld sills

According to Sharpe (1982), the tremolite mineral characteristic of this sill type is a secondary mineral that pseudomorphed primary pyroxenes. This author also noted that
various stages of the tremolitization process might be observed in relevant lithologies. When affecting a pyroxenite sill, this process may give rise to a tremolite rock with a mineral assemblage of tremolite, biotite and altered plagioclase (Sharpe, 1982).

1.1.3. Ultramafic pre-Bushveld sills

Sharpe (1982) noted that the ultramafic sill type was rare, relative to other pre-Bushveld sills (Figure 1.1.). The ultramafic sills only occurred in the upper part of the Silverton Formation (Figure 1.1) as bases of differentiated pre-Bushveld sills (Sharpe, 1982). Sharpe (1982) studied one 40 m thick ultramafic sill on Boomplaats 29 JT. The rock was a retrogressed dunite with a mineral composition made up of about 75 per cent of secondary talc that derived from primary olivine, 15 per cent of serpentine and about 10 per cent of tremolite and euhedral carbonate grains (Sharpe, 1982).

1.2. SYN-BUSHVELD SILLS

In contrast to the sills considered as pre-dating the Bushveld Complex, the units of presumed Bushveld age are orthopyroxene-bearing and only occur above the Machadodorp Volcanic member (Sharpe, 1982) (Figure 1.1). The syn-Bushveld sills bared petrographical and geochemical similarities to the RLS and could be arranged in either pyroxenitic (B1 sills) or gabbroic (B2, B3 sills) subgroups, depending on the parentage of the relevant lithologies (i.e. the Lower and lower Critical Zones, the upper Critical Zone, and the Main Zone the RLS (Barnes et al., 2010)).

1.2.1. Pyroxenites syn-Bushveld sills (B1 subgroup)

Sharpe (1982) coded these sills, that are generally coarse-grained with narrow chilled margins, as B1 sills (Table 1.1) and further arranged them into quench-textured micropyroxenite sills (B1qpx sills), ultramafic sills (UM sills), pyroxenitic sills (B1px sills) and feldspathic pyroxenitic and noritic sills (B1n sills) (see Table 1.1).
1.2.1.1. Quench-textured micropyroxenites syn-Bushveld sills (B1 sills)

Frick (1967) first described the micropyroxenites west of Lydenburg. Sharpe (1978) mapped similar units in the Vermont formation above the Magalieberg Quartzite (Figure 1.1.) and named the relevant rocks “cone-diabase” because of the resemblance of their quench cells with shallow cones. The micropyroxenites had a thickness generally comprises between 10 and 100m (Barnes et al., 2010). Their mineralogy was dominated by tremolite, plagioclase, and amphibole. Different types of micropyroxenite sills could be distinguished. The rapidly-cooled type was made up of phenocrystic, zoned, euhedral orthopyroxenes (0.4-1.5mm) set in a matrix of dark, devitrified glass (Barnes et al., 2010). The glass-rich type consisted of skeletal orthopyroxene grains up to 0.3 mm long or 0.1 m diameter euhedral, unzoned grains (Sharpe, 1982). The olivine-rich type with comb-textured plagioclase and megacrystic orthopyroxene occured as offshoots of the lower Critical Zone of the RLS.

1.2.1.2. Ultramafic syn-Bushveld sills (B1 UM sills)

Early study of ultramafic syn-Bushveld sills was done by Willemse (1959) and Liebenberg (1964) in the Burgersfort and Wildebeestkraal peridotites, and by Schwellnus et al. (1962) in the Wimbledon sill. Sharpe (1982) mapped these sills in the contact zone between the lower and lower Critical zones of the RLS, and the Pretoria Group (Sharpe and Hulbert, 1985). Barnes et al. (2010) coded them as B1 UM sills. Sills in the Burgersfort region consisted of coarse-grained peridotite that showed a little modal variation from the base upwards (Sharpe, 1982). In the north of Marone Station, the B1 UM sills cut into the Magaliesberg Quartzite and displayed a medium-grained marginal phase, which sometimes developed orthopyroxene and plagioclase quench textures. Sharpe and Hubert (1985) and Sharpe (1982) recognized a harrisitic variety of peridotite sill which occurs east of Burgersfort. The rock consisted of blades of olivine that enclose orthopyroxene, clinopyroxene, plagioclase and sulphides. Chromite mineral was also present. The harrisitic peridotite possibly represents either the initial magma to the Lower
Zone of the RLS (Hubert and Sharpe, 1981) or may be a crescumulate that grew on the bottom of magma chamber. At Wildebeestkraal, B1 UM sills were essentially harzburgites (Sharpe, 1982). In contrast of Burgersfort sills, the harzburgites were differentiated by an increase in the amount of interstitial feldspar. Sharpe (1982) studied thin sections of the relevant rocks and found a mineral composition dominated by olivine, orthopyroxene, clinopyroxene. The accessory minerals consisted of biotite/phlogopite, chromite and intercrystalline feldspar. The 200 m thick Wimbledon sill was different from the Wildebeestkraal and Burgersfort units and consisted entirely of harzburgites (Sharpe, 1982). The same author mapped two other ultramafic sills similar to the Wimbledon type south of Steelpoort. These were the 20 m thick Zwakwater sill and the 50m thick Rietfontein sill (Sharpe and Hulbert, 1985). All three sills were of spoon shape, with a maximum diameter of 1000m for the Wimbledon sill, 600 m for the Rietfontein and 200 m for the Zwakwater sills. Sharpe (1982) also noted that the Rietfontein and Zwakwater sills have an extension as a 10 m thick pyroxenite dyke. The dominant minerals for all three sills were olivine (Fo 89), orthopyroxene (En 87-90) and plagioclase (An 65). The lithologies of Rietfontein and Zwakwater sills displayed a differentiation between olivine-predominant harzburgite and 50-50 olivine-orthopyroxene type. The three sills were believed to derive from ultramafic liquids that intruded into the floor rocks.

1.2.1.3. Pyroxenite, feldspath pyroxenite and norite syn-Bushveld sills

Sills of this subgroup were the most common ones found by Sharpe (1982) in Mpumalanga province. All three sill types sometimes occurred in a same lithological succession as result of a differentiation. Pyroxenite sills generally appeared to be fresh than norite units. Sharpe (1982) distinguished pyroxenite sills with long orthopyroxene grains and the ones with stubby prisms orthopyroxene. Sharpe (1982) further noted that the long-grain pyroxenites and feldspathic pyroxenites contain zoned, euhedral orthopyroxene (up to 15mm long), and granophyric intergrowths of quartz and feldspar. Inclusions of semi-digested floor rocks were also identified. Mineral assemblage in
noritic sills was dominated by orthopyroxene of various size and interstitial plagioclase. In the altered rocks units, the plagioclase mineral broke down into fine-grained micaceous products and the orthopyroxene was penetrated by tremolite and sericite.

1.2.2. Geochemistry of the B1 subgroup

Major and trace elements of seventeen samples from the B1 and B1 UM Bushveld marginal rocks and sills were studied by Barnes et al. (2010). In terms of major element geochemistry, these rocks were generally characterized by high MgO and low TiO$_2$, relative to the other sill subgroups. In the total alkalis versus silica diagram (Le Bas et al., 1986), Barnes et al. (2010)’s samples generally fall in the basaltic andesite field and display a tholeiitic affinity in the AFM diagram (Irvine and Baragar, 1971). In terms of Mg#, the B1 and ultramafic B1 sills ranged from 63 to 72, indicating that they mostly derived from primary magmas (Barnes et al., 2010). Based on their major element contents, the B1 and ultramafic B1 sills are close to the boninites (Barnes et al., 2010). In terms of incompatible trace elements, Barnes et al. (2010) noted that the B1 and B1 ultramafic sills displayed similar REE profiles, with B1 rocks being more enriched. These authors obtained La/Sm ratio of 4, Gd/Er ratio of 1.9 and Er/Lu ratio of 0.9 for both sills, and Eu/Eu* ranging between 0.85 and 1.15. Barnes et al. (2010) also noticed that incompatible element patterns of B1 and B1 UM sills, contrary to the major elements, were not similar to the boninites, but rather bared similarities to the upper continental crust. The mantle normalized multi-element spidergrams of Barnes et al. (2010)’s samples were similar in shape, but the B1 group samples plotted more enriched. The spidergrams involved a steep profile due to strong negative Ta, Nb, P and Ti, and positive Pb anomalies. In terms of PGE, the B1 group samples were highly concentrated in S and Se, relative to B1 UM, B2 and B3 sills (Barnes et al., 2010). It was found that Cu/Pd ratio for B1 sills compared well with the mantle rocks (1000-10 000), and this led Barnes et al. (2010) to suggest that all sulfides were expelled from the magma chamber during the formation of these sills. This idea was further strengthened by the value 38 x 10$^{-7}$ that these authors obtained for the ratios Pt/TiO$_2$ and Pd/ TiO$_2$ for both sill groups. One of the
features of B1 sills was their unusual high Pt/Pd ratio (1.5), which Barnes et al. (2010) attributed to the high concentration of Pt rather than low Pd content. B1 UM rocks appeared to be depleted in Pt and Pd, relative to B1 rocks, but these elements were more concentrated, relative to other incompatible elements (Barnes et al., 2010). It results from this that the Pt/TiO$_2$ and Pd/TiO$_2$ ratios calculated by Barnes et al. (2010) for B1 UM sills were higher, relative to the B1 group. Comparisons of the major and trace elements geochemistry of the B1 and ultramafic B1, as well as crystallization order and composition of different minerals led Barnes et al. (2010) to suggest that these rocks derived from the same magma as the Lower and lower Critical zones of the RLS.

1.2.3. Gabbros syn-Bushveld sills (B2, B3 subgroup)

Sharpe (1982) divided the gabbroic syn-Bushveld sills into three subgroups. These are the microgabbroic sills, the gabbronorite and norite sills (B2 subgroup) associated with the Critical Zone, and the gabbroic sills (B3 subgroup) associated with the Main Zone of the RLS (Figure 1.1).

1.2.3.1. Microgabbro syn-Bushveld sills

Only few microgabbroic sills were found in Mpumalanga Province, generally as units occurring along the bedding planes of the Steenkampsberg Quartzite and the Dullstroom Basalt Formation (Sharpe, 1982). The sill units rarely exceed 20 m in thickness. Mineral composition of microgabbro was dominated by plagioclase, clinopyroxene, and orthopyroxene which represent more than 90 per cent of the rock (Sharpe, 1982). Accessory minerals were about 4 per cent and included magnetite and ilmenite. The grain size of mineral was generally comprised between 0.1 mm and 0.5 mm. Microgabbro textures varied from quench aligned pyroxene and plagioclase to evenly-distributed grains. This author also noted that some gabbroic sills contain quartzite inclusions, pegmatitic segregations, poikiloblasts of clinopyroxene and clinopyroxenite veins.
1.2.3.2. Gabbronorite and norite syn-Bushveld sills associated with the Critical Zone (B2 subgroup)

Gabbronorite and norite sills were mapped above the stratigraphic level of the Critical Zone of the RLS in the Steenkampsberg, Lakenvalei and Nedershorst formations (Sharpe, 1982) (Figure 1.1). The mineral composition of the sills consisted of orthopyroxene and clinopyroxene in equal proportions, with well-developed tabular plagioclase and abundant magnetite (Sharpe, 1982). Lower down in the stratigraphy, the sills were mostly differentiated in pyroxenite sills, feldspathic pyroxenites, norites, or pyroxene-bearing granophyres. Noritic sills sometimes crosscut the pyroxenitic group and this was regarded by Sharpe (1982) as evidence of the influx of new magma after the emplacement of the lower Critical Zone.

1.2.3.3. Gabbro syn-Bushveld sills associated with the Main Zone (B3 subgroup)

The representatives of this subgroup of syn-Bushveld sills were rare. Sharpe (1982) only reported one major sill of this type and few minor ones. This major Main Zone sill was first described as syn-Bushveld unit by Frick (1967), but was believed to be pre-Bushveld by Willemse (1959). The body occurred at the contact zone with the Main Zone of the RLS. Its thickness was of about 150 m and decreases of some 20m on Houtenbek 93 JT where the sill is truncated by a fault (Sharpe, 1982). Hybrid quartz dolerites formed at the maximal thickness of the sill (Sharpe, 1982). The mineralogy of the sill was dominated by orthopyroxene-bearing gabbro, clinopyroxene, plagioclase, and abundant magnetite (Sharpe, 1982).

1.2.4. Geochemistry of the B2 and B3 subgroups

Major element contents of fifteen B2 sills and eight B3 ones sampled by Barnes et al. (2010) were generally similar. However, these authors noted some differences between the two sill subgroups in terms of Mg#, TiO₂, K₂O, and P₂O₅ contents, which were
generally high in B2 sills, relative to B3 sill type. In the AFM diagram, Barnes et al. (2010)’s samples failed in the tholeiitic area, and plot as basalts in the total alkalis versus silica diagram. The relatively low Mg# for B2 sills (58-66) and B3 sills (43-63) led these authors to suggest that the parental magmas of these sills are evolved. In terms of incompatible elements, Barnes et al. (2010) found that the B2 sills were less enriched in LREE, but were more concentrated in MREE and HREE, relative to the B1 sill type. In general, the REE profiles for the B2 sills were slightly smooth with low La/Sm (2.5) and Gd/Lu (1.6), relative to the B1 and B1 UM sills. The B3 sills generally appeared less enriched in REE, relative to the B2 sills, but showed concentrations in LREE and fractionation in HREE in similar range with the B2 sills (Barnes et al., 2010). This was attested by the La/Sm (2.3) and Gd/Lu (1.3) for B3 sills that were otherwise close to those of the B2 rocks. All B3 sills exhibited pronounced Eu anomalies which with Eu/Eu* (> 1.4) relative to the other sill groups (0.85-1.15). Barnes et al. (2010) also noted that the multielement profiles of the B2 and B3 sills shared some similarities such as positive Ba, Pb, Sr, and Eu anomalies; however, the B2 sills were enriched in REE, Y, Ti, P, and V relative to the B3 sills; the profiles of B2 and B3 sills were generally smooth, relative to the B1 sills. In terms of PGE, B2 and B3 sills are less enriched, relative to the B1 rocks. The B2 and B3 also display low Pd/Ir ratios (27 and 28 respectively) compared to the B1 rocks (30) (Barnes et al., 2010). The plots for the mantle normalized metals of the B3 sills generally compared well in shape with the B1 sills. However, the B1 sills plotted more enriched from Ni to Pt, relative to B3 rocks (Barnes et al., 2010). This was not the case for the B2 sills which revealed similar shape with B1 rocks from Ni to Pt. According to the same authors, the B2 rocks generally displayed a high Cu/Pd ratio, relative to the mantle, while Pt/TiO₂ and Pd/TiO₂ ratios were less than the mantle. In contrast, the B3 rocks displayed Cu/Pd ratio in the range of that of the mantle rocks (1000-10 000), leading Barnes et al. (2010) to suggest that all sulfides were expelled from the magma chamber during the formation of these rocks. An idea that was further strengthened by the value 38 x 10⁷ and 35.5 x 10⁷ obtained for Pt/TiO₂ and Pd/ TiO₂ respectively. Comparisons of the major and trace elements geochemistry of the B2 and B3, as well as crystallization order and composition of
different minerals led Barnes et al. (2010) to suggest that these rocks derived from the same magma as the upper Critical Zone and Main Zone of the RLS.

1.2.5. Geochronological data of syn-Bushveld sills

Except the strontium isotope results from Harmer and Sharpe (1985), no radiometric data are available on the post-Transvaal sills. These authors analysed the strontium isotope compositions of 26 samples from the marginal rocks that occur along the basal contact of the eastern BIC, in order to provide an age for these units. These authors were able to distinguish between the ultramafic (B1 UM magma related) and gabbroic members (B2 and B3 related) of their samples from the Rb/Sr ratios, as the gabbroic rocks yielded low Rb concentrations. This prevented an age to be calculated for the gabbroic marginal rocks, in contrast to the B1 and B1 UM members. Harmer and Sharpe (1985) plotted the results from B1 and B1 UM sills on a conventional isochron diagram and obtained an apparent age of 2015 ± 215 Ma, and an initial Sr ratio (R₀) of 0.7049 ± 13. This age correlated with that of ~2050 Ma of Hamilton (1977) from the main Bushveld Complex, and which was at the time of Harmer and Sharpe’s study the only available Sr isotopes for this complex.

1.3. BIBLIOGRAPHIC REFERENCES


APPENDIX 2

PETROGRAPHY AND GEOCHEMISTRY OF POST-TRANSVAAL INTRUSIONS IN THE EASTERN KC

1. DESCRIPTION OF THIN SECTIONS

Here detailed petrographic observations from the various sills and one dyke sampled from the sill suite that intrudes the Pretoria Group in the eastern KC are described according to the stratigraphic heights at which these intrusions occur. Intrusions are described from the base upwards (i.e. from HWQ to HWV, see Figure 2.1.).

1.1. HWQ

HWQ is intensively altered, and its primary sub-ophitic texture is highly obliterated. Amphibole, orthopyroxene, and plagioclase constitute the dominant minerals. Quartz occurs as an accessory mineral. These minerals, that generally do not exceed 0.5 mm in size, are set in an altered fine grained matrix. Amphibole appears as greenish anhedral prisms and laths with prominent cleavages that generally entirely pseudomorphs euhedral laths of orthopyroxene (Figure 2.2). Plagioclase is variably saussuritized and consists of subhedral polysynthetic laths that are embayed by amphibole and less commonly relics of orthopyroxene. The rock also contains a small amount of quartz which occurs as small, anhedral, to subhedral grains.

1.2. HWR

Thin section of HWR reveals an altered fine grained rock. In some places where the igneous features have been preserved, a sub-ophitic texture involving clinopyroxene and plagioclase can be recognized (Figure 2.2). Small amounts of orthopyroxene and granophyric and interstitial quartz also occur. Pyroxene consists of 1-2mm anhedral elongated and cracked crystals which are variably altered. Relicts of this mineral are enclosed by laths of fresher elongated polysynthetically twinned plagioclase that range generally between 1-1.5 mm. Some clinopyroxene crystals are altered to amphibole, which is easily identified by its cleavage. The
quartz occurs as small, anhedral, to subhedral grains or small aggregates in between the pyroxene and plagioclase.

Figure 2.1. Stratigraphic setting of sampling sites of the study in the Pretoria Group
1.3. HWA

The mineral composition of HWA is dominated by orthopyroxene with an extinction angle of about 55°. This mineral generally occurs as 1-2 mm sub-euhedral elongated, zoned crystals that are generally altered along cracks and cleavage planes (Figure 2.2). Phenocrysts are set in a devitrified groundmass of fine orthopyroxene crystals associated with a considerable amount of opaque minerals.

1.4. HWB

HWB is mainly made up of orthopyroxene that appears as cracked, euhedral to subhedral lath-shaped crystals up to 3 mm long and smaller stubby prismatic grains (Figure 2.2). This is sometimes associated with a small amount of secondary plagioclase in the altered portion of the rock. Plagioclase occurs as sparse grains associated to darkish patches that penetrate the orthopyroxene. The matrix is rich in near uniformly sized acicular orthopyroxene crystals and considerable amount of opaque minerals.

1.5. HWD

Thin section of HWD is mainly made up of orthopyroxene, clinopyroxene and plagioclase. Large sub-euhedral, cracked, elongate, and prismatic orthopyroxene crystals are enclosed by elongate and multishaped crystals of clinopyroxene. These minerals together with plagioclase needles are set in a devitrified groundmass of preferentially oriented elongated plagioclase, grains of pyroxene, and a small amount of opaque minerals (Figure 2.2).

1.6. HWS

HWS has a poikilophitic texture, with large plagioclase, orthopyroxene and clinopyroxene that enclose equant olivine grains (Figure 2.2). Olivine are generally fresh and consists of euhedral cracked small prismatic or sub-rounded grains (<0.25mm in size) with high relief. Pyroxene is variably chloritized or sericitized, especially along cracks and cleavage planes, and occurs as ~1mm euhedral elongated zoned crystals or anhedral grains that are generally intergrown with plagioclase. Plagioclase appears as large blades or elongated sub-euhedral to euhedral polysynthetic twinned crystals (~2mm) that are generally fresh.
Figure 2.2. Microphotographs of some of the studied samples. HWQ: crystal of orthopyroxene (opx) partially pseudomorphed by amphibole (amph). HWR: Sub-ophitic texture involving euhedral phenocrysts of clinopyroxene (cpx), plagioclase (plg), secondary amphibole (amph), and granophytic quartz (qtz) set in a fine grained groundmass. HWA and HWB: Pyroxenite with blades of orthopyroxene (opx) set in a fine grained groundmass. HWD: Oriented fine grained plagioclase (plg) in a devitrified matrix. HWS: poikilophitic texture with olivine (olv) enclosed by large blades of pyroxene (opx and cpx) and plagioclase (plg).
1.7. HWM

HWM has a fine-grained sub-ophitic texture that is made up of fairly fresh phenocrysts (orthopyroxene, clinopyroxene, plagioclase, and quartz) set in a matrix of pyroxene and opaque mineral grains. Pyroxene phenocrysts generally occur as ~1mm long anhedral lath-shaped zoned crystals, some of which intergrown with laths and needles of polysynthetic twinned crystals of plagioclase. Some pyroxene crystals are pseudomorphed by amphibole (Figure 2.3). Occasionally, small, anhedral, to sub-euhedral grains of quartz occur between pyroxene and plagioclase crystals.

1.8. HWL

Thin section of HWL reveals a fine-grained rock with a sub-ophitic granular texture. The rock mainly consists of clinopyroxene, and plagioclase. These minerals, which are set in a fine grained matrix of plagioclase and opaque minerals, are sometimes altered and replaced by secondary minerals. Plagioclase which occurs as ~1mm anhedral laths, are variably saussuritized. Pyroxene appears as anhedral corroded blades or grains that are variably altered in amphibole and clay minerals (Figure 2.3).

1.9. HWF

HWF has a hypocrystalline texture involving skeletal, euhedral lath-shaped phenocrysts as well as basal sections of orthopyroxene enclosed by a brown glassy matrix (Figure 2.3). Orthopyroxene, which is frequently altered to chlorite, ranges from 1-2 mm. No plagioclase phenocryst is seen in this rock. The matrix consists of fine grained material of needle-like chloritized pyroxenes and opaque minerals.

1.10. HWG

The mineral assemblage of HWG is mainly constituted by clinopyroxene, orthopyroxene, plagioclase, and quartz. These minerals are generally well-preserved in a sub-ophitic texture. Clino and orthopyroxene occur in near equal proportion and constitute the dominant phases. They occur as sub-euhedral cracked phenocrysts with a medium grain size. Some pyroxenes
display alteration along grain cracks, boundaries or cleavages and have a cloudy aspect. The alteration product is chlorite and sericite, and rarely amphibole. Plagioclase consists of 0.5-1 mm anhedral polysynthetically twinned laths or basal sections that are intergrown with the pyroxenes (Figure 2.3). Occasionally, granophyric quartz and calcite enclose anhedral small grains or crystals of clinopyroxene and plagioclase.

1.11. HWT

In thin section, HWT reveals an altered medium-grained rock. Originally, the rock probably had a sub-ophitic texture involving clinopyroxene and plagioclase set in a dark fine grained matrix. Small amounts of granophyric and interstitial quartz and calcite are now present. Most phenocrysts of pyroxene are now altered to amphibole (Figure 2.3) and clay minerals (probably chlorite). Original pyroxene consisted of 1-2mm anhedral elongated and cracked crystals. Relicts of this mineral are enclosed by laths of elongated polysynthetically twinned plagioclase that range generally between 1-1.5 mm. Plagioclase is now variably saussuritized. Quartz and calcite occur as small, anhedral, to sub-euhedral grains or small aggregates that are intergrown with some pyroxene and plagioclase.

1.12. HWN

Thin section of HWN reveals an altered fine-grained rock with sub-ophitic to granular texture. Originally the rock probably consisted of pyroxene and plagioclase. These minerals, which were set in a fine grained matrix of plagioclase and opaque minerals, are now largely replaced by secondary minerals. The rock also contains a considerable amount granophyric intergrowth of quartz. Relicts of plagioclase reveal that this mineral occurred as ~1mm anhedral laths, which are now saussuritized. Pyroxene is variably altered to amphibole (Figure 2.3) and clay minerals and has a chalky aspect. Quartz appears as heterogeneous white patches that occur together with mafic minerals. Some quartz grains are also disseminated in the matrix.
Figure 2.3. Microphotographs of some of the studied samples: HWM: Crystal of clinopyroxene (cpx) partially pseudomorphed by amphibole (amph). HWL: Granular clinopyroxene (cpx) partially replaced by amphibole (amph). HWF: Hypocrystalline texture showing skeletal phenocrysts of orthopyroxene (opx) in a fine grained groundmass. HWG: Intergrowth of orthopyroxene (opx) and plagioclase (plg). HWT: Euhedral crystal of amphibole (amph) replacing the primary orthopyroxene (opx) in a fine grained matrix. HWN: Anhedral crystal of clinopyroxene (cpx) entirely pseudomorphed by granular amphibole (amph).
1.13. HWU

HWU has a sub-ophitic to granular texture. The rock is mainly composed of clinopyroxene and plagioclase. Abundant granophyric quartz and biotite also occur. Clinopyroxene consists of 1-2mm anhedral elongated crystals (Figure 2.4) which are generally fresh. This mineral is enclosed by laths of ~0.5 mm elongated polysynthetically twinned plagioclase crystals. Quartz and biotite have a characteristic white aspect and occur as small, anhedral crystals, some of which enclose the mafic minerals. Small quartz grains also occur in the groundmass, together with other fine grained, granular and variably altered minerals that are believed to have been plagioclase, pyroxene and biotite.

1.14. HWY

HWY has a poikilophitic texture made up of olivine grains that are enclosed by phenocrysts of plagioclase, orthopyroxene and clinopyroxene (Figure 2.4). Olivine is easily identifiable by its high relief and consists of generally fresh euhedral cracked small prismatic or sub-rounded grains (<0.25m in size). Pyroxene, which is variably altered, especially along the cracks, occurs as ~0.5 mm long euhedral zoned crystals or anhedral grains that are generally intergrown with plagioclase. Plagioclase consists of relatively fresh large blades or elongated sub-euhedral to euhedral polysynthetic twinned crystals (~3mm).

1.15. HWX

HWX is an intensively altered, fine grained rock with a granular texture. Original igneous features are largely obliterated by alteration. Originally, the rock probably consisted of clinopyroxene, plagioclase, quartz, and opaque minerals, set in a fine-grained matrix (Figure 2.4). Orthopyroxene phenocrysts have an average size of ~1 mm and are altered to both amphibole and clay minerals (probably chlorite and sericite). Orthopyroxene is variably intergrown with plagioclase, which is commonly fresh and appears as subhedral elongated (~0.25 mm) polysynthetically twinned laths. However, variably saussuritized plagioclases, with cloudy aspect have also been observed. Granophyric quartz and calcite occur as accessory minerals and consist of small, anhedral, to subhedral grains or small aggregates that are intergrown with mafic minerals.
1.16. HWI

HWI is relatively fresh and primary igneous features are preserved. The rock is mainly composed of orthopyroxene, clinopyroxene, and plagioclase. Abundant granophyric and interstitial quartz and calcite also occur. Clinopyroxene consists of 1-1.5mm anhedral, elongated, and cracked zoned crystals (Figure 2.4), some of which have been altered. Plagioclase is fresher and involves elongated polysynthetically twinned laths that range generally between 1-1.5 mm. Intergrowth of pyroxene and plagioclase is very common. Aggregates of quartz and calcite occur in abundance and are occasionally intergrown with pyroxene and plagioclase.

1.17. HWP

HWP has a sub-ophitic texture that involves fairly fresh clinopyroxene and plagioclase phenocrysts set in a matrix of fine grained pyroxene, plagioclase, and opaque minerals. Clinopyroxene generally occurs as ~1mm long anhedral lath-shaped crystals, some of which intergrown with laths and needles of polysynthetic twinned plagioclase. Some clinopyroxene crystals are variably altered to amphibole (Figure 2.4), which occur as anhedral or lath-like crystals.

1.18. HWH

HWH is relatively fresh and igneous features (sub-ophitic texture) are preserved. The rock is mainly composed of clinopyroxene and plagioclase (Figure 2.4). Small amounts of orthopyroxene and quartz also occur. Clinopyroxene consists of ~1mm anhedral elongated and cracked zoned crystals, some of which are completely replaced by chlorite. Plagioclase is generally fresh, although some saussuritized crystals of this mineral have been noted. It occurs as elongated polysynthetically twinned laths that range generally between 1-1.5 mm. Intergrowth of pyroxene and plagioclase is common. Aggregates of quartz and calcite occur in abundance and are occasionally intergrown with pyroxene and plagioclase.
Figure 2.4. Microphotographs of some of the studied samples. HWU: Anhedral blades of clinopyroxene (cpx) set in a granular matrix. HWY: Poikilophitic texture with olivine (olv) enclosed by large blades of pyroxene (cpx and opx) and plagioclase (plg). HWX: Granular texture involving small crystals and grains of altered clinopyroxene (cpx) set in a fine grained matrix. HWI: Sub-ophitic texture with bundles of clinopyroxene (cpx) and abundant granophyric quartz (qtz) set in a granular matrix. HWP: Anhedral crystal of clinopyroxene (cpx) partially pseudomorphed by amphibole (amph). HWH: Medium grained sub-ophitic texture involving variably altered clinopyroxene (cpx) that are intergrowth with plagioclase (plg), and granophyric quartz (qtz).
1.19. HWW

HWW is an intensively altered, fine-grained rock with a granular texture. Original igneous features are largely obliterated by alteration. Originally, the rock probably consisted of clinopyroxene and plagioclase set in a fine-grained matrix of pyroxene, plagioclase and opaque minerals. Clinopyroxene phenocrysts have an average size of 1.5 mm and are highly altered in both amphibole (Figure 2.5) and clay minerals (probably chlorite and sericite). Clinopyroxene is variably intergrown with frequently saussuritized plagioclase, which involves sub-euhedral elongated (~0.25 mm) polysynthetically twinned laths or anhedral blades.

1.20. HWO

HWO is an intensively altered, fine grained rock with a granular texture. Original igneous features are obliterated by alteration. Original mineral composition probably consisted of orthopyroxene, clinopyroxene, plagioclase, quartz and opaque minerals, set in a fine grained granular texture of matrix (Figure 2.5). Orthopyroxene occurs as skeletal laths or granular fragments that are partially replaced by secondary clay minerals (dominantly chlorite). Anhedral polysynthetically twinned plagioclase laths, which are largely saussuritized, are embayed by relicts or alteration products of orthopyroxene phase. The rock also contains an abundant amount of granophyric quartz and calcite.

1.21. HWV

In thin section, HWV appears as a highly altered medium-grained rock with an obliterated sub-ophitic texture. Originally, the rock probably consisted of clinopyroxene and plagioclase. Elongated (~2mm) and bundled clinopyroxene blades are variably replaced by chlorite and other clay minerals (Figure 2.5). Plagioclase is generally fresher than clinopyroxene and consists of 1-2 mm long sub-euhedral polysynthetically twinned crystals that enclose pyroxenes. The phenocrysts are set in a granular matrix that involves fine-gained altered products of plagioclase, pyroxene, and opaque minerals. Large pods of granophyric intergrowth of quartz and plagioclase are very common in this thin section (Figure 2.5).
Figure 2.5. Microphotographs of some of the studied samples. HWW: Granular texture involving small crystals as well as large laths of altered clinopyroxene (cpx) and grains of plagioclase (plg) in a fine grained matrix. HWO: Fine grained texture involving small crystals of ortho (opx) and clinopyroxene (cpx) and plagioclase (plg) set in a granular opaque-rich groundmass. HWV: Sub-ophitic texture involving bundles of clinopyroxene (cpx) and abundant quartz (qtz) in a granular matrix.

2. CORRELATIONS OF GEOCHEMICAL RESULTS FROM POST-TRANSVAAL INTRUSIONS OF THE EASTERN KC TO THE STRATA-BOUND IGNEOUS SUITES ON THE KC

In this section, detailed comparisons of the studied intrusions to previously published geochemical results from Paleoproterozoic and younger units on KC (i.e. the older than 2.05 Ga Dullstroom Lavas, the sills and marginal rocks of the basal contact of the eastern Bushveld Complex, the ~ 1.9 Ga post-Waterberg intrusions and Black Hills dykes, the ~1.1 Ga Umkondo sills, and the ~ 0.18 Ga Karoo intrusions) are done.
2.1. >2.05 Ga Dullstroom lavas

The older than 2.05 Ga Dullstroom Lavas were geochemically studied by Buchanan et al. (1999) who arranged these rocks into three chemical groups i.e. the Ti-rich, low-Ti, and felsic groups.

2.1.1. HWD

In terms of major elements geochemistry, the low Ti and high-Ti Dullstroom Lavas rocks range from basaltic andesite to andesite in the IUGS total alkali versus silica (TAS) system (Le Bas et al., 1986), the felsic units from andesite to dacite (Buchanan et al., 1999), while sample HWD plots as andesite. In the AFM diagram (Irvine and Baragar, 1971), Dullstroom Lavas as well as sample HWD fall in the calco-alkaline field. Mg# (~69) for sample HWD is, however, high, relative to all Dullstroom Lava samples (35-59.9).

REE geochemistry of Dullstroom Lavas displayed on a chondrite normalized plot (McDonough and Sun, 1995) correlates in shape with sample HWD for the first three LREE, but the lavas plot slightly more enriched (Figure 2.6A). For other LREE, Sm and Eu anomalies are more pronounced in sample HWD, relative to Dullstroom Lava rocks (Figure 2.6A). This results in La/Sm ratios for sample HWD (~4.3) and Dullstroom Lava rocks (~3.46) (Buchanan et al., 1999) to be different. MREE and HREE profiles for Dullstroom Lava samples are slightly flat, with Tb/Lu ratios ranging between ~1.2 and ~1.37 (Buchanan et al., 1999), relative to sample HWD that has Tb/Lu of about 1.42.

Comparisons of spidergrams reveal that both Dullstroom Lava samples and sill HWD are generally depleted in Ba, Nb, Ta, Sr, P, Zr and Ti relative to HREE (Figure 2.6B). However, the anomalies for Ta, P, Zr are more pronounced in samples of Dullstroom Lavas (Figure 2.6B). Sample HWD and Dullstroom Lavas are similarly enriched in U, K, and Nd (Figure 2.6B). The positive Pb, P and Dy anomalies observed in sample HWD cannot be confirmed in samples of Dullstroom Lavas since these elements were not analyzed by Buchanan et al. (1999) (Figure 2.6B).

2.1.2. HWA, HWB, HWF, HWH, and HWG

In the IUGS total alkali versus silica (TAS) system (Le Bas et al., 1986), samples HWA, HWB, HWF, HWH (C+/- remanence) and HWG (lightning affected) plot as basaltic andesite, similar to some Dullstroom Lava samples (Buchanan et al., 1999). In the AFM plot (Irvine and Baragar,
1971), the Dullstroom Lavas fall in the calco-alkaline field. This is in contrast of the samples studied here which, with exception of HWH, are all tholeiitic. The samples from the present study also differ from Dullstroom Lavas in terms of Mg# (~67 - ~72 for HWA, HWB and HWF, and ~52.7 - ~55 for HWG and HWH, and 35-59.9 for Dullstroom Lavas).

In terms of REE, Dullstroom Lavas and samples HWA, HWB, HWF, HWH and HWG are similar in shape for the first three LREE (Figure 2.6A). However, the lavas plot slightly more enriched relative to the samples studied here. For the other LREE, Sm and Eu anomalies are more pronounced in the studied samples, relative to Dullstroom Lava rocks (Figure 2.6A). This explains the slight difference in La/Sm ratios between the post-Transvaal intrusions samples (~3.91) and Dullstroom Lava rocks (~3.46). Samples HWA, HWB, HWF, HWH and HWG, and Dullstroom Lava rocks generally display similar MREE and HREE patterns (Figure 2.6A). This is attested by a correlation in terms of Tb/Lu ratios between Dullstroom Lavas (~1.2 and ~1.37) and the studied post-Transvaal intrusions (~1.2- ~1.40).

Multi-element plots (spidergrams) generally reveal similarities of the studied samples to Dullstroom Lavas, in terms of shape (i.e. steep patterns for the LILE and the HREE, smooth curves for the MREE, and nearly flat profiles for HREE (Figure 2.6B). However, negative anomalies (e.g. Ta, P, and Ti) are generally more pronounced in Dullstroom Lavas, relative to the samples studied here (Figure 2.6B). The samples from the present study and Dullstroom Lavas are also similarly enriched in U, K, and Nd. However, the positive Pb, Pr and Y anomalies observed in the studied samples cannot be confirmed in Dullstroom Lava rocks since these elements were not analyzed by Buchanan et al. (1999) (Figure 2.6B).

**Figure 2.6.** Comparisons of trace elements geochemistry of studied samples with those reported from the older than 2.05 Ga Dullstroom Lavas after Buchanan et al., (1999). A: Rare earth elements normalized to chondrite of McDonough and Sun (1995). B: Multi-element plot (Spidergram) normalized to pyrolite of McDonough and Sun (1995).
2.2. Marginal rocks and sills of the eastern Bushveld Complex

Geochemical study of the marginal rocks and related sills from the basal contact of the RLS in the eastern KC have been recently conducted by Barnes et al. (2010). The aims were to provide reliable estimates of the parental magma compositions which formed this suite. These authors were able to correlate the studied samples with respectively the B1 magma of the Lower Zone and lower Critical Zone, the B2 magma of the upper Critical Zone, and the B3 magma of the Main Zone of the RLS.

2.2.1. HWD

If compared to the geochemical signatures obtained by Barnes et al. (2010), except the common andesitic character and tholeiitic affinity, the site HWD does not generally correlate well with the B2 or the B3 sills. However sample HWD shares some similarities with the B1 sills and B1 UM (B1 ultramafic) sills. The Mg# value (~69) in site HWD is so in good correspondence with that (~71) of the B1 and B1 UM sills and marginal rocks (Barnes et al., 2010). But sample HWD is more enriched in SiO$_2$ (~57wt. %), as attested by the andesite nature of this rock in the TAS plot (Le Bas et al., 1986), in contrast to the B1 and B1 UM sills that are of basaltic andesite composition (Barnes et al., 2010).

In terms of trace elements, chondrite-normalized REE profile (McDounough and Sun, 1995) of sample HWD bears a little resemblance to either the B2 sills, or the B3 sills of Barnes et al. (2010) (Figure 2.7A). Sample HWD, however, generally shares similarities with the B1 and B1 UM sills of Barnes et al. (2010) (Figure 2.7A). La/SmN (~4.3) of sample HWD is consistent with that (4) of the B1 and B1 UM sills. However, Eu/Eu* = ~0.80 for sample HWD is smaller, relative to B1 and B1 UM sills (Eu/Eu* 0.85-1.15). MREE an HREE patterns in site HWD are smooth (Figure 2.7A), with Gd/ErN (~1.58) lower than that (1.9) reported by Barnes et al. (2010). In terms of Er/LuN, the value (0.9) reported from the B1 and B1 UM magma sills is also lower than that (~1.12) yielded by sample HWD.

Multi-element plot (spidergram) of sample HWD does not compare well with those of B2 and B3 sills, but display remarkable similarities in shape (steep profile due to strong negative Ta, Nb, P and Ti anomalies, positive Pb anomaly) and level of enrichment with the B1 sills (Figure 2.7B). B1 UM spidergram is also similar in shape to sample HWD, but plot slightly depleted (Figure 2.7B).
2.2.2. HWA, HWB, HWF, HWH and HWG

In terms of major elements, little correlation exists between samples HWA, HWB, HWF and HWH (C+/− remanence) and HWG (lightning affected) and B2 and B3 sills of Barnes et al. (2010). However, remarkable similarities were found between the studied samples and B1 and B1 UM sills. The Mg# values of the studied samples (~67 - ~72), except sites HWG (lightning...
affected) and HWH (C+ remanence) (~52.7 - ~55) are close to that (~71) reported for the B1 and B1 UM sills by Barnes et al. (2010). The basaltic andesite character of the samples from the present study in the bivariate diagram of total alkali vs. silica (Le Bas et al., 1986) and their tholeiitic affinity in the AFM diagram (Irvine and Baragar, 1971) (except for site HWH which is calco-alkaline) also correlate well with the B1 and B1 UM sills of Barnes et al. (2010).

In terms of REE patterns, the samples studied here bear little resemblance to the B2 sills and B3 sills, but show good overlap with the B1and B1 UM sills (Figure 2.7A). The La/Sm value of the studied samples (~3.91) are so in good correspondence with that (~4) reported by Barnes et al. (2010) for the B1 and B1 UM sills. However, the MREE patterns for the samples from the present study here are smooth, relative to the B1 and B1 UM sills (Figure 2.7A). This is confirmed by the Gd/Er ratio (~1.37) of the sill and dyke samples that is lower than that (~1.9) of the B1 sills and B1 UM sills. In terms of HREE, the nearly flat patterns of the studied samples, confirmed by Er/LuN of ~1.05 correspond to one of the common features of B1 sills and marginal rocks (Figure 2.7A).

Multi-element plots (spidergram) of samples HWA, B, D, F, G and H reveal some resemblance with those of B2 and B3 sills, but display remarkable similarities in both shape (steep profile due to strong negative Ta, Nb, P and Ti anomalies, positive Pb anomaly) and level of enrichment with the B1 sills (Figure 2.7B). B1 UM spidergram is also similar in shape to the studied samples, but plot slightly depleted (Figure 2.7B).

2.3. ~1.9 Ga post-Waterberg intrusions and Black Hills dykes

The ~1.9 Ga intrusions that occur into the sedimentary rocks of the Waterberg Group were geochemically studied by Hanson et al. (2004). Similarly aged dykes that crosscut the Archean Basement in the Black Hills area were sampled by Klausen et al. (2010) for a geochemical study.

2.3.1. HWD

Major element geochemistry reveals that the ~1.9 Ga post-Waterberg intrusions and Black Hills dykes fell in the tholeiitic field of the AFM diagram (Irvine and Baragar, 1971), similarly to sample HWD. However, the ~1.9 Ga rocks generally plot as basalt in the alkalis vs. SiO₂ plot (Le Bas et al., 1986), contrary to sample HWD which fell in the andesite field. The relative low
Mg# values of the Black Hills dykes (~37.7-60) and the post-Waterberg intrusions (~53 to ~58) contrast with that (69) obtained for sample HWD (B remanence).

In terms of REE, the post-Waterberg intrusions and the Black Hills dykes are characterized by a smooth pattern for LREE, relative to sample HWD (Figure 2.8A). This is confirmed by a low La/Sm (~2) for samples studied by Hanson et al. (2004) and Klausen et al., (2010), relative to the value (4.3) in site HWD. In terms of MREE-HREE, the post-Waterberg intrusions and Black Hills dykes are generally more enriched than sample HWD (Figure 2.8A). But the differentiation observed for these elements is less pronounced relative to sample HWD. The ratios for Gd/Er (~1.5) and Er/Lu (~1.05) reported by Klausen et al. (2010) and Hanson et al. (2004) are low compared to the values in site HWD (~1.58 and ~1.12 respectively).

Multi-element plot (spidergram) of sample HWD reveals a correlation from Rb to K with samples studied by Hanson et al. (2004) and Klausen et al. (2010) (Figure 2.8B), but from La onwards, sample HWD generally bears little resemblance to the 1.9 Ga post-Waterberg intrusions and Black Hills dykes (Figure 2.8B). For instance, the pronounced P, Zr, and Ti anomalies revealed in 1.9 Ga rocks are not observed in site HWD (Figure 2.8B).

2.3.2. HWA, HWB, HWF, HWH and HWG

In terms of major elements, the ~1.9 Ga post-Waterberg intrusions and Black Hills dykes and all samples (except HWH) fall in the tholeiitic field of the AFM diagram (Irvine and Baragar, 1971). However, the ~1.9 Ga rocks are generally less enriched in SiO$_2$, plotting as basalt in the alkalis vs. SiO$_2$ plot (Le Bas et al., 1986), while the studied samples fell in the basaltic andesite field. Mg# values (~53 to ~58) of the post-Waterberg dolerites and Black Hills dykes (~37.7-60) are lower than those yielded by the sites HWA, HWB and HWF (67-72), but are in good correspondence with those (52.7-55.5) calculated for sites HWG and HWH.

In terms of REE, the post-Waterberg intrusions and Black Hills dykes generally less fractioned in LREE relative to samples HWA, HWB, HWF, HWG and HWH (Figure 2.8A). The La/Sm value (2) of the ~1.9 Ga rocks are so lower than that (~3.91) of the studied samples. The post-Waterberg intrusions and Black Hills dykes are also less fractioned in MREE and HREE, and display smooth curves for these elements (Figure 2.8A). This is confirmed by Gd/Er (~1.5) and
Er/Lu (~1.05) ratios reported by Hanson et al. (2004) and Klausen et al. (2010) that are lower than those (Gd/Er (~1.37) and Er/LuN (~1.05)) calculated for the studied samples. In terms of multi-element plot (spidergram), the studied samples generally match the ~1.9 Ga rocks for the LILE (Figure 2.8B). But, from Pb onwards, little similarities exist between these samples and the ~1.9 Ga post-Waterberg intrusions and Black Hills dykes (Figure 2.8B). For instance, the pronounced P, Zr, and Ti anomalies revealed in 1.9 rocks profiles are not observed in the samples from the present study (Figure 2.8B).

**Figure 2.8.** Comparisons of trace elements geochemistry of studied samples with those reported from the ~1.9 Ga Black Hills dykes (Klausen et al., 2010) and post-Waterberg intrusions (Hanson et al., 2004). A: Rare earth elements normalized to chondrite to McDonough and Sun (1995). B: Multi-element plot (spidergram) normalized to pyrolite of McDonough and Sun (1995).

### 2.4. ~1.1 Ga Umkondo sills

A geochemical study was recently conducted on the ~1.1 Ga Umkondo sills by Bullen et al. (2012). The majority of Umkondo sills defined a geochemical subgroup that Bullen et al. (2012) named the Mesoproterozoic post-Waterberg sills A (MPWA sills), while few samples could be classified as Mesoproterozoic post-Waterberg sills B (MPWB sills).

#### 2.4.1. HWD

In the AFM diagram (Irvine and Baragar, 1971) the ~1.1 Ga Umkondo sills and sample HWD fall in the same area, i.e. the tholeiitic field. This similarity is not observed in the TAS diagram (Le Bas et al., 1986) since the 1.1 Ga rocks, which have a low SiO₂, relative to HWD exhibit a basaltic andesite composition, while sample HWD plots as andesite. The relative low Mg#
values of the MPWA and MPWB Umkondo sills (~44- ~65) also contrast with that (69) yielded by site HWD.

In terms of REE, it can be said that the Umkondo sills (MPWA and MPWB subgroups) and sample HWD present comparable enrichment for the first four LREE (Figure 2.9A). For the other LREE, the negative Sm and Eu anomalies are more pronounced in sample HWD, relative to Umkondo LIP rocks (Figure 2.9A). This is attested by low La/Sm ratios (2.3 and 3) for Umkondo sills, relative to that (La/Sm = 4.3) of sample HWD. In terms of MREE and HREE, the Umkondo sills are generally less fractioned in LREE, but are more enriched compared to sample HWD. Gd/Er ratios for the MPWA (1.1 -1.2) and MPWB (~1.85) are different from that (~1.58) of site HWD. Er/Lu ratios of Umkondo sills (0.9-1 for MPWA subgroup and ~1.33 for MPWB subgroup) are also different from that (~1.12) of HWD.

In terms of multi-element plot (spidergram), except for the first four LILE, sample HWD and 1.1 Ga Umkondo sills do not show much correlation (Figure 2.9B). The remarkable negative K, P and Ti anomalies observed in 1.1 Ga Umkondo rocks are absent in sample HWD (Figure 2.9B).

2.4.2. HWA, HWB, HWF, HWH and HWG

In the AFM diagram (Irvine and Baragar, 1971), the studied samples (with the exception of HWH) and the ~1.1 Ga Umkondo sills fall in the same area, i.e. the tholeiitic field. Similarly, the studied samples (including HWH) and the 1.1 Ga rocks reveal a basaltic andesite composition in the TAS plot (Le Bas et al., 1986). However, Mg # values of MPWA and MPWB Umkondo sills (~44- ~65) do not correspond with either those yielded by sites HWA, HWB and HWF (67-72), or the values (52.7- 55.5) obtained for sites HWG and HWH.

In terms of REE, the ~1.1 Ga Umkondo sills (MPWA and MPWB subgroups) and the studied samples present comparable enrichment for the first four LREE. But Sm and Eu negative anomalies are more pronounced in the studied samples (Figure 2.9A). This is confirmed by low La/Sm ratios (2.3 and 3) for ~1.1 Ga Umkondo sills, relative to that (La/Sm = 3.9) of samples HWA, HWB, HWF, HWH and HWG. In terms of MREE and HREE, the Umkondo sills are generally less fractioned relative to the LREE (especially the MPWA subgroup), but are more enriched compared to HWA, HWB, HWF, HWH and HWG (Figure 2.9A). Gd/Er ratios for the MPWA (1.1-1.2) and MPWB (~1.85) are so different from that (~1.37) of the studied samples.
Er/Lu ratios of Umkondo sills (0.9-1) for MPWA subgroup however, correlate with that (~1.05) of the samples. This is not the case for the MPWB subgroup for which Er/Lu is around 1.33. Multi-element plot (spidergram) of the studied samples do not show much resemblance with those reported by Bullen et al., (2012) (Figure 2.9B). Except for the first four LILE, the studied samples patterns and those of Umkondo rocks are clearly different (Figure 2.9B). The drastic depletion in P and Ti that characterized the 1.1 Ga Umkondo LIP rocks is not observed in the studied samples, which rather display smooth curves Sr onwards (Figure 2.9B).

**Figure 2.9.** Comparisons of trace elements geochemistry of studied samples with the results from the ~1.1 Ga Umkondo LIP after Bullen et al. (2012). A: Rare earth elements normalized to chondrite of McDonough and Sun (1995). B: Multi-element plot (Spidergram) normalized to pyrolite of McDonough and Sun (1995).
2.5. ~180 Ma Karoo lavas, sills and dykes

A geochemical study was conducted on the ~0.18 Ga Karoo intrusions (i.e. Lavas, sills and dykes) in Southern Africa (Botswana, Zimbabwe and South Africa) by Jourdan et al. (2007). These authors were able to arrange their samples into two major geochemical subgroups namely the high-TiO$_2$ group (TiO$_2$ > 2 wt %) and the Low-Ti group (TiO$_2$ > 2 wt %).

2.5.1. HWD

The 180 Ma Karoo intrusions studied by Jourdan et al. (2007) are generally less enriched in SiO$_2$, but contain more TiO$_2$, relative to sample HWD. SiO$_2$ enrichment of Karoo LIP rocks are attested in the total alkalis-silica diagram (TAS) (Le Bas et al., 1986), in which they range from basaltic to trachy-andesitic in composition while sill HWD plots as andesite.

In terms of trace elements, the Karoo LIP rocks and sample HWD also display contrasting behaviors. Chondrite-normalized (McDounough and Sun, 1995) REE patterns of Karoo LIP rocks are generally more enriched, relative to sample HWD (Figure 2.10A). Karoo LIP rocks are significantly fractioned in LREE relative to MREE and HREE (Figure 2.10A). They display La/Sm of ~2 for lavas, sills, and picrites, ~1.72 for dykes, and ~1.98 for low-Ti lavas, in contrast to the 3.9 for sample HWD. This sample also differs from the high-Ti group of Karoo LIP rocks studied by Jourdan et al. (2007) by having a flatter MREE and HREE profile (Figure 2.10A). Gd/Er ratio of sample HWD (~1.58) is low, relative to those (~1.58 - ~3.67) reported by Jourdan et al. (2007) for the high-Ti group of Karoo LIP rocks. However, this ratio is higher than that (~1.2) of the low-Ti group of Karoo rocks. Er/Lu ratio of sample HWD (~1.12) is also different from those of high-Ti (~1.42 - ~1.75) and low-Ti (~0.98) Karoo LIP rocks.

Multi-element plot (spidergram) of sample HWD does not generally compare well with those reported by Jourdan et al. (2007) (Figure 2.10B). Positive K, Pb and Nd anomalies observed in sample HWD are not observed in Jourdan et al. (2007)’s samples while positive Ba, Ta, La, P and Ti anomalies revealed by Karoo LIP rocks are absent in sample HWD (Figure 2.10B).

2.5.2. HWA, HWB, HWF, HWH and HWG

In terms of major elements, samples HWA, HWB, HWF, HWH and HWG contain low TiO$_2$ and high SiO$_2$, relative to the 180 Ma Karoo intrusions studied by Jourdan et al. (2007). Most Karoo
LIP rocks plot as basalt in TAS diagram (Le Bas et al., 1986), and only few fall in basaltic andesite field. In comparison, all the studied samples reveal basaltic andesite composition in the same diagram.

**Figure 2.10.** Comparisons of trace elements geochemistry of studied samples with results from the 180 Ma Karoo intrusions after Jourdan et al. (2007). A: Rare earth elements normalized to chondrite of McDonough and Sun (1995). B: Multi-element plots (Spidergram) normalized to pyrolite of McDonough and Sun (1995)

In terms of REE, samples HWA, HWB, HWF, HWH, and HWG from the present study are different from rocks studied by Jourdan et al. (2007) in that chondrite-normalized REE patterns of Karoo LIP rocks are generally more enriched relative to samples studied here (Figure 2.10A). This enrichment is, however, less pronounced for low-Ti Karoo LIP samples (Figure 2.10A). LREE profiles of all Karoo LIP rocks are generally less steep, compared to samples of the present study (Figure 2.10A). This is attested by La/Sm ratios of Karoo LIP rocks (~1.72 - ~2) that are low, relative to the studied samples (La/Sm = 3.9). These samples also differ from Karoo LIP rocks which generally have steep MREE and HREE patterns, apart from the low-Ti group (Figure 2.10A). This is confirmed by Gd/Er ratios of Karoo LIP rocks (~1.58 - ~3.67) that are high, relative to the studied samples (Gd/Er is around 1.37). Gd/Er for the low-Ti group of Karoo...
LIP rocks is ~1.2 (Jourdan et al., 2007). Er/Lu ratio for samples studied here (~1.05) is also different from those of high-Ti (~1.42 - ~1.75) and low-Ti (~0.98) Karoo LIP rocks. Multi-element plots (spidergram) of samples from this study bear little resemblance to those reported by Jourdan et al. (2007) (Figure 2.10B). These samples are enriched in K, Pb and Nd, in contrast to the Karoo LIP rocks (Figure 2.10B). On the other hand, positive Ba, Ta, La, P and Ti anomalies revealed by Karoo LIP rocks are not present in the studied samples (Figure 2.10B).

3. BLIBLIOGRAPHIC REFERENCES


APPENDIX 3

1. PETROGRAPHY OF POST-TRANSVAAL SILLS IN THE WESTERN KC

Here detailed petrographic observations from the various sills sampled in the sill suites that intrude the Pretoria Group in the Bronkhorstspruit and Rustenburg areas (western KC) are described according to the stratigraphic heights at which these intrusions occur. Intrusions are described from the base upwards (i.e. BRD to BRE in Bronkhorstspruit area, and from RUE to RUC in Rustenburg area) (see Figure 3.1)

**Figure 3.1.** Stratigraphic setting of the sampling sites in the Pretoria Group

3.1. Sites in Bronkhorstspruit area

3.1.1. BRD

BRD is a SE-trending sill with a thickness of ~100m. Hand sample suggests a coarse grained altered pyroxenite. The rock reveals a sub-ophitic texture that involves cumulus of orthopyroxene and plagioclase minerals set in a matrix of pyroxene and opaque mineral grains...
(Figure 3.2). Orthopyroxene mineral, which is variably altered, especially along the cracks occurs as ~1mm to ~2mm euhedral elongated crystals or anhedral grains that are generally intergrown with plagioclase. Plagioclase involves large blades or elongated sub-euhedral to euhedral polysynthetic twinned crystals (~2mm) that are generally fresh, relative to orthopyroxene.

3.1.2. BRA

BRA is a ~80 m thick dolerite that exposes as fresh angular blocks. The sill displays some grain size variation. It is coarse at the sill margin and becomes very coarse towards the centre of the intrusion. In thin section, the rock is characterized by a sub-ophitic texture (Figure 3.2). Clinopyroxene and plagioclase constitute the main mineral phases. A small amount of quartz is also present. Clinopyroxene consists of ~2-3 mm anhedral elongated and cracked crystals, some of which are partially replaced by chlorite. Plagioclase is generally fresh, although some saussuritized crystals of this mineral have been observed. This mineral involves elongated polysynthetically twinned laths that range generally between 1-1.5 mm. Radial intergrowth of pyroxene and plagioclase is very common.

3.1.3. BRC

BRC is a ~60m thick dolerite striking approximately E-W and dipping 12° to the north. The rock has a fine grained sub-ophitic texture that involves clinopyroxene and plagioclase. Quartz and biotite occur as minor accessory mineral phases. Clinopyroxene consists of 0.5mm sub-euhedral elongated crystals (Figure 3.2) which are generally fresh. This mineral is enclosed by laths of ~0.5 mm elongated polysynthetically twinned plagioclase bodies. Quartz and biotite have a characteristic white aspect and occurs as small, anhedral crystals, some of which occur as intercumulus phases. Small quartz grains also occur in the groundmass, together with other fine-grained, granular and variably altered minerals that probably replaced plagioclase and pyroxene.

3.1.4. BRB

BRB consists of a ~60m altered dolerite with a strike of 90° and a shallow dip of about 12° to the north. The sill is a fine grained rock with igneous features that are generally disturbed (Figure 3.2). Phenocrysts (clinopyroxene and plagioclase) are strongly altered. The matrix is composed
of plagioclase and opaque minerals. Plagioclase, which occurs as ~0.75 mm anhedral laths, is variably saussuritized. Clinopyroxene involves anhedral corroded blades or grains that are sometimes replaced by amphibole and clay minerals.

Figure 3.2. Microphotographs of selected samples from the present study. BRD: Altered cumulus of orthopyroxene (opx) set in a fine grained matrix. BRA: Intergrowth of orthopyroxene (opx) and plagioclase (plg) in a sub-ophitic to granular texture. BRC: Anhedral pyroxene (opx and cpx) and plagioclase (plg) set in a fine grained quartz-rich matrix. BRB: Sub-ophitic to granular texture with bundles of altered clinopyroxene (cpx) and plagioclase (plg) set in a fine grained matrix. BRE: Anhedral variably altered crystals of orthopyroxene (opx) set in a granular texture of quartz-rich matrix.
3.1.5. BRE

BRE is a ~ 200m thick, NW-trending, shallowly dipping (12°) sill, characterized by a prominent columnar jointing. The sill is essentially composed of pyroxene and plagioclase. Orthopyroxene is the most dominant pyroxene and occurs in close association with the clinopyroxene. Due to the interstitial nature of the pyroxene minerals growing around the plagioclase, a subophitic to ophitic texture is developed. Phenocrysts are strongly altered (Figure 3.2). Secondary mineral phases include different clay minerals (serpentine, sericite and chlorite), and sometimes amphibole. Plagioclase involves fine grained crystals which are variably saussuritized. Orthopyroxene involves anhedral corroded blades or grains that are largely altered to amphibole and clay minerals. The groundmass consists of small quartz grains and other fine grained, granular and variably altered minerals that are believed to have replaced plagioclase and pyroxene.

3.2. Sites in Rustenburg area

3.2.1. RUE

RUE is a ~50m thick sill (160°/16° NE) that intrudes through the upper Timeball Hill Formation (Figure 3.3). Hand sample suggests a coarse grained altered pyroxenite, with igneous features being partially preserved. The mineralogy is composed of cumulus orthopyroxene blades, this mineral being the dominant phase, followed by small amount of interstitial plagioclase. Orthopyroxene involves skeletal-to-subhedral orthopyroxene present as large blades and laths highly altered to amphibole and clay minerals. Interstitial plagioclase commonly displays alteration to sericite, which appears as brownish specks. The phenocrysts are set in a matrix composed of pyroxene and opaque minerals.

3.2.2. RUF

RUF is a weathered dolerite of ~ 40 m thickness that essentially consists of clinopyroxene and plagioclase. Clinopyroxene is interstitial to cumulus plagioclase. Phenocrysts are strongly altered (Figure 3.3). The matrix is composed of saussuritized plagioclase and opaque minerals. Plagioclase phenocrysts, which occur as ~0.75 mm anhedral laths, are variably saussuritized.
Pyroxene involves anhedral corroded blades or grains that are largely altered to amphibole and clay minerals.

3.2.3. RUG

RUG is a ~35m thick sill (160°/ 6° NE). Hand sample contains stubby black phenocrysts of pyroxene and amphibole set in a dark coarse-grained matrix. Small amounts of quartz also occur. Pyroxene consists of ~1mm anhedral prismatic blades which are variably replaced by chlorite or sericite. This mineral is partially embedded in plagioclase which is generally fresh, although some saussuritized crystals of this mineral have been noted. Plagioclase involves elongated polysynthetically twinned laths that are in the order of 1mm in length. Intergrowth of pyroxene and plagioclase is common. Aggregates of quartz occur in abundance and occasionally are intergrown with pyroxene and plagioclase.

3.2.4. RUI

RUI has a strike of ~130° and a dip of ~ 12° towards the north north east. The sill is essentially composed of clinopyroxene and plagioclase. Clinopyroxene is interstitial to cumulus plagioclase. The rock has a subophitic texture that involves intergrowth of clinopyroxene around the plagioclase (Figure 3.3). Phenocrysts are generally fresh, with alteration being restricted along cleavage planes, cracks and grain boundaries. The matrix is not abundant. Clinopyroxene consists of ~1.5 mm anhedral elongated and cracked crystals, some of which are partially replaced by chlorite. Plagioclase involves elongated polysynthetically twinned laths (1-1.5 mm) that are generally fresh, although some saussuritized crystals of this mineral have been noted.

3.2.5. RUH

RUH is a weathered sill of about 70 m thickness. The N-S striking sill dips 15° to the east and is intrusive into the Silverton Formation. In thin section, the rock displays a very fine grained texture. Phenocrysts are generally rare in the rock. Micro crystals (< 0.25mm) of pyroxene and plagioclase are set in abundant granular groundmass composed of small quartz grains and other fine grained and variably altered minerals that are believed to replace plagioclase and pyroxene (Figure 3.4).
Figure 3.3. Microphotographs of selected samples from the present study. RUE: Cumulus of skeletal blades of orthopyroxene (opx) set in a fine grained groundmass. RUF: Granular texture involving skeletal blades of clinopyroxene (cpx) set in a fine grained groundmass. RUG: Granular texture involving small crystals and grains of altered clinopyroxene (cpx) set in a fine grained matrix. RUI: sub-ophitic texture with bundles of clinopyroxene (cpx) and plagioclase (plg).

3.2.6. HKP

Sill HKP intruded near the base of the Silverton shales (Figure 3.4). Hand specimen displays a relatively fresh blue-grey medium-grained rock with coarse-grained patches. The mineralogy is composed of cumulus clinopyroxene blades, this mineral, together with plagioclase, being the dominant phases. Abundant granophyric quartz and what it is believed to be biotite also occur. Clinopyroxene consists of 1-2mm anhedral elongated crystals (Figure 3.4) which are generally fresh. This mineral is enclosed by laths of ~0.5 mm elongated polysynthetically twinned plagioclase crystals (1-1.5 mm) that are generally fresh, although some saussuritized crystals of this mineral have been noted. Quartz and biotite have a characteristic white aspect and occurs as small, anhedral crystals, disseminated in the groundmass, together with other fine grained, granular and variably altered minerals that have replace plagioclase and pyroxene.
3.2.7. RUB

RUB is a ~300m thick and prominent sill (130°/18°NE). The sill is a highly altered, fine-grained rock with a granular texture. Original igneous features are quite obliterated. Clinopyroxene is the dominant pyroxene and occurs as interstitial to cumulus plagioclase. Secondary mineral phases include clay mineral and amphibole. Clinopyroxene phenocrysts have an average size of 0.5-1 mm and are frequently pseudomorphed by both amphibole (Figure 3.4) and clay minerals (chlorite). Clinopyroxene is variably intergrown with frequently saussuritized plagioclase, which involves sub-euhedral elongated (~0.25 mm) polysynthetically twinned laths or anhedral blades.

3.2.8. RUJ

Sill RUJ is essentially composed of cumulus of clinopyroxene and plagioclase set in an intercumulus opaque-rich matrix that includes small amounts of quartz, clinopyroxene and biotite. Due to the interstitial nature of the clinopyroxene growing around the plagioclase, an ophitic texture is well-developed (Figure 3.4). Phenocrysts are relatively fresh, with alteration being preferentially developed along cleavage planes, cracks and grain boundaries. Clinopyroxene involves sub-euhedral elongated crystals, some of which are variably altered to amphibole and clay minerals. Plagioclase involves elongate well-developed polysynthetic twinned crystals (~2mm) that are generally fresh relative to pyroxene.

3.2.9. RUD

Sill RUD intruded into the upper part of the Silverton Formation (160/15°NE). The hand specimen is characterized by phenocrysts of plagioclase and stubby black phenocrysts of pyroxene set in a generally coarse-grained matrix. In thin section cumulus orthopyroxene grows around plagioclase crystals in a well-developed ophitic texture (Figure 3.4). Matrix is not abundant and includes opaque minerals, altered pyroxene and small amounts of quartz and biotite. Alteration of phenocrysts is generally restricted along cleavage planes, cracks and grain boundaries. Plagioclase involves elongated well-developed polysynthetic twinned crystals (~2mm) that are generally fresh, relative to the pyroxenes. Orthopyroxene involves sub-euhedral cracked, elongated slightly altered crystals or corroded blades.
Figure 3.4. Microphotographs of selected samples. RUH: rock entirely composed of fine grained matrix. HKP: Sub-ophitic texture with anhedral clinopyroxene (cpx) blades enclosing plagioclase (plg) crystals. RUB: Granular texture involving small crystals and grains of altered clinopyroxene (cpx) set in a fine grained matrix. RUJ: Well developed ophitic texture involving cumulus of clinopyroxene (cpx) and plagioclase (plg). RUD: Elongated phenocrysts of orthopyroxene (opx) in an altered matrix. RUC: Igneous texture disturbed by alteration, involving orthopyroxene (opx) and plagioclase that are largely replaced by secondary minerals.

3.2.10. RUC

Sill RUC intrudes the Silverton Formation (170°/13°E). Thin section reveals a coarse-grained altered rock with igneous features being relatively disturbed (Figure 3.4). Cumulus of orthopyroxene grows around plagioclase mineral phase, so developing an ophitic texture.
Phenocrysts are variably altered. Secondary mineral phases include different clay minerals, and sometimes amphibole. Pyroxene involves anhedral corroded blades or grains that sometimes display a cloudy aspect. Plagioclase is fresh, relative to pyroxene and involves elongated well-developed polysynthetic twinned crystals (~2mm) (Figure 3.4) that are generally fresh, relative to orthopyroxene. The groundmass is abundant and consists of small quartz grains and other fine grained, granular and variably altered minerals that are believed to be plagioclase, pyroxene and biotite.
APPENDIX 4

PETROGRAPHY AND GEOCHEMISTRY OF POST-TRANSVAAL DYKES NEAR LYDENBURG, EASTERN KC

1. DESCRIPTION OF THIN SECTIONS

Here, thin sections of dykes sampled from the swarm that intrudes the Pretoria Group near Lydenburg are described. Dykes were sampled in the southeast and the northeast of Lydenburg (see Figure 4.1).

Figure 4.1. Geological map of the Transvaal Supergroup in the area of Lydenburg showing the different sampling sites. Dykes are mapped as “Jurassic units”
1.1. Dykes southeast of Lydenburg

1.1.1. LDH

Site LDH represents a ~50 m wide NNE-oriented dyke. Hand specimen consists of fresh looking fine grained dolerite. In thin section cumulus orthopyroxene grows around plagioclase crystals with a well-developed ophitic texture (see Figure 4.2). These two minerals occur in almost equal proportion and constitute the dominant phases. Clinopyroxene and opaque minerals constitute minor phases. The matrix is not abundant and includes opaque minerals, altered pyroxene and small amounts of quartz and what is suspected to be altered biotite. Orthopyroxene consists of sub-euhedral cracked phenocrysts with a medium grain size (generally < 1mm) (see Figure 4.2). This mineral generally displays alteration along grain cracks, boundaries or cleavages and the most altered crystals sometimes have a cloudy aspect. The alteration product is chlorite and sericite, and rarely amphibole. Plagioclase consists of 0.5-1 mm anhedral polysynthetically twinned laths or lamellae sections that are generally less altered, relative to the orthopyroxene with which it intergrowths (see Figure 4.2).

1.1.2. LDB

Towards the north-west of the previous site (LDH), a prominent ~100m thick NNE-trending dyke occurs. Hand sample consists of fresh looking, medium grained dolerite. In thin section the rock reveals a hypocrystalline texture involving skeletal, euhedral lath-shaped phenocrysts as well as basal sections of orthopyroxene enclosed by a brown glassy matrix (see Figure 4.2). Orthopyroxene, which is frequently altered to chlorite, is about 1mm size. No plagioclase phenocryst is observed in this rock (see Figure 4.2). The matrix consists of fine grained (needle-like) chloritized material and a consistent amount of opaque minerals.
1.1.3. LDC

Not far from site LDH, a weathered NNE-oriented medium to coarse-grained ~50 m thick dolerite dyke occurs. The rock essentially consists of orthopyroxene and plagioclase that are strongly altered (see Figure 4.2). Small amount of quartz was also found. Phenocrysts are set in a groundmass composed of saussuritized plagioclase and opaque minerals. Orthopyroxene phenocrysts have an average size of 1-1.2 mm and are highly altered to both amphibole and clay minerals (chlorite and sericite). Orthopyroxene is variably intergrown with frequently saussuritized plagioclase, which involves sub-euhedral elongated (~0.25 mm) polysynthetically twinned laths or anhedral blades (see Figure 4.2).
1.1.4. LDA

In the close vicinity of the previous sites (in the western side), a weathered north-north-east oriented ~25 m thick fine-grained dyke occurs. Thin section reveals that the original igneous features are obliterated by alteration. It results in a granular texture that involves altered orthopyroxene, plagioclase set in a fine-grained matrix (see Figure 4.2). The matrix consists of fine-grained material of needle-like chloritised material, abundant opaque minerals and small amounts of quartz. Orthopyroxene phenocrysts, which have an average size between ~1 mm, are highly altered to both amphibole and clay minerals (chlorite and sericite). Plagioclase involves small (~0.25 mm) polysynthetically twinned anhedral grains.

1.2. Dykes northeast of Lydenburg

1.2.1. LDD

LDD is a quite weathered 70m thick fine-grained dyke. The rock is essentially composed of orthopyroxene and plagioclase (see Figure 4.3). Small amounts of granophyric quartz also occur. Orthopyroxene phenocrysts, which have an average size of ~0.75 mm, are highly altered into amphibole and clay minerals (chlorite and sericite). Plagioclase occurs as small anhedral (~0.25 mm) polysynthetically twinned anhedral grains. Quartz occurs as small, anhedral crystals, disseminated in the groundmass, together with other fine-grained, granular and variably altered minerals (see Figure 4.3.) that are believed to be plagioclase, pyroxene and biotite.

1.2.2. LDE

Site LDE occurs close to LDD and exposes a weathered ~20m wide NNE-oriented fine-grained dyke. The rock is mostly composed of orthopyroxene. This mineral, together with plagioclase, are the dominant phases. The phenocrysts are set in a granular matrix (see Figure 4.3.) that consists of variably altered minerals that are believed to be plagioclase, orthopyroxene and biotite. Orthopyroxene is highly altered into amphibole and clay minerals (chlorite and sericite).
Appendix 4

Plagioclase involves small (~0.25 mm) polysynthetically twinned anhedral grains. Quartz constitutes a minor phase and occurs as small, anhedral crystals, disseminated in the groundmass.

1.2.3. LDF

At site LDF, a ~50m thick north north-east-trending dyke is exposed. Thin section reveals that the igneous features are obliterated by alteration (see Figure 4.3). A disturbed granular texture that involves altered orthopyroxene, clinopyroxene, and plagioclase is observed. Secondary mineral phases include clay minerals and amphibole. Phenocrysts are set in a matrix that consists of fine-grained material of needle-like chloritized pyroxenes, abundant opaque minerals and small amounts of quartz. Orthopyroxene phenocrysts have an average size of ~0.5 mm and are frequently pseudomorphed by amphibole and clay minerals (chlorite and sericite). Clinopyroxene variably shows intergrowth with frequently saussuritized plagioclase, which involves sub-euhedral elongated (~0.25 mm) polysynthetically twinned laths or anhedral blades (Figure 4.3).

1.2.4. LDG

Not far from the previous sites, a ~80m weathered medium grained dolerite dyke (LDG) was sampled. Thin section reveals that orthopyroxene is the dominant mineral, together with plagioclase. Secondary mineral phases include clay minerals and amphibole. Due to the interstitial nature of the orthopyroxene growing around the plagioclase, a sub-ophitic texture, now largely obliterated by alteration, is developed. Orthopyroxene consists of ~1mm skeletal anhedral elongated crystals (see Figure 4.3.), some of which are largely altered. Plagioclase involves small (~0.25 mm) polysynthetically twinned anhedral bodies. The groundmass is fine-grained and consists of variably altered minerals (see Figure 4.3) that are believed to be plagioclase, pyroxene and biotite.
Microphotographs of some dyke samples: LDE, LDF and LDI display granular texture involving altered orthopyroxene (opx) and plagioclase (plg) in a fine grained matrix. LDD, LDG and LDJ display altered blades of orthopyroxene (opx) showing intergrowth with plagioclase in a medium-grained subophitic texture.

1.2.5. LDI

At this site, a weathered north north-east oriented ~60m thick fine grained dyke is exposed. The mineralogy of this rock is composed of cumulus orthopyroxene and plagioclase (see Figure 4.3.). Small amounts of granophyric quartz also occur. Orthopyroxene phenocrysts, which have an average size of ~0.5 mm, are altered to amphibole and clay minerals (chlorite and sericite) (see Figure.4.3) Plagioclase occurs as small (~0.25 mm) polysynthetically twinned anhedral
grains. Quartz consists of small anhedral crystals disseminated in the groundmass, together with other fine grained, granular and variably altered minerals that are believed to be plagioclase, pyroxene and biotite.

1.2.6. LDJ

In close vicinity of dyke LDI, a weathered ~60m thick medium grained dolerite dyke (LDJ) occurs. The rock has a subophitic texture that involves intergrowth of orthopyroxene minerals around plagioclase. Orthopyroxene consists of ~1mm skeletal anhedral elongated crystals (see Figure 4.3), some of which are largely altered. Plagioclase minerals generally consist of small (~0.25 mm) polysynthetically twinned anhedral bodies. These phenocrysts are set in a matrix of altered orthopyroxene and opaque mineral grains and small amounts of another mineral (see Figure 4.3) that is suspected to be biotite.

2. CORRELATIONS OF GEOCHEMICAL RESULTS FROM LYDENBURG DYKES TO THE STRATA-BOUND IGNEOUS SUITES ON THE KC

In this section, comparisons of the geochemical data from dykes LDA, LDD, LDE, and LDF to previously published results from Paleoproterozoic and younger units on KC (i.e. the older than 2.05 Ga Dullstroom lavas, the sills and marginal rocks of the basal contact of the eastern BIC, the ~1.9 Ga post-Waterberg intrusions and Black Hills dykes, the ~1.1 Ga Umkondo sills, and the 180 Ma Karoo sills, lavas, and dykes) are done.

2.1. ~2.2 Ga Hekpoort Lavas

The ~2.2 Ga Hekpoort Lavas were geochemically studied by Crow and Condie (1990). All but one fall reveal basaltic andesite in composition in the Alkalis vs. SiO₂ plot. The studied samples generally revealed a basaltic andesitic composition in the same diagram. The Hekpoort Lavas display variable Mg# ranging from ~25.6 to ~73. The dyke samples show a range of values between ~60 and ~64.
REE distributions of Hekpoort Lavas generally show strong enrichment in LREE (with La/Sm = ~3.4 – ~4.8) compared to the studied Lydenburg dykes (La/Sm= ~2.6- ~3.05) (Figure 4.4A). The Hekpoort Lavas have rather flat LREE and HREE profiles with only slight positive Tb and negative Yb anomalies (Figure 4.4A), producing Tb/Lu ratios of ~1.33--1.52. All but one dyke samples display a similar behaviour, with Tb/Lu ranging between ~1.28 to ~1.4.

In terms of multi-element plot (spidergram), samples LDA and LDD share some similarities with the mafic Hekpoort Lavas in terms of positive K, Pb, and negative Nb, La, Ce, Sr kinks (Figure 4.4B). Although slightly enriched, samples LDE and LDF also bear resemblance to the Hekpoort Lavas (particularly the felsic sample) (Figure 4.4B). But the negative Ti kink of the felsic Hekpoort Lavas is absent here (Figure 4.4B).

**Figure 4.4.** Comparison of trace elements geochemistry of studied samples with those reported from the Hekpoort Lavas after Cow and Condie (1990). A: Rare earth elements normalized to chondrite of McDonough and Sun (1995). B: Multi-element plot (Spidergram) normalized to pyrolite of McDonough and Sun (1995).

2.2. > 2.05 Ga Machadodorp Member

Crow and Condie (1990) sampled the Machadodorp Member for a geochemical study. All but one sample reveal basaltic composition in the Alkalis Vs SiO₂ plot. In the same diagram, the studied Lydenburg dykes plotted in the basaltic andesite field. In terms of Mg#, the Machadodorp Member rocks show lower values (~46.4 - ~55.8) compared to dyke samples (~60-~64).
REE distributions of Machadodorp Lavas are characterized by smooth LREE and MREE curves that contrast with the steep profiles of Lydenburg dykes (Figure 4.5A). This is attested by La/Sm of Machadodorp Member rocks (~0.84 – ~1.98) that are lower relative to the studied dyke samples (La/Sm= ~2.6- ~3.05). The Machadodorp Lavas also have smooth HREE profiles with only slight positive Tb and negative Yb anomalies (Figure 4.5A), producing Tb/Lu ratios of ~0.84~1.18. The studied samples show Tb/LU ratios that range between ~1.13 to ~1.4.

Multi-element plots (spidergrams) of Lydenburg dykes reveal some similarities with the Machadodorp Lavas in terms of positive K, Pb, Ti and negative Ce, Sr and Eu kinks (Figure 4.5B).

Figure 4.5. Comparison of trace elements geochemistry of studied samples with those reported from the Machadodorp member after Cow and Condie (1990). A: Rare earth elements normalized to chondrite of McDonough and Sun (1995). B: Multi-element plot (Spidergram) normalized to pyrolite of McDonough and Sun (1995).

2.3. > 2.05 Ga Dullstroom Lavas

The older than 2.05Ga Dullstroom Lavas were geochemically studied by Buchanan et al. (1999). These authors arranged the Dullstroom Lavas rocks into three chemical groups i.e. the Ti-rich, low-Ti, and felsic groups. The low-rich and high-Ti groups range from basaltic andesite to andesite in the IUGS total alkali versus silica (TAS) system (Le Bas et al., 1986), and the felsic units from andesite to dacite (Buchanan et al., 1999). In comparison, the studied Lydenburg dykes range from basalt (LDB and LDC) to basaltic andesite (LDA, LDD, LDE, LDF and LDG). These samples display relatively high Mg# (~60–~64) compared to Dullstroom Lavas (35 – 59.9).
In terms of REE, the studied dykes (La/Sm= ~2.6 --~3.05; Tb/Lu= ~1.28- ~1.4) bear resemblance to the Dullstroom Lavas (La/Sm= ~3.46; Tb/Lu= ~1.2-~1.37) (Figure 4.6A). Multi-element plots of samples LDA, LDD, LDE, and LDF are also generally similar in term of shape (e.g. negative Mb, Ta, Ce and Eu and positive U, K and Nd anomalies) and level of enrichment to the Dullstroom Lavas (Figure 4.6B).

**Figure 4.6.** Comparison of trace elements geochemistry of studied samples with those reported from the older than 2.05 Ga Dullstroom lavas after Buchanan et al. (1999). A: Rare earth elements normalized to chondrite of McDonough and Sun (1995). B: Multi-element plot (spidergram) normalized to pyrolite of McDonough and Sun (1995).

### 2.4. Marginal rocks and sills of the eastern Bushveld Complex

Geochemical results of the marginal rocks and sills that occur at the basal contact of the RLS in the eastern KC have been recently published by Barnes et al. (2010). These authors suggested relationships between the studied rocks and the B1 magma of the Lower Zone and lower Critical Zone, the B2 magma of the upper Critical Zone, and the B3 magma of the Main Zone of the RLS.

In terms of major elements, little correlation generally exists between the studied Lydenburg dykes (basaltic andesite with Mg# between ~61 and ~64) and the B1, B2, and B3 sills (tholeiitic basalts with Mg# of ~71, ~55 and ~62 respectively) of Barnes et al. (2010).

Similarly, chondrite-normalized REE profiles of dyke samples generally reveal a little match with the B1, B2 sills and B3 sills (Figure 4.7A) as attested by the following ratios. B1 sills: La/Sm=4, Gd/Er =1.9, Er/Lu = 0.9; B2 sills: La/Sm = 2.5, Gd/Lu = 1.6; B3 sills: La/Sm = 2.3, Gd/Lu = 1.3; dyke samples: La/Sm = 2.6 - 3.05, Gd/Er = 1.16 - 1.3, Er/Lu = 1.28 -1.4.
Multi-element plots (spidergram) of the studied dykes do not compare well with the B2 and B3 sills (Figure 4.7B). However the Lydenburg dykes display some similarities in both shape (negative Nb, Ta, Ce and Pr and positive U, K and Pb kinks) and level of enrichment with the B1 sills (Figure 4.7B). But the characteristic negative Ti anomaly of B1 sills is absent in the studied dykes. Multi-element plots of samples LDA and LDG bear some resemblance to the B1 UM sills but plot slightly enriched (Figure 4.7B).

**Figure 4.7.** Comparison of trace elements geochemistry of studied samples with results reported from sills and marginal rocks of the RLS in the same area after Barnes et al. (2010). A: Rare earth elements normalized to chondrite of McDonough and Sun (1995). B: Multi-element plot (Spidergram) normalized to pyrolite of McDonough and Sun (1995).
2.5. ~1.9 Ga post-Waterberg intrusions and Black Hills dykes

In the AFM diagram (Irvine and Baragar, 1971), the ~1.9 Ga post-Waterberg intrusions studied by Hanson et al. (2004) and the similarly aged Black Hills sampled by Klausen et al. (2010) plot as tholeiitic contrary to the Lydenburg dykes from the present study that are calco-alkaline. The Black Hills dykes and the post-Waterberg intrusions display relatively lower Mg # (~37.7-60 and ~53 -~58) compared to dyke samples (~61--64).

In terms of trace elements, the post-Waterberg intrusions and Black Hills dykes are characterized by a smooth pattern for LREE, relative to the studied dykes samples (Figure 4.8A).

This is confirmed by a low La/Sm (~2) for samples studied by Hanson et al. (2004) and Klausen et al. (2010), relative to the values (2.60 -3.05) of the Lydenburg dykes. MREE-HREE curves of the post-Waterberg intrusions and Black Hills dykes, with Gd/Er =~1.5 and Er/LuN= ~1.05, also bear no resemblance to samples LDA, LDD, LDE, and LDF, (Gd/Er =~1.16- ~1.3) and Er/Lu =~1.06 -~1.18) (Figure 4.8A).

Multi-element plots (spidergrams) of ~1.9 Ga rocks reveal a relative correlation from Rb to P with samples LDA, LDD, LDE, and LDF (Figure 4.8B). But from P onwards, no reasonable correlation is found between the Lydenburg dyke samples and the 1.9 rocks (Figure 4.8B).

2.6. ~1.1 Ga Umkondo sills

Geochemical results from the ~1.1 Ga Umkondo LIP were recently published by Bullen et al. (2012). These authors arranged the Umkondo sills into two classes i.e. the Mesoproterozoic post-
Waterberg sills A (MPWA sills) and Mesoproterozoic post-Waterberg sills B (MPWB sills). Following the AFM diagram (Irvine and Baragar, 1971) the ~1.1 Ga Umkondo sills were tholeiitic in contrast to the studied Lydenburg dykes that plotted in the calco-alkaline field. In the TAS diagram (Le Bas et al., 1986), the 1.1 Ga rocks reveal a basaltic andesite composition while the Lydenburg dykes mainly plot as basaltic andesite. Mg # values of Umkondo sills (~44-~65) are generally in the range of the studied dykes (~61-~64).

2.7. ~180 Ma Karoo lavas, sills and dykes

The 180 Ma Karoo intrusions in Southern Africa (Botswana, Zimbabwe and South Africa) were geochemically studied by Jourdan et al. (2007). These authors classified the Karoo intrusions into two main classes, in terms of Ti content, i.e. the high-TiO₂ class (TiO₂ > 2 wt %) and the
Low-Ti class (TiO2 > 2 wt %). Most of Karoo LIP rocks plot as basalt in TAS diagram (Le Bas et al., 1986), and only few failed in basaltic andesite field. In comparison, the studied Lydenburg dykes displayed basaltic andesitic composition in the same diagram.

In terms of trace elements, samples LDA, LDD, LDE and LDF from the present study are different from rocks studied by Jourdan et al. (2007) in that chondrite-normalized REE patterns of Karoo LIP rocks are generally more enriched (except for the low-Ti Karoo rocks), relative to Lydenburg dykes (Figure 4.10A).

![Figure 4.10](image)

**Figure 4.10.** Comparisons of trace elements geochemistry of studied samples with results from the 180 Ma Karoo intrusions after Jourdan et al. (2007). A: Rare earth elements normalized to chondrite of McDonough and Sun (1995). B: Multi-element plots (Spidergram) normalized to pyrolite of McDonough and Sun (1995)

Karoo LIP rocks also reveal moderate steep LREE profiles attested by low La/Sm (~1.72 - ~2), relative to the studied Lydenburg dykes (La/Sm= 2.60-3.05) (Figure 4.10A). These dykes also differ from Karoo LIP rocks by having flat MREE and HREE patterns (Figure 4.10A). This is confirmed by low Gd/Er ratios of dyke samples (~1.16 ~1.3) relative to Karoo LIP rocks (~1.58 - ~3.67). Er/Lu ratios (~1.06~1.18) of dyke samples do also not compare well with both high-Ti (~1.42 ~1.75) and low-Ti (~0.98) Karoo LIP rocks.

The spread of multi-element profiles of the Lydenburg dykes also reveal no consistence with the Karoo LIP (Figure 4.10B).
3. BIBLIOGRAPHIC REFERENCES


