Drilling the Bushveld Intrusion

ICDP Workshop Agenda

September 7 Sunday **Holiday Inn Rosebank**
Afternoon: arrival and registration of hotel guests

18:00-19:00 Holiday Inn Tyrwhitt Rooms 1&2 - Welcome & Introduction

19:00 - 23:00 Icebreaker / dinner with finger food and drinks

September 8 Monday **Witwatersrand University, Geosciences**

8:00 Bus pickup at Hotel, travel to and registration at Wits Geosciences
Participants arriving separately see campus map

9:00 - 9:30 Welcome addresses
Lewis Ashwal (Wits) for the School of Geosciences
Robert Trumbull (GFZ Potsdam) for the organising committee
Ulrich Harms (GFZ Potsdam), ICDP manager

9:30 - 11:00 Introductions to the main science themes (titles subject to change)

9:30 - 10:00 Grant Cawthorn (Wits): *Bushveld Overview: (a) Structure & emplacement, (b) Petrology and metallogenesis*
10:00 - 10:15 Susan Webb (Wits): *Geophysical surveys of the BIC*
10:15 - 10:30 Kai Wittheuser (UFS): *Deep groundwater research in the BIC*
10:30 - 10:45 Tom Kieft (New Mexico Tech): *Deep biosphere research in the BIC*
10:45 - 11:00 Frederick Roelofse (UFS): *Overview of existing BIC drillcores*

11:00- 11:30 Teabreak

11:30 – 13:00 Begin discussing science themes and synergies in plenum

13:00 – 14:00 Lunch

14:00 – 14:15 Prof. Allan Wilson (Wits) - *Lessons learned from ICDP Barberton*

14:15 - 14:30 Intro for the breakout groups / science teams

14:30 - 16:00: Science teams define priority goals and links to other topics

16:00 – 16:30 Teabreak

16:30 – 18:00 Team reports to plenum, final discussion of ICDP science plan

18:30 Bus transfer to Hotel Holiday Inn Rosebank

19:30 Workshop dinner at The Grillhouse Rosebank (walk from Hotel)

ICDP Workshop Agenda

September 9 Tuesday **Witwatersrand University, Geosciences**

8:00	Bus pickup at Hotel
9:00-10:00	Presentation of a draft science plan and general discussion
10:00-11:00	Begin discussing drilling site options with respect to science plan Summary of site options suggested in the workshop proposal Suggestions for new site options Reality check: funding and regulations
11:00-11:30	Teabreak
11:30 -13:00	Continue with Pros and Cons of drillsite options
13:00-14:00	Lunch
14:00-16:00	Continue drillsite and science plan debate
16:00-16:30	Teabreak
16:30-17:30	Funding options
17:30-18:00	Finalize workshop results, identify follow-up teams and duties
18:30	Bus transfer to Holiday Inn

Dinner in Rosebank on individual expense and initiative

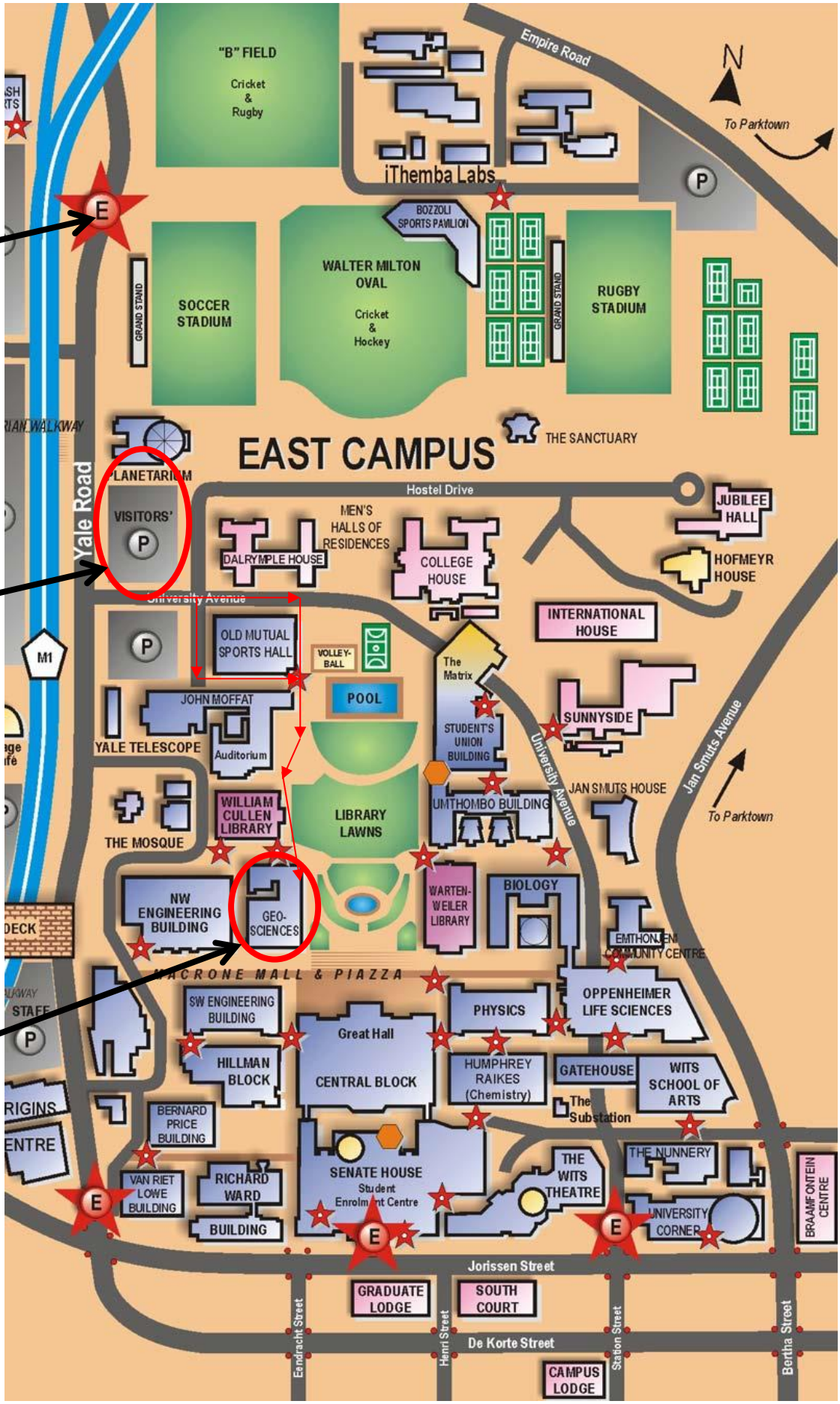
Main Entrance (Yale Rd)

To W Campus

Parking & bus drop-off

To W Campus

WORKSHOP



ICDP Workshop: Bushveld Scientific Drilling Project

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ICDP Workshop *DRILLING THE BUSHVELD INTRUSION*

Participant Information

Name	**SHAFICK ADAMS**
Institution	Water Research Commission
Main Discipline	**Hydrogeology**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

In short, deep hydrogeology.

What techniques do you plan to use?

Adding assessment and characterisation techniques where available…. Isotope hydrology, chemistry, etc. Some of the geological and geophysical information will also be used – through a groundwater hydrology lens.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Not sure yet.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

NO

What comparable information or research exists already on other sections of the complex?

None

Why can you not use existing outcrop or borehole material for this study?

It is not giving insight into deep hydrogeology.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

Improved understanding of fluid movement and occurrence. Groundwater hydrology is intimately linked to all the proposed activities.

Please add suggestions or comments that might support the workshop success, thank you.

The Water Research Commission will publish a call for proposals – one of the proposals is entitled: Characterisation and protection of potential deep aquifers in South Africa.

Name	**AMY ALLWRIGHT**
Institution	Institute for Groundwater Studies (IGS); University of the Free State (UFS)
Main Discipline	**Hydrogeology** **Heatflow**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate*?*

South Africa's available deep hydrogeological (groundwater) data is limited, and the collaboration on a deep drilling project provides a valuable opportunity to collect hydrogeological information at these depths.

The most important hydrogeological information to be collected includes:

- Water strikes (fractures) water levels (recorded during drilling and after)
- Groundwater quality samples for each distinct geological formation (aquifers)

Additionally,

- Groundwater temperature profiles along the length of boreholes
- Hydraulic conductivity values for distinct geological formations (aquifers)

The collected data would be applied to:

- Characterize the deep groundwater system in the study area
- Determine temperature ranges at depths within the study area to gauge geothermal energy potential at these depths
- Characterize the groundwater quality at these depths, and possible identify chemical reactions taking place within the groundwater

A summary of the main questions planned to investigate include:

1. Identification and characterisation of deep groundwater systems (Is there groundwater and if so, where is it?)
2. Investigation of groundwater quality at depths within the subsurface, and possible reactions taking place
3. Determining the geothermal energy potential in the study area (Would geothermal energy extraction [or EGS – enhanced geothermal systems] be possible in the study area?)

What techniques do you plan to use?

A range of hydrogeological techniques will be required to achieve all the planned research investigations.

Characterisation of the deep groundwater systems, include conceptualizing the defined geological characterisation of the study area into hydrogeological units with associated hydraulic parameters. Hydraulic conductivity parameters for these geological formations conceptualised as aquifers, would require hydraulic pumping tests to optimally define these parameters, otherwise inferred values from literature would be used.

Groundwater quality will be evaluated using techniques such as Piper diagrams to determine the nature of the groundwater and possible sources for the minerals found in the water. Changes in groundwater chemistry over the depth of the boreholes will also be investigated, and possible reactions identified.

The main technique to be applied for the investigations will be groundwater modelling, of both groundwater flow and solute transport within the groundwater system. Modelling programmes to be used will include FEFLOW and SPRING.

Additional techniques, such as geothermometry (Geothermometry makes use of chemical data and geothermal gradients to infer depths of groundwater circulation) will be identified and potentially applied within the investigation to optimize the available data.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Interest is not directed toward a specific stratigraphic horizon, but identified aquifers (geological formations able to store and transmit groundwater) would be focused on for further investigation.

Similarly, there is no pre-identified depth of investigation, other than the objective of collection of deep groundwater information. Deep groundwater is generally defined as deeper than 300 m. However, groundwater information from deeper than 1 km is uncommon, and would be the optimal zone of investigation.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

No.

What comparable information or research exists already on other sections of the complex?

Extensive groundwater studies have been conducted within the Bushveld Igneous Complex, but the focus is often on the shallow groundwater systems, containing resources conventionally used for water supply. Recent developments in South Africa, such as shale gas development, injection of brines into deep aquifers, carbon sequestration and geothermal energy are definitely steering the focus of groundwater towards deeper reaches.

In reality, numerous deep boreholes have been drilled in the study area (geological characterisation; reserve determinations), but groundwater data is usually not recorded, or not reported and shared.

Existing geothermal evaluations of the study area, as well as in South Africa, are rare mainly due to the fact that South Africa's craton foundation does not promote large geothermal discovery. However, with new advances such as Enhanced Geothermal Systems, even low enthalpy resources can be harness to generate energy. A geothermal study conducted by Dhansay, De Wit and Patt (2013) evaluated harnessing low-enthalpy geothermal energy in the Limpopo Province of South Africa and similar conclusions were drawn. The current investigation would attempt to confirm this hypothesis with the collection of present, deep temperature data.

Why can you not use existing outcrop or borehole material for this study?

The only comprehensive set of deep borehole from which groundwater data was collected and recorded was for the 24 historic SOEKOR (Southern Oil Exploration Corporation) deep (up to 4 692 m) hydrocarbon exploration boreholes from the 1960s and 70s. These boreholes, in combination with a few thermal springs, comprises the currently available deep hydrogeological data on a national scale. The age of these boreholes, however has incorporated some uncertainty in terms of their current condition and the accessibility of the data. These boreholes are thus not sufficient to characterize the deep groundwater systems, and thus alternative sources of information needed to be explored.

In terms of assessing the geothermal energy potential, temperature profiles are required. A database of deep groundwater temperature profiles is freely available, sporadically over South Africa, but the latest data recorded was for 1994.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

The proposed research would provide analysis of the hydrogeological data to the ICDP project in the form of:

- Geohydrological characterisation of geological layers;
- Description of groundwater chemistry specifically for the study area, and generally throughout the BIC;
- Groundwater flow model of the study area; and
- Simulated geothermal energy model

In terms of benefits from other research efforts:

- Improved geological characterisation results in better hydrogeological characterisation of those layers and thus the groundwater system
- Temperature profiles conducted by geophysical probes will greatly influence the determination of the geothermal potential of the area
- Geomicrobiological results from depths within the study area could serve to explain the chemical reactions taking place with the groundwater
- Additionally benefits will surely be identified during the course of the project as objectives and procedures are defined and conducted

Please add suggestions or comments that might support the workshop success, thank you.

General comment: Has Packer Testing been considered for:

1) hydraulic testing of geological layers (aquifers) by means of pumping tests to gauge the hydraulic conductivity values (measure of the ease with which water will move through the formation)
2) Sampling of distinct geological layers.

It would be important to note that Packer Tests need to be performed with the assistance of the drill rig, and if these tests are to be performed, this would need to be taken into account when estimating the time of use, and thus cost of the drill rig. Hydro-Geo Services, a company in South Africa, has been identified as being able to conduct the packer tests, but only to a depth of 1.2 km.

Alternatively, there has been an indication of a downhole geophysical tool that could be used to calculate permeability, but the reliability of the results are yet to be proven.

Name	**MARCELENE ANDREWS-VOIGT**
Institution	Council for Geoscience
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

In the past I worked on the Platreef, with emphasis on using geochemical exploration tools such as chemostratigraphy and geochemical vectoring for the PGE and BMS mineralisation. We are currently working on geometallurgical studies across the Bushveld (UG2, Merenksy Reef and Platreef). And in the near future I would like to work on what people call the “Flatreef”. Our work is mostly related to PGE and BMS characterisation, and solving refractory problems that the mining companies are experiencing.

For the next four years, the Bushveld deposits are one of our main projects, and this focuses on Bushveld regionally (all limbs). And I think it will be great opportunity to participate in this workshop.

Name	**IRINA ARTEMIEVA**
Institution	University of Copenhagen, Denmark
Main Discipline	**Geophysics** **Heatflow**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

- Volume and geometry of intrusion;
- age – single event vs pulses;
- cooling time;
- uplift time; secondary chanbers?
- composition – homogeneous vs heterogeneous; volatiles;
- physical properties of intrusive material – densities, porosity, grain size, evidence for deformation, rheology

What techniques do you plan to use?

- geophysics (seismic combined with geothermal and gravity);
- calibration of geophysics by petrology;
- calibration of geophysics by lab data on drill cores.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

No particular horizons, rather the picture as the whole. It means broad scale, maximum possible

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Not at the moment, but I would guess that it may be important to have one location in the central part of the complex, and the other one – at its peripheral part.
What comparable information or research exists already on other sections of the complex?
Thermal model of the lithosphere based on regional heat flow and compared to xenolith P-T arrays from the region. New SASE-based model on crustal structure.

Why can you not use existing outcrop or borehole material for this study?

Does not provide large-scale information on the intrusive body, its origin, and its impact on modification of the cratonic lithosphere

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

My interest is multi-fold:

- large-scale processes (e.g. geodynamic origin like plume or not) which control emplacement of the complex, i.e. melting conditions (depth), magma source (composition, fluids, and temperature),
- local lithosphere controls of magma emplacement, e.g. pre-existing weakness zones, depth of magma origin (aka LAB depth), compositional modification of both host rock and magma body;
- the effect of the complex on the later regional geodynamics (e.g. deformation, GDS; etc),
- modification of cratonic crust and the lithospheric mantle by the event (vertical extent, lateral extent, amplitude); lithosphere heterogeneity (compositional, mechanical),
- calibration of geophysical data by lab measurements on rock samples.

These type of questions can be addressed only through a large-scale regional multi-disciplinary geophysical study. A comparison of the cratonic lithosphere around the BIC with other cratons is important to understand global lithosphere evolution.

Name	**LEW ASHWAL**
Institution	Wits University
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

What is the cryptic variation in mineral compositions throughout the drillcores ?
What is the origin of the subtle cyclicity in lithological variation known to exist in the Main and Upper Zones?
What is the significance and origin of the troctolite layer in the Northern Limb?
How many magmas are involved in the construction of the Bushveld Complex, and what is their crystal content?

What techniques do you plan to use?

Detailed electron microprobe anlaysis
Whole-rock geochemistry, including major, minor & trace elements
Tracer isotopic compositions (Sr, Nd, Pb, Hf, Os) of whole-rocks and constituent minerals

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Entire Upper, Main, Critical and Lower Zones (for cryptic variations)
Select horizons in Main & Upper Zones that display reversals and/or cyclicity
Troctolite horizon in Northern Limb

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Eastern Limb to complement extensive database in Western Limb.
If possible, 2 or 3 deep boreholes to achieve continuity of entire stratigraphy of Rustenburg Suite, as best as possible.
Troctolite horizon in Northern Limb

What comparable information or research exists already on other sections of the complex?

Extensive datasets of mineralogical and geophysical data in Northern Limb (Bellevue and Moordkopje boreholes)

Why can you not use existing outcrop or borehole material for this study?

Outcrop is too poor to carry out detailed cryptic variation. Study of reversals and cyclicity requires borehole sampling. Bottom of troctolite in Northern Limb has never been sampled by boreholes.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

Detailed min-pet-geochem characterization will be complemented by geophysical data (magnetic susceptibility, density, heat production, conductivity, seismic velocity).

Name	**ALAN BOUDREAU**
Institution	Duke University
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry** **(Hydrogeology)**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

My main interest is in the trace mineral assemblages of the complex. The late –forming assemblages preserve evidence in changes in sulfur fugacity and halogen variations, critical to understanding degassing of the intrusion, possible fluid involvement in PGE transport and potential source of isotopically distinct contaminants (and cause) of isotopic mineral-mineral disequilibrium. Previous work on the Bushveld and the Stillwater complexes has shown the hydrous igneous minerals in these two intrusions, particularly apatite, to be anomalously enrich in Cl below the PGE Reefs. More recent work has shown these Cl-enriched footwall sections can have high temperature carbonate minerals and extensive petrographic evidence for the remobilization of ore components.

What techniques do you plan to use?

Extensive microprobe for characterization of the trace mineral assemblage (composition and phase mapping), supplemented with microdrilling for isotopic work and bulk rock geochemical analysis.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Comparison of Lower and Critical Zones with the Main Zone.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Proposed study is largely stratigraphic, but some lateral variation comparison (Eastern vs. Western Limbs) would be good as well. Otherwise, as we have some data from the Eastern limb, something from the Western limb would be best. Otherwise stay away from later faults/fracture networks to get as fresh samples as possible.

What comparable information or research exists already on other sections of the complex?

Away from the ore zones, most studies have attempted to use bulk rock analyses of S, base and noble metals, and other elements to infer chalcophile element behavior during crystallization (e.g., Maier and Barnes 1999; Barnes and Maier 2002; Barnes et al. 2009). With few exceptions (most notably, Liebenberg 1970 and Kanitpanyacharoen and Boudreau 2013) the petrography of the sulfide assemblages and the accessory minerals with which they may be associated in ”barren” Bushveld rocks are rarely described, and even in these cases the authors focus on the more sulfur-rich parts of the Bushveld Complex (e.g., Von Gruenewaldt 1976; Li et al. 2004).

Why can you not use existing outcrop or borehole material for this study?

The trace interstitial mineral assemblages are typically the first minerals to experience weathering in even the freshest surface samples. Fresh drill core without evidence of infiltration and reaction with surface water or ground water would be invaluable for these studies. Also, I would assume that most existing drill core is confined to near the ore horizons and not stratigraphically extensive in their coverage, but I may be wrong.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

While I am not sure what others are proposing, I would assume this study would be of interest to those interested in Bushveld fluids (including fluid inclusions), ore petrogenesis and causes of isotopic disequilibrium in the Bushveld Complex.

More broadly, the recent findings of high temperature carbonate minerals in both the Bushveld and Stillwater Complex has implications for carbonate magma petrogenesis in general.

Please add suggestions or comments that might support the workshop success, thank you.

Perhaps keep the discussions open to fresh thinking?

Name	**GRANT BYBEE**
Institution	School of Geoscience, University of the Witwatersrand
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

On the broadest scale I wish to use the isotopic and geochemical data from a comprehensive stratigraphic section through the Bushveld Complex to assess the degree of mantle vs. crustal material involved in magma genesis and investigate how lithospheric interaction (if any) has affected magmatic differentiation.

More specifically, I am interested in improving the isotopic resolution throughout critical zones of the stratigraphy of the Bushveld Complex using Sm-Nd, Rb-Sr, Lu-Hf and Re-Os isotopes. Current published isotopic resolution is above the 10m-scale at best and, at this scale, many important compositional variations, which would aid in our understanding of magma petrogenesis, may go unnoticed. An important, related aspect is in assessing the degree of internal isotopic disequilibrium observed between mineral phases (e.g. plagioclase, pyroxenes) in various horizons of the Bushveld Complex.

Recent work on mineral separates (either hand-picked or micro-drilled) and LA-ICP-MS analyses of samples from the BC and other layered intrusions have shown the presence of enigmatic differences in initial isotopic ratios of a variety of elements and on a wide variety of scales (e.g. Roelofse and Ashwal, 2012; Yang et al., 2013; Chutas et al., 2012; McBirney and Creaser, 2003; Prevec et al., 2005; Tepley and Davidson, 2003). This work is starting to challenge our current knowledge on the petrogenesis of large layered intrusions and a better understanding of this phenomenon, within the context of a detailed whole-rock isotopic stratigraphy has potential impacts for elucidating aspects related to the origin of layering and the magma chamber dynamics within large layered intrusions.

What techniques do you plan to use?

A combination of extensive clean- room facilities, Thermo-Fisher Triton thermal ionization and Nu multicollector ICP-MS instruments for Rb-Sr, Sm-Nd, Lu-Hf, and Re-Os analyses. These techniques and equipment are available at the Department of Terrestrial Magnetism at the Carnegie Institute of Washington through continued collaboration between Rick Carlson, Steve Shirey, myself and Lew Ashwal.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

My primary interest is sampling through horizons where the most isotopic variation is observed (e.g. in Rb-Sr isotopic composition). These horizons include, but are not limited to the Lower, and Critical Zones with some sections from the lower Main Zone and transition between the Main and Upper Zones.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Not necessarily.

What comparable information or research exists already on other sections of the complex?

Several workers have identified isotopic disequilibrium at various stratigraphic intervals within the Bushveld Complex (Roelofse and Ashwal, 2012; Yang et al., 2013; Chutas et al., 2012; Prevec et al., 2005), but these data have not be placed within a high resolution whole-rock isotopic framework for the Bushveld Complex as the current isotopic resolution is on a ~10 m scale.

Why can you not use existing outcrop or borehole material for this study?

Using outcrop material will not provide the required stratigraphic resolution or control and, although borehole material does exist for various stratigraphic sections through different sections of stratigraphy, these boreholes occur in different areas of the Bushveld Complex (various limbs and geographic locations within limbs). It would be more desirable to perform detailed, high-resolution sampling for

isotopic work in a core or series of continuous cores, covering a significant section of Bushveld Complex stratigraphy in one geographic location location.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

This work will provide a detailed isotopic profile through a stratigraphic section of the Bushveld Complex and provide better characterization of the changes that the magma chamber experiences during crystallization and differentiation (probably at different levels, perhaps in staging chambers). This knowledge can be linked to mineralization studies and may provide better constraint of degree of differentiation and its role in mineralization.

Name	**GRANT CAWTHORN**
Institution	Retired
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Is there mafic Bushveld in the centre of the basin?

How does the composition of the Bushveld Granite vary vertically?

What techniques do you plan to use?

A borehole at Vergenoeg fluorite mine

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

The borehole would be collared at the top of the Bushveld Granite. The base of the granite should be at about 2 km depth. Then one might intercept (1) metamorphosed Transvaal sediments/ felsites; (2) Upper Zone; (3) Main Zone. Further drilling ought to intercept all three.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

It has to be at Vergenoeg fluorite mine because that is where the top of the granite is exposed. Also it is close to the geographic centre between all three lobes of the Bushveld

What comparable information or research exists already on other sections of the complex?

Absolutely nothing on whether there is mafic rock in the centre.
No good vertical section through the granite.

Why can you not use existing outcrop or borehole material for this study?

Fairly obvious from previous answers.

Name **JANINE COLE**

Institution Council for Geoscience

Main Discipline **Geophysics**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

I am currently modelling the gravity and magnetic data of the Bushveld Complex in 3D and can assist in locating areas where the Rustenburg Layered Suite (RLS) is possibly closer to the surface. One of the main aims of my project is to study the possible connectivity between the eastern and western lobes.

What techniques do you plan to use?

3D modelling of existing potential field data

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

My modelling uses regional data so I cannot distinguish between layers that are too fine. At the moment I am looking at the RLS as a whole and will then subdivide it into zones, but I won't go down further into individual layers. The exception is the magnetite layers in the Upper Zone which I can model as packages of layers within the Upper Zone.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

I am modelling the whole Bushveld Complex and one of my aims is to study the possible connectivity of the eastern and western lobes in more detail than has been done before. However, I know drilling into the center is not viable, so I would like to see drilling close to some of the domes/fragments/diapirs that are located towards the center and preferably on the side of the dome/fragment/diapir that is furthest away from the lobes.

What comparable information or research exists already on other sections of the complex?

2.5D Modelling was done along a profile that crossed the Bushveld Complex from west to east (Webb, S.J., Cawthorn, R.G., Nguuri, T., James, D. (2004). Gravity modelling of Bushveld Complex connectivity supported by Southern African Seismic Experiment results, SAJG, 107, pp. 207-218). My work basically builds on this since, although the 2.5D model put the possibility of connectivity firmly back on the table, it is not well suited to complex geometries.

Why can you not use existing outcrop or borehole material for this study?

I am using the existing outcrop to constrain the model, but I am more interested in the areas where there is no outcrop. The deep borehole logs (800 to 1500 m deep) that I have access to in the areas of no outcrop all end in granite.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

3D modelling can provide possible configurations of the RLS at depth

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Name	**RAY DURRHEIM**
Institution	University of the Witwatersrand, Johannesburg
Main Discipline	**Geophysics**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

The deep boreholes will provide ground truth for experiments to determine how well geophysical techniques (especially seismics) can resolve the geological structure of the subsurface, and be used to extrapolate the structure away from the borehole.

What techniques do you plan to use?

Active seismic: e.g reflection and vertical seismic profiling, using a weight drop, explosives or vibroseis as the energy source.

Passive seismics: using mining-induced tremors, and local, regional and teleseismic earthquakes as energy sources; and analysis techniques such as P- and S-wave receiver functions, H-k stacking; joint inversion of receiver functions and surface waves, waveform modelling.

Physical properties: measurements of density, P- and S-wave velocity, and other rock mechanical properties in the field (wireline logging) and in the laboratory.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

The entire column that will be drilled, an then all the way to the Moho and beyond.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

It would be ideal if the hole(s) were situated close to an existing reflection seismic profile (or even better, within a 3D survey) or near to a South African Seismic Experiment (SASE) broadband seismic station.

What comparable information or research exists already on other sections of the complex?

Many reflection seismic profiles have been surveyed for mineral prospecting and mine planning purposes, and two as part of the National Geophysics Programme.

About a dozen broadband stations were deployed in the Bushveld as part of the South African Seismic Experiment (SASE). The data have been analysed by several researchers, including Eldridge Kgaswane of the Council for Geoscience. I co-supervised his PhD thesis, which was awarded in November 2013.

We currently have a 3-station broadband array situated along the 50 km National Geophysics Programme line near Pretoria. This experiment is being run by my postdoctoral fellow, Dr Alain Tokam Kamga, with support from the Council for Geoscience.

Why can you not use existing outcrop or borehole material for this study?

We want to explore and extend the limits of geophysical imaging of the upper crust in an area that has both scientific and economic interest.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

It will extrapolate the geology found in the borehole over a greater area and to greater depths.

Name	**STOFFEL FOURIE**
Institution	Tshwane University of Technology
Main Discipline	**Geophysics**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Evidence that the different lobes of the Bushveld Complex might be interconnected in the deep crust.

What techniques do you plan to use?

Long period Magnetotellurics and BB Magnetotellurics, Seismic Reflection

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Crustal expression of the Bushveld Complex

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

No, as long as we can profile across more than one lobe at a time and the profile can be placed in such a way that minimum electric interference is possible.

What comparable information or research exists already on other sections of the complex?

Not a lot, just a MT profile that was done by SAMTEX in 2004, and two seismic lines by the CGS in 1986 1nd 1989.

Why can you not use existing outcrop or borehole material for this study?

Too deep.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

If the lobes are connected it means that they all definitely originate from the same magma chamber and that geochemically they should look the same.

Deep drilling might confirm this as the lithologies might be altered in such a way due to the pressure and heat that it will be difficult to separate visually from the crustal host rocks. However it might be possible electrically and geochemically.

Please add suggestions or comments that might support the workshop success, thank you.

None. It will be my first time.

Name	**CHRISTOPH GAUERT**
Institution	Dept. of Geology, University of the Free State, Bloemfontein, RSA
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

I plan to investigate accessory minerals of selected portions of the Rustenburg Layered Suite to gain insight into its late magmatic and post-magmatic evolution history.
Part of this investigation is the study of the distribution of elements present in a late to 'hydro magmatic'stage of the crystallizing magma of the Bushveld magma chamber. Those are mostly of incompatible, such as Ti, Zr, Y, P, S, Pd, Pt, Rh, and rare earth elements.
The main question is which mechanisms control the distribution of such elements and under which physico-chemical conditions does this take place?

1. Such a systematic study will involve the investigation of mineral chemistry and trace element content of 'late stage' minerals containing incompatible elements, such as clinopyroxene, titanite, apatite, secondary ilmenite, zircon, rutile, secondary magnetite, baddeleyite, zircon, xenotime, sulphides. In this context I plan to analyse rare earth elements of clinopyroxene specifically in pegmatoidal gabbronoritic to pyroxenitic sequence, following Mathez et al. (1995) who found a decoupling of incompatible trace and major elements of interstitial pyroxene and explained it by a metasomatic process contributing to the formation of the Merensky Reef.
   The trace element chemistry of titanite in evolved amphibole-bearing gabbroic rocks and their metasomatised equivalents constitutes a tool for understanding late-stage igneous and metasomatic processes. According to Colwell et al. (2011), the understanding of titanite chemistry allows constraints on conditions of crystallization, metasomatic reactions, and the nature of hydrothermal fluids.
   Zr-in-titanite temperatures will be compared to Ti-in-zircon temperatures from coexisting zircons;.zircons can contain minor amounts of P_2O_5, CaO, and of ThO_2, as well as traces of Na_2O, Al_2O_3, TiO_2, MnO, FeO and REE.
   Late stage apatite is commonly associated with interstitial quartz in the anorthositic, gabbroic and in pegmatoidal, feldspathic pyroxenitic units. A chemical characterization will show the P_2O_5 and CaO compositions, however variable minor F, Cl, and Nb_2O_3 contents, as well as traces such as K_2O, SiO_2, Na_2O, Al_2O_3, FeO and BaO. 'Apatite compositional heterogeneity within samples and internally in crystals may reveal a complex history of late-stage magma evolution in the Bushveld Complex possibly within short timescales' (citation).

2. The data will allow to decide whether trace element enrichment in late stage phases is a result of liquid immiscibility or can be explained by the trapped liquid shift effect (e.g. Cawthorn, 2008). In

the latter, the true late cumulus phase compositions re-equilibrated with trapped liquid as it solidified.
To find out about this, the partition behaviour of incompatible elements into primary cumulus minerals which could act as 'a major buffering influence on the enrichment of such elements in late stage minerals during the solidification process' (Cawthorn, 2008) has to be investigated. Trace element modeling using Rayleigh fractionation and latest partition coefficients will allow a comparison of modeled and measured data of late-stage cumulus minerals. Another aim is to differentiate cumulus and intercumulus phases chemically and deduce change in late stage melt composition.

3. One goal is to define more precisely the temperature path the late-stage melt follows when cooling off using geothermometers calibrated for trace elements in titanite and rutile (Zr), zircon (Ti) to determine mineral formation temperatures. Those will be compared with temperature data obtained from melt and fluid-inclusion studies on amphibole and mica (similar to study of Seifert et al., 2009).

4. How does the composition of the late stage melt and exsolved fluids in intervals of the Bushveld Complex change and in which time and temperature intervals does this happen? Do the fluids add to a decrease in crystallization temperature of the late-stage cumulus and intercumulus phases and to the fluids assist in a transfer and enrichment of incompatible trace elements into late-stage mineral phases.
To investigate this, a study of the hydrous late stage phases such as phlogopite, muscovite, and amphibole in selected pegmatoidal layers of the Bushveld Complex will be necessary. An investigation of the mineral chemistry of micas and possibly of δD in micas, will be important.

5. Finally, are enrichment processes and mineralization events related to the late stage element distribution in the Bushveld Complex of economic importance, i.e. ore-forming? The aim is to find out about the relationship between late stage mineral chemistry and Pt, Pd, and Au enrichments of Bushveld Complex rocks which can be transferred to other layered intrusions (e.g. Kläppsjö Gabbro, Sweden). Can those be indicative of mineralization events? This hypothesis in conjunction will make use of an investigation of PGM and PGE in base metal sulphides in various MG and LG chromitite and pegmatoidal pyroxenite layers of the Critical Zone.

What techniques do you plan to use?

In sequence of application: High resolution optical microscope, XRD, SEM_E/WDX, fluid inclusion stage, FE-EMPA, LA_ICP-MS, Sy-µ-XRF, nano-SIMS, ICP_MS.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Selective intervals of ortho-cumulate rocks with high amount of interstitial liquid through the entire stratigraphy such as pegmatoidal layers from the Lower Zone, Critical and Main Zone transitions, as well as two intervals of the Upper Zone and roof of the intrusion, possibly for comparison sake also into the Bushveld granites.

The sampling focus lies on the upper Critical Zone, and parts of the Main Zone, and the lowermost to upper Upper Zone.

The study is concerned over an added vertical distance of about ***150m***.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Northern or southern compartment of the eastern BIC, because outside the Critical Zone, those are less well investigated.

What comparable information or research exists already on other sections of the complex?

Northern Bushveld:

Ashwal, L. D.,Webb, S. J. & Knoper, M. D. (2005). Magmatic stratigraphy in the Bushveld Northern Lobe: continuous geophysical and mineralogical data from the 2950m Bellevue drillcore. South African Journal of Geology 108, 199-232.

Eastern BIC:

Kottke-Levin, J, Tredoux, M., and Gräbe, P.-J. (2009) An investigation of the geochemistry of the Middle Group of the eastern Bushveld complex, South Africa Part 1 – the chromitite layers. Applied Earth Science (Trans. Inst. Min. Metall. B) Vol 118 No 3/4, 111-130.

Lee, C and Parry, (1988). Mineralogy and geochemistry of the Lower and Middle group chromitite of the eastern Bushveld Complex.

Bushveld general:

Ballhaus, C.G., and Stumpfl, E.F., 1986, Sulfide and platinum mineralization in the Merensky reef - Evidence from hydrous silicates and fluid inclusions: Contributions to Mineralogy and Petrology, v. 94, p. 193–204.

Boudreau, A.E. and Kruger, F.J. (1990). Variation in the Composition of Apatite through the Merensky Cyclic Unit in the Western Bushveld Complex Economic Geology, Vol. 85, pp. 737-745.

Cawthorn, R. G. & McCarthy,T. S. (1985). Incompatible trace-element behaviour in the Bushveld Complex. Economic Geology 80, 1016-1026.

Cawthorn, R. G. &Walraven, F. (1998). Emplacement and crystallization time for the Bushveld Complex. Journal of Petrology 39, 1669-1687.

Li, C., Ripley, EM, Merino, E. and Maier WD (2004) Replacement of base metal sulphides by actinolite, epidote, calcite, and magnetite in the UG2 and Merensky Reef of the Bushveld Complex, South Africa, Economic Geology, Vol. 99, pp. 173–184.

Lundgaard, K. L., Tegner, C., Cawthorn, R. G., Kruger, F. J. & Wilson, J. R. (2006). Trapped intercumulus liquid in the Main Zone of the eastern Bushveld Complex, South Africa. Contributions to Mineralogy and Petrology 151, 352-369.

Mathez et al., 1995. Magmatic metasomatism and formation of the Merensky reef, Bushveld Complex. The rare earth element (REE) contents of pyroxenes and other minerals from the Merensky reef and stratigraphically adjacent rocks of the Atok section, Bushveld Complex, have been determined with the ion microprobe.

Cawthorn, R.G. (2013). Rare earth element abundances in apatite in the Bushveld Complex—A consequence of the trapped liquid shift effect. The Residual or Roof Zone of the Bushveld Complex, South Africa. Geology 41, 603-606.

Willmore, CC, Boudreau, AE, and Kruger, F, (2000) The Halogen Geochemistry of the Bushveld Complex, Republic of South Africa: Implications for Chalcophile Element Distribution in the Lower and Critical Zones. Journal of Petrology 41(10), 1517-1539. Study of apatite through the BIC but few in the MZ and UZ.

Western Bushveld Complex:

Teigler, B (1990). Platinum-group element distribution in the lower and middle group chromitites in the western Bushveld Complex, Miner. Petrol., 42, 165–179.

Teigler B. and Eales, HV (1993). Correlation between chromite composition and PGE mineralization in the Critical Zone of the western Bushveld Complex', Miner. Depos., 28, 291–302.

Maier, WD and Barnes, S.J. (2008). Platinum-group elements in the UG1 and UG2 chromitites, and the Bastard reef, at Impala platinum mine, western Bushveld Complex, South Africa: Evidence for late magmatic cumulate instability and reef constitution South African Journal of Geology, v. 111, p. 159-176.

Why can you not use existing outcrop or borehole material for this study?

Outcrop material often too weathered and chemically altered, especially the sulphides and the hydrous minerals; borehole material is mostly confined to the Critical Zone, little borehole material outside the lower Main Zone - Critical Zone, except for the lowermost part of the Upper Zone, which is also of interest to industry.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

What can this research offer to others:

This research will offer fundamental data to other disciplines, e.g. such as petrophysical and susceptibility data to geophysics and information on the cooling history to heat flow research.

Furthermore, the research will complement results on rock-forming cumulus minerals in terms of igneous petrology and related mineralisation / ore-forming process research.

Indirectly drilling / logging technology will benefit from any deeper drilling project by improving drilling and core capturing techniques; hydrogeology could receive porosity and permeability data if those are measured from the core.

How will this study benefit from the results of others?

This research will benefit from results of others on rock-forming cumulus minerals in terms of liquid line of descend, determined crystallization temperature and ages of the late-stage cumulus and intercumulus phases and related results on the mineralisation / ore-forming process.

Please add suggestions or comments that might support the workshop success, thank you.

- Clarify what core is already available at the National core facility,
- Liaise with industry,
- Advertise / try lobby work in terms of finances before the meeting,
- Contribute / share literature database and make available to all participants.

Name	**KARSTEN HAASE**
Institution	GeoZentrum Nordbayern, Univ. Erlangen-Nuernberg, Germany
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Does the complete Bushveld Complex consisting of the layered mafic rocks, the granitoids and the thick volcanic sequence represent one magmatic event related to a mantle plume?
If the rocks are related, how did they evolve from a parental mafic magma and what is the influence of crustal assimilation and volatile exsolution? Which are the main volatile species that were released and

which volume? Is partial melting of the subcontinental lithospheric mantle responsible for the unusual geochemical signature or can this be explained by crustal assimilation?

What techniques do you plan to use?

Electron microprobe, XRF, ICP-MS, LA ICP-MS, MC ICP-MS, Laser fluorination O isotopes

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

From the Rustenburg Layered Suite, Lebowa granites, Rashoop Granophyre to Rooiberg volcanics

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

No, we plan to focus on the Eastern Lobe because we also study the Vergenoeg mineralization and want to study the genetic links of this mineralzation to the Bushveld Complex.

What comparable information or research exists already on other sections of the complex?

We started to work on the Vergenoeg/Plattekop mineralizations and Lebowa granites with Master students and continue with a PhD student.

Why can you not use existing outcrop or borehole material for this study?

We hope that a deeper borehole gives a more complete section of the rock formations and especially of the boundaries .

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

We hope to be able to contribute to a better understanding of the petrogenetic processes occurring during formation of a large mafic intrusion as an example of a magma system of a large igneous province. As such people working on ore deposits will benefit from a improved model of the formation of such intrusions.

Name	**CHRIS HARRIS**
Institution	University of Cape Town
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

What is the relation between between the layered mafic/ultramafic rocks and the felsic rocks (granites and granophyres)? Petrogenetically, spatially, temporally.

Is the RLS of the Busheld crustally contaminated? By how much? Were the initial magmas also crustally contaminated?

What techniques do you plan to use?

Oxygen isotopes by laser fluorination.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

LZ and specifically the base of the LZ

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Not really, but it would be nice to know how the felsic rocks are related to the RLS and that would mean drilling where there are felsic rocks present?

What comparable information or research exists already on other sections of the complex?

Numerous publications on O-isotopes. But very little on the LZ.

Why can you not use existing outcrop or borehole material for this study?

Good question. Drill core is much fresher than outcrop and that is crucial to O-isotope work.I would hope that the drill core would show the spatial and relative age relations of the RLS and the felsic rocks. These are otherwise not obvious (at least to me!).

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

O-isotopes are potential indicators of fluid-rock interaction and crustal contamination. Hard to answer without know the plans of others in detail. Being able to concentrate on O-isotopes and not have to do all the other analyses required (mineral chemisty etc) is a big advantage

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Name	**LUTZ HECHT**
Institution	MfN Berlin
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

What is the role / importance of country rock assimilation and/or late-magmatic mass transfer for the formation of PGE-rich mineralization in chromitite layers in relation to crystal fractionation or mechanical sorting during or after cumulate formation.

What techniques do you plan to use?

Detailed mineral chemistry including stable isotopes of silicate minerals and spinel across chromitite layers and adjacent hanging and footwall lithologies. Radiogenic isotopes (Sr, Nd) may also be applied.

It is envisaged to use the SIMS at GFZ Potsdam to study small scale isotopic variations within chromitite layers.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

The study will be focused on the Critical Zone comparing profiles from the margin with those from the center of the Bushveld Complex.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

The central region of the Bushveld Complex.

What comparable information or research exists already on other sections of the complex?

Mineral chemistry studies on many drill core profiles have been performed in the Western and Eastern (and Northern) Bushveld, however very detailed mineral chemistry studies (including isotopes) across chromitite layers are rare (e.g. Junge et al. 2014).

Why can you not use existing outcrop or borehole material for this study?

There are no outcrops in the Critical Zone in the central part of the Complex. However, it is out of my knowledge if there is drill core material available from the central part of the Complex.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

This study would contribute to the general understanding of igneous cumulate formation and associated mineralization. It would contribute to and benefit from studies from other stratigraphic levels of the Bushveld Complex.

Please add suggestions or comments that might support the workshop success, thank you.

A summary and short discussion of current models (maybe including none-published ideas?) on the genesis of the Bushveld complex with special focus on “what do we need to solve the major remaining questions”. This would help to better integrate each special approach into a bigger maybe interdisciplinary research program.

Name	**SIBONGISENI HLATSHWAYO**
Institution	Council for Geoscience.
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

(1) Petrology and geochemistry of northern sector Platreef.
(2) Possible hypothesis of origin and emplacement of Platreef zone.

(3) Relationship of base metals, sulphur and PGE mineralization.

What techniques do you plan to use?

(1) Handheld XRF analyses for selecting mineralized intervals to be sampled and analyzed.
(2) ICP-MS (4 Acid digest) analyses -Trace and ultra-trace elements
(3) Scanning Electron Microscope – petrology- mineral assemblage and paragenesis.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Northern sector of Platreef is about 50 m thick but sampling can be done at selected intervals, where there are mainly sulphides, potential PGE mineralization and xenoliths. Usage of handheld XRF can be useful in determining the sulphide rich and PGE mineralized zones.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

(1). Northern Limb of the Bushveld complex = Northern sector of platreef with its granitic footwall.

Reasons:

(1) The northern sector of Platreef is less studied as compared to southern sector and other Limbs of the Bushveld Complex.
(2) More new discoveries along the Northern Limb, such as the discovery of the Waterberg reef by Platinum Group Metals Company. Is it the continuation of Platreef or not?

What comparable information or research exists already on other sections of the complex?

(1) Kinnaird JA, Hutchinson D, Schurmann L, Nex PAM, deLange R.(2005) Petrology and mineralization of the southern Platreef, northern limb of the Bushveld Complex, South Africa. Miner Depos 40:576–597.

(2) Armitage PEB, McDonald I, Edwards SJ, Manby GM (2002).Platinum-group element mineralisation in the Platreef and calcsilicate.footwall at Sandsloot, Potgietersrus District, South.Africa. T I Min Metall 111:B36–B45

Why can you not use existing outcrop or borehole material for this study?

(1) The northern sector of northern limb is mainly covered by younger formation such as Waterberg sediments.
(2) Existing boreholes are not known or not drilled.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

(1) Platreef mineralization and petrology style can be better understood.
(2) This can also assist the exploration companies in terms of Platreef style mineralization.
(3) Petrology and geochemistry of the northern sector can possibly reveal the origin and ore-forming processes of the heterogeneous Platreef.

Please add suggestions or comments that might support the workshop success, thank you.

Open scientific discussions but mainly focusing on relevant workshop priorities.

Name	**MARIAN HOLNESS**
Institution	University of Cambridge
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

My main interest is in microstructural development and how it influences the physical properties of rock during changes in temperature or pressure. I have interests in processes occurring in metamorphic and igneous environments, on both heating and cooling paths. For this project my main interest is in understanding how we can interpret microstructure of fully solidified cumulates and link them with geochemistry and thermal and fluid dynamical models of the magma chamber to develop our understanding of processes that acted during solidification. Such processes include: the progressive reduction of porosity in the crystal mushy layer on the floor and implications for rheology (which affects fractionation via its effect on compaction), permeability and the onset of in situ fractionation (with the possibility of liquid immiscibility); the role of convection in redistributing mass in the magma chamber; the formation of layering and fabrics in cumulates; and the mechanisms involved in mineralization.

What techniques do you plan to use?

The entry point for all my work is provided by petrographic thin sections, with an optical microscope (fitted with a universal stage and camera). I supplement my primary observations with geochemical analysis (electron microprobe, laser ICP-MS, bulk XRF) and observations under CL and with backscatter (SEM). I am currently exploring the possibility of expanding my 2-D studies using 3-D imaging obtained with X-ray tomography to quantify fabrics and grain shapes in gabbros. I work with colleagues in the BP Institute here in Cambridge on developing fluid dynamical frameworks for mafic intrusions and will continue this collaboration during the Bushveld project.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

My study interestes are very general and I see potential for fruitful work on all levels in the intrusion. I am, however, particularly interested in horizons in which it can be demonstrated that a new phase joined the liquidus assemblage of the bulk magma, and in UZ in which we have found evidence for late-stage reactive interstitial liquids that bear great resemblance to those attributed to phase separation of immiscible liquids in the Skaergaard Intrusion.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

No.

What comparable information or research exists already on other sections of the complex?

My approach to microstructural interpretation is novel, with few other practitioners. There is therefore very little comparable work to that I am proposing, although the paper by Boorman et al. (2004)[+] provides a springboard for future work. I have already published a small study demonstrating step-wise changes in plag-plag-cpx dihedral angles in UZ*. There is nothing yet published on the possibility of the late-stage

reactive microstructures being a fingerprint for liquid immiscibility in the mushy layer with its implications for the development of the mineralization.

*Holness, M.B., Namur, O. and Cawthorn, R.G. 2013 Disequilibrium dihedral angles in layered intrusions: a microstructural record of fractionation. *Journal of Petrology*, 54, 2067-2093. doi:10.1093/petrology/egt041.
+Boorman, S., Boudreau, A., Kruger, F.J. (2004) The Lower Zone – Critical Zone transition of the Bushveld complex, a quantitative textural study. Journal of Petrology, 45: 1209-1235.

Why can you not use existing outcrop or borehole material for this study?

My work is dependent on very carefully collected sample suites, in which the relative positions of each sample in the stratigraphy are well-known. Borehole material is ideal for this purpose, particularly as its orientation relative to the Earth's gravitational field is known.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

My expertise in microstructural interpretation can be applied to problems related to the development of the mineralization and other questions relating to the evolution of the magma chamber. I can thus collaborate with members of the general petrological community. I would welcome developing collaborative projects with other members of the ICDP group on 3-D imaging of gabbros for microstructural analysis.

Name	**TOM KIEFT**
Institution	New Mexico Tech
Main Discipline	**Petrology-mineralogy-geochemistry** **Hydrogeology** **Drilling / logging technology** **Geomicrobiology**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Hypothesis 1: Rock-water reactions in the Bushveld Igneous Complex generate H_2, CH_4, and short-chain hydrocarbons that support indigenous microbial activities.

Hypothesis 2: The microbes in deep, ancient fracture waters of the Bushveld Igneous Complex represent ancient lineages that are specifically adapted to extreme conditions and to utilizing abiotically generated gaseous energy sources.

What techniques do you plan to use?

Geochemical analyses of porewater including dissolved organic carbon, major anions and cations, C, H, O, S isotopes, and dissolved gases; analyses of core fracture surfaces for biological signatures; groundwater dating using noble gases; DNA- and RNA-based analyses of microbial communities; isolation of microbial cultures.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Ideally, a variety of depths and mineralogies, but the highest priority samples are those featuring ultramafic rocks with potential for H_2 generation and also the deepest samples possible.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

I need to check with colleagues before I can give a good answer here.

What comparable information or research exists already on other sections of the complex?

We have some preliminary data on the geochemistry and microbiology of deep fracture waters from the western portion of the Bushveld complex that we collected in Zondereinde (Northam) mine.

Why can you not use existing outcrop or borehole material for this study?

Microbes associated with outcrops represent recent colonization, exposure to oxidizing conditions, etc. Similarly, archived cores are subject to contamination by surface microbes, oxidation by contact with the atmosphere, etc.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

There's a strong connection with anyone else studying the geochemistry and mineralogy. There's a good chance of combining forces on the geochemical analyses. Groundwater dating may be of use to other researchers, too. Microbial activities can affect mineral precipitation and mineral dissolution, so this may be of interest to other researchers, as well.

Please add suggestions or comments that might support the workshop success, thank you.

Sampling for geomicrobiology requires some added considerations for drilling/coring, including careful selection of drilling fluids, use of tracers to quantify contamination, disnfection of core barrels, possible use of core barrel liners, and use of an anaerboic chamber at the drill site; so I'm delighted with the opportunity to discuss these in the workshop at an early stage in the development of the project.

Name	**CHRIS LEE**
Institution	Retired
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry** **Drilling / logging technology**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

I was told about the workshop, and invited to be there to contribute what I can to the planning session. This contribution would be based on my field work and research endeavors over the 30 years or so that I was with the platinum industry (Anglo Platinum).

Name	**WOLFGANG MAIER**
Institution	Cardiff University
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Is there systematic down-dip compositional and lithological variation in the complex, as would be expected in the case of a slurry model as proposed by Maier et al in the 2013 Min Deposita paper. So far, we only have info from the mines that covers a few km down-dip distance.

What techniques do you plan to use?

Whole rock and mineral geochemistry (Laser ablation ICP for Sr isotopes and trace elements), microfabric petrography, field studies

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

All of the layered suite.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

As far inward from the margins as possible, while still intersecting the layered suite

What comparable information or research exists already on other sections of the complex?

Essentially the Union section profile of the Rhodes University Group, plus more local and smaller scale studies of specific intervals elsewhere (MZ and UZ in northern lobe by Ashwal et al., LZ in eastern lobe by Lee and Tredoux, LZ in EBC by Wilson et al.)

Why can you not use existing outcrop or borehole material for this study?

It is important to check whether compositionally distinct horizons that mat represent magmatic or hydrothermal or seismic events can be correlated across the complex.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

The research will constrain the mechanism of formation of the layering, including the ore horizons, but also other layers such as the enigmatic anorthosites. For example, if we can demonstrate that anorthosites or pyroxenites show more isotopic and trace element heterogeneity between grains than norites, then this might support a model of mixing of slurries.

Name	**TAWANDA MANYERUKE**
Institution	Nkwe Platinum
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry** **Drilling / logging technology**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

I am coming to observe but interested in mineralization, petrology-mineralogy-geochemistry and drilling / logging technology.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Critical Zone

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Eastern limb of the Bushveld Complex

Name	**ED MATHEZ**
Institution	American Museum of Natural History
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

(1) The extent and architecture of the Busvheld magma chamber.

(2) The formation of Bushveld magmas, more specifically the extents to which their compositions are due to assimilation of continental crust or reflect those of the mantle source region.

(3) The extent to which reorganizations in the crystal mush can produce the massive chromitites and the anorthosites associate with some of the pyroxenites and magnetitites.

What techniques do you plan to use?

Petrographic and mostly micro-analytical techniques, such as electron probe, ion probe, and LA-ICPMS.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

The above questions relate to the entire intrusion, but probably the Critical, Main and Upper Zones mostly.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

For structure and architecture the eastern Busvheld. Especially poorly known as far as I am aware is the southeast sector of the intrusion. Also, the structure where strikes trend E-W east of Loskop Dam is enigmatic. Although most of the region has been adequately mapped, the subsurface structure and rock sequences are not well-known.

What comparable information or research exists already on other sections of the complex?

There is pretty good stratigraphic information on the northern sector of the eastern Bushveld, south of the Oliphants River valley, for example, from the work of Cameron, Molyneux, and von Gruenewaldt.

Why can you not use existing outcrop or borehole material for this study?

The outcrop is generally poor, especially in the SE. Surely the mining companies have drill cores, but finding them would probably be difficult, and they are likely short and stratigraphically localized.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

Petrogenetic and geophysical hypotheses depend on actually looking at the rocks!

Please add suggestions or comments that might support the workshop success, thank you.

One outcome of the workshop should be a clear curation plan. This is very important, and at least to the US community this is becoming increasingly important.

Name	**JOHN MAVROGENES**
Institution	Research School of Earth Sciences, Australian National University
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

1) Do the trace element patterns across olivine, orthopyxoxene, clinopyroxene and plagioclase feldspar crystals show evidence of diffusive re-equilibration?
2) Can trace sulfur contents of silicate/oxide phases identify sulfide saturation horizons?

What techniques do you plan to use?

I intend to analyse diffusion profiles and elemental zoning by SEM, EMPA and LA-ICPMS.

Trace sulfur will be measured by the SHRIMP-SI at RSES, an instrument designed specifically to measure light elements.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

I would like to focus on the sequence from the bottom of the Basal Series through the Critical Zone to the base of the Main Zone.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Not sure, I would hope to learn from those that know the region better.

What comparable information or research exists already on other sections of the complex?

To my knowledge, the only work on diffusive re-equilibration on the Bushveld is our work on the Northern Limb.

Why can you not use existing outcrop or borehole material for this study?

I have not been able to get a series of samples across the Critical Zone. This may be the perfect opportunity to do so.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

Our work on the Northern Limb was based entirely on Lew Ashwal's exhaustive study of the Belleview core. Collaborative work on the proposed core will be useful to all. Our work on re-equilibration and sulfur saturation would greatly advance our understanding of the Bushveld specifically and layered mafic intrusions more generally.

Name	**IAIN MCDONALD**
Institution	Cardiff University
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

The question of how stratigraphy and magmatic processes can be correlated across the different limbs of the Bushveld Complex. Specifically whether the northern limb (and its unusual Ni-Cu-PGE mineralization and olivine-rich Main Zone cumulates) was ever connected to the other limbs of the complex. This has implications for the timing and mechanisms of magma injection, the size and volume of different magma pulses, and for recognizing and correlating common mineralization events across the Bushveld Complex.

What techniques do you plan to use?

Petrography

Mineral bulk chemistry determined by SEM/EPMA
Mineral trace element chemistry determined by LA-ICPMS
Major, trace and platinum-group element geochemistry of whole rock samples
Sr, Nd and O isotope analyses on mineral separates from key parts of the northern llimb stratigraphy.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

The missing stratigraphy between the top of the MO1 borehole and the base of the Bellevue borehole in the northern limb of the Complex. This should equate to <500m of stratigraphy but in conjunction with Bellevue and MO1 will provide the first fully continuous core record through the Bushveld northern limb. This will provide a unique resource with which to compare with other areas of the complex drilled by the ICDP project.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Northern limb Main Zone, collared above the Troctolite Unit and extending through and below the unit. Farms such as Vriesland 761LR or Inhambane 102LR or Moordkopje 813LR would be the best locations.

What comparable information or research exists already on other sections of the complex?

Studies have already been carried out on the Bellevue and MO1 boreholes

Ashwal et al. (2005) South African Journal of Geology, v.108, p.199-232.
Roelofse and Ashwal (2012) Journal of Petrology, v. 53, p.1449-1476.
Tanner et al. (2014) Journal of Petrology, v.55, p. 859-882.

Why can you not use existing outcrop or borehole material for this study?

The surface outcrop is too poor and patchy to properly reconstruct the stratigraphy between the Bellevue and MO1 boreholes. New drilling would provide a complete core log through the northern limb stratigraphy.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

The study to complete the northern limb stratigraphy will have offer benefits for other groups looking to understand the overall evolution of the Bushveld Complex and whether all the limbs operated together or as isolated magma chambers. New studies by other groups working on the poorly known portions of the Main Zone in other areas of the complex will also feed back into the northern limb study to help understand the input of magma into the Main Zone, the potential for magmatic sulphide mineralization and the transition from the Main to the Upper Zone in different limbs of the complex.

Name	**FRANK MELCHER**
Institution	University of Leoben, Austria
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Fine-scale distribution of metals in mineralization / reefs. Metal host, mineralogy and mineral chemistry of base metal sulfides, PGM, chromite, magnetite; trace element chemistry of BMS; quantitative mineralogy

What techniques do you plan to use?

SEM-EDX (ZEISS EVO with Particle analysis program “Smart PI”); EPMA (E.F. Stumpfl laboratory); LA-ICP-MS (Agilent Triple Quad with 213 nm laser); Micro-Raman investigations.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Critical Zone – especially reefs (chromitite, Merensky Reef, Platreef,…); magnetite seams

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

no

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

I would like to connect with the BGR group studying mineralization on a fine scale over selected intervals of core.

Name	**NAMUR OLIVIER**
Institution	University of Hannover
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

They are different questions that are of interest for the team in Hannover, all of them being related to the differentiation of the most evolved liquid of the Bushveld Complex. Following tasks are amongst the priorities:

1. Perform a detailed study of the cumulate rocks from the Upper Zone in terms of mineral compositions, mineral modes, and melt inclusions to determine the magma chamber processes having occurred during the crystallization of the unit. Ideally.
2. Understand the link between mafic units and the evolved rhyolites occurring at the top of the Bushveld and puttingt constraints on the material (if any; composition, volume) that has been erupted during the crystallization of the magma chamber.
3. Investigate in more details whether or not magma chamber replenishments occurred during the formation of the Upper Zone.
4. Another point of interest would be to determine whether or not immiscibility played a role in the formation of these cumulates, at what scale and if it played any role, what are the composition of

the immiscible melts. Can we link them with the rhyolites? When did we intersect the immiscibility field and did we get out of it during the differentiation process.

5. Understand the fate of the interstitial melt during progressive solidification of the crystal mush. This could be done by analyzing the chemical evolution of the interstitial phases in cumulate rocks. This will also provide new constraints on crystal mush processes (diffusion, thermal buffering) and should also help constraining the physical properties of the crystal mush which is critical to understand how efficient was convection in the mush.

What techniques do you plan to use?

Textural analysis of the rocks and a series of geochemical tools, mainly electron microprobe, X-ray fluorescence and laser ICP-MS.

For melt inclusions, there will be an important step of homogeneisation which would be performed in internally heated pressure vessels under controlled oxygen fugacity.

High pressure and high temperature experiments will be useful to quantify and constrain the models elaborated from petrological and geochemical investigations (e.g., role of volatiles on differentiation, compositions of immiscible melts). The facilities at Hannover allow us to model conditions for mafic as well as silicic systems (P up to 700 MPa, T up to 1300°C).

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Ideally we would need detailed sampling from the upper part of the Bushveld from the pyroxenite marker to the top of the layered series and the lower part of the overlying felsic rocks. This is a zone where there are significant changes in cumulus assemblages, which will allow us putting strong constraints on the Bushveld liquid line of descent and compare with overlying felsic rocks.

A long drill core through the Upper Zone will also allow us constraining the bulk composition of this rock and see whether or not liquid was erupted during crystallization. This will be done by comparing the bulk composition with an estimate of the parent magma of the Upper Zone. This estimate will be refined in the next months thanks to an ongoing experimental investigation performed in Hannover.

The investigation of silicic rocks at the top of the Bushveld is also of interest for the team in Hannover.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

An adequate zone would be in the West of the Bellevue drill core but starting slightly higher in stratigraphy (in the felsic rocks).

What comparable information or research exists already on other sections of the complex?

There are data existing on the Bellevue and Bierkraal drill cores but they mainly concern mineral compositions. No data on mineral microstructures, bulk-rock compositions and mineral modes are available yet. These data would be crucial to constrain the liquid evolution in the upper part of the Bushveld complex.

Why can you not use existing outcrop or borehole material for this study?

It would be useful to have access to larger samples on which bulk-rock analyses and mineral separation can be performed. We also need a continuous section through the Upper Zone to be able to identify in detail the evolution of mineral modes and minerals textures. This will be useful to constrain cotectic proportions and to use them to put constraints on the Bushveld liquid line of descent. This will be also

useful to determine to what scale segregation of potential immiscible melts occurred. A continuous sampling would also allow to get a better estimate of the bulk composition of the Upper Zone.

Finally, to put constraints on the crystal mush thickness we need relatively large and closely space on which we can perform a detailed textural analysis that will be coupled with geochemical measurements. The stratigraphic interval between changes in mineral structures and mineral chemistry should allow accurate estimate of the thickness of the crystal mush.

Continuous sampling would also allow investigating the porosity distribution both a small and large scale as it was recently shown for the Skaergaard distributuion that the porosity is heterogeneous at a scale ranging from mm to km.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

This study will be very complementary with the group looking at dihedral angles in Cambridge. By using our geochemical approach together with the measurements of dihedral angles, we should be able to refine models of crystal mush development.

The experimental approach with internally heated pressure vessels used at Hannover is well suited to simulate conditions relevant for Bushveld emplacement conditions. The facilities can be of interest for other groups who may want to test or constrain petrological hypotheses (e.g., phase relations, differentiation, thermobarometers).

Please add suggestions or comments that might support the workshop success, thank you.

It would maybe useful to give some time to interested participants to show recent results acquired on other layered intrusions or Bushveld that could stimulate the discussion and give ideas for the new drilling project.

Name	**OBERTHÜR JUNGE, (RAMMLMAIR MEIMA)**
Institution	Federal Institute for Geosciences and Natural Resources (BGR), Germany
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry** **Drilling / logging technology (Hyperspectral mapping)**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Quantitative mineralogy, stratigraphic aspects in the core and linking between cores, cryptical chemical layering, paragenetic sequences, mineralization,
Special focus on the fine-scale distribution of metals in the reefs. Metal host, mineralogy and mineral chemistry of base metal sulfides, PGM, chromite, magnetite; trace element chemistry of BMS; quantitative mineralogy.

What techniques do you plan to use?

- 2D-hyperspectral optical investigation (destruction free)

- 2D-Laser induced breakdown spectroscopy (LIBS, minimal 30µm destruction) elemental distribution maps (almost all elements including light elements such as H and C), chemical quantification, hyperspectral evaluation, phase and lithological classification and visualization.
- SEM-EDX
- EPMA

Selected zones for better resolution

- 2D high resolution (20 µm) element mapping of selected un- or polished or zones (20 cm length). Hyperspectral evaluation, phase classification and visualization of parageneses (destruction free)

Selected areas for polished and polished thin sections

- EDXRF-microscopy
- MLA of relevant positions on pol
- Micro probe analysis for validation of cryptic chemical variation in minerals along the core
- LA-ICP-MS

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Mineral inventory of the complete core but with special focus on the reefs of the Critical Zone (chromitite, Merensky Reef, Platreef,…)

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

No

What comparable information or research exists already on other sections of the complex? Detail information of small sections of cores

Numerous analyses of Merensky Reef, UG-2, Platreef ….

Why can you not use existing outcrop or borehole material for this study?

Can be used for testing the efficiency of the method and eventually for stratigraphic comparison of cores, but is not continuous through the intrusion

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

- High resolution chemical and mineralogical information (100µm spot size) of individual minerals layers and sections of full core length
- Mineral distribution, grain size, shape, paragenetical
- Mineralization (sulfides), alteration, metasomatism, shear zones, veining
- Stratigraphic aspects: lamination, cryptic layering, grain size grading

We would like to connect with Frank Melcher from the University of Leoben to study the fine scale distribution of metals over selected intervals of core.

Name	**DAVID L. REID**
Institution	Geological Sciences, University of Cape Town
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Ultra-ferrous magmas produced by immiscibility and their effect on the layered series

What techniques do you plan to use?

Down hole magnetics, bore hole magnetics, mineralogy and geochemistry

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Lower, Critical and Main Zones

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Where the Lower, Critical and Main Zones are present

What comparable information or research exists already on other sections of the complex?

Open pit and underground exposures of the Upper Critical Zone, where it is mined for PGEs

Why can you not use existing outcrop or borehole material for this study?

Existing profiles restricted to the Upper Critical Zone

Other cores did not intersect much ultra-ferrous lithologies

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

Fe-rich lithologies within the Bushveld Complex profoundly influences the magnetic signature at both local and regional scales

Liquid immiscibility and its role in the petrogenesis of the Rustenburg Layered Suite and its associated metallogenesis

Name	**COLIN RICE**
Institution	COLIN RICE EXPLORATION AND TRAINING (PTY) LTD
Main Discipline	**Drilling / logging technology**

Potential contributions to the science plan

I have been involved in the South African Exploration industry for the past 30 years and I now work as a consultant to several mining companies on exploration projects.

I believe that the proposed borehole will require several different approaches in terms of the drill rig and the contractor that will do the work. I would like to contribute to these and other aspects of drilling phase of the project.

Name	**JAMES ROBERTS**
Institution	University of Pretoria
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

I am primarily interested in the later stages of crystallization in the intrusion, particularly the Upper Zone and the interval above the appearance of apatite. I am interested in how much material has erupted from the chamber and the mechanisms involved.

What techniques do you plan to use?

A mixture of microprobe and in-situ analysis techniques (hopefully including isotopes) will be used. If possible, Mössbauer spectrometry on oxides and SIMS on apatite will be done. This will be complemented by classical petrography and bulk rock analysis, and interpretation will involve thermodynamic modeling.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Primarily the Upper Zone, covering 1500- 2500m. I am also interested in working on the Lower Zone, if time and funding allows.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Fairly complete borehole sections through the Upper Zone exist from the South Western Limb and Northern Limb, so ideally an Eastern Limb location.

What comparable information or research exists already on other sections of the complex?

The Bierkraal and Bellevue boreholes have been studied, and a large amount of data is available. However, many issues such as volatile content and oxygen fugacity remain contentious, as does the liquid composition and line of descent for the Upper Zone magma(s).

Why can you not use existing outcrop or borehole material for this study?

Outcrop is extremely poor, and weathering can be extreme. Existing boreholes are either incomplete or have little material remaining, and are not necessarily representative of the whole stratigraphy.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

The final stages of crystallization are important for understanding the crystallization sequence of the intrusion, and for answering questions related to the composition and origin of parental magmas. Constraining the amount of magma lost and the mechanisms for such loss are broadly applicable to all layered intrusions.

Name	**FREDDIE ROELOFSE**
Institution	University of the Free State
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

I would like to be involved in augmenting the lack of in-situ mineral chemical and isotopic data on the RLS of the Bushveld Complex. It is anticipated that the data that I would like to generate will shed light on the ways in which large layered intrusions are constructed, on aspects related to magma chamber dynamics, on the origin of layering and on the interaction of mantle derived magmas and the crust into which they are intruded.

What techniques do you plan to use?

EPMA, LA-ICP-MS, TIMS (?), petrographic work using SEM and light microscopy etc.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Currently I am working on the Main and Upper zones of the RLS, focusing mainly on plagioclase. My work is currently focused on the Northern Limb, but drill core material sampling the Main and Upper zones of the other limbs will be useful as well, particularly to determine the extent of disequilibrium features throughout the RLS.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

No.

What comparable information or research exists already on other sections of the complex?

Comparatively little. A couple of papers have recently seen the light on the aspects that I would like to investigate, but all of these were not done on a sufficiently large scale so as to start making generalizations based on them.

Why can you not use existing outcrop or borehole material for this study?

I am not prevented from using existing material for my study. Using ICDP collected drill core material would, however, be beneficial because of the fact that various collaborators will be studying different aspects on the same material, allowing for better refinement of models developed by myself and by collaborators.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

The Bushveld Complex is the planet's largest layered intrusion, yet, also the most enigmatic. Very little consensus exists regarding virtually all aspects of the petrogenesis and geological setting of this intrusion. It is my contention that advances will only be made through directed, multi-disciplinary avenues of enquiry – something that can potentially be achieved through an ICDP project.

Name	**CHRISTIAN TEGNER**
Institution	Department of Geoscience, Aarhus University, Denmark
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

a) What are the mechanisms of extreme igneous differentiation?

b) What are the petrogenetic relationships between evolved mafic cumulates, granites, and the Rooiberg volcanics.

c) Is there really not a role for assimilation and fractional crystallization (AFC) processes in the Bushveld Complex.

What techniques do you plan to use?

Electron microprobe and LA-ICP-MS for major and trace element compositions of minerals
XRF and ICP-MS major and trace element compositions of bullk rocks (LA) MC-ICP-MS for isotopic compositions

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

The Main and Upper Zones, granites, and Rooiberg volcanics.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

The Eastern Bushveld limb

What comparable information or research exists already on other sections of the complex?

There are long and continuous drill cores of the western and northern limbs that have been studied in detail, although more could be done leading up to the proposed drilling. A student of mine is presently investigating the uppermost mafic cumulates and the overlying granites in the Bierkraal and Fairfield drill cores. I hope to be able to present the initial results at the workshop. Lew Ashwal and his group has studied this section in the Bellevue core of the northern limb.

Why can you not use existing outcrop or borehole material for this study?

Although excellent outcrops of most of the stratigraphy of the Eastern Bushveld exist and have been described, these outcrops are scattered and prevents continuous sampling. Continuous drill core would allow for detailed spatial resolution. To my knowledge the roof contact between mafic and granitic rocks, in particular, is poorly exposed throughout the complex, and certainly in the Stoffberg area where I seen it.

Name	**HANS THYBO**
Institution	University of Copenhagen, Denmark
Main Discipline	**Geophysics**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

What are the amounts of magma that intruded? Geometry? Possible source and origin?

What techniques do you plan to use?

Geophysics: seismology, seismics, gravity and magnetics.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

I would be interested in studying the overall geometry of the intrusion and to link the results with the findings from the drilling, regarding the composition and cooling time as well as using the drilling results for calibration of the geophysics. A main question to be solved is the actual volume of the intrusion, including whether it is one continuous body or divided into two or more units.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

n/a

What comparable information or research exists already on other sections of the complex?

We have used the SASE data for studying the overall geometry. However, higher resolutions studies are required.

Why can you not use existing outcrop or borehole material for this study?

n/a

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

I propose an overall, integrated geophysical (seismology, seismics, gravity and magnetic) study of the intrusion which will be required for providing understanding of the actual drilling data. I have experience from geophysical studies of similar large intrusion as well as of large intrusions in rift zones.

Name	**TROND H TORSVIK**
Institution	CEED University of Oslo
Main Discipline	**Geophysics**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Magnetic Reversals and cooling rates

What techniques do you plan to use?

Paleomagnetism, Rock Magnetism

Name	**ROBERT TRUMBULL**
Institution	GFZ Potsdam German Research Centre for Geosciences
Main Discipline	**Mineralization** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

I am motivated by the bimodal nature of Bushveld and would like to work on questions related to the felsic magmas. Questions relate to the origin of Bushveld Granites (Lebowa Suite) and their inter-relationships as well as their position in the "big picture" of the complex: RLS, Rooiberg volcanics. Additional interests are the processes of hydrothermal alteration and Sn-F mineralization in the Bobbejankop granite.

What techniques do you plan to use?

After standard petrologic tools of component-tracing with bulk and in-situ microanalysis for major and trace elements, selected SIMS and TIMS analysis for stable and radiogenic isotope ratios of relevant phases, including melt- and fluid inclusion studies of the evolved facies of granites.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Ideal would be a vertical section through parts of the granite showing (a) mineralization features and (b) the contact/Transition to mafic units below.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Studies related to mineralization must be in mineralized areas, clearly.

What comparable information or research exists already on other sections of the complex?

There has been recent O-isotope work by Fourie and Harris (2011-J Petrology) on the granites, the Sn mineralization in Zaiplaats and other locations has been described in various publications from the late 1980s and 1990s. I am not aware of modern quantitative studies on the metallogenesis.

Why can you not use existing outcrop or borehole material for this study?

The vertical succession is very important for understanding evolution processes of the granite cupola and relating it to the inner parts of the intrusion; additonally, the need for unweathered samples in a continuous sequence to one another is only attainable with drillcore.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

There will be other groups looking at the felsic-mafic connections, and a focus on the geochemical specialization of the granites and their mineralization is a complementary topic to the igneous petrogenesis.

Name	**BENJAMIN M. TUTOLO**
Institution	University of Minnesota Department of Earth Sciences
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry** **Hydrogeology** **Heatflow**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

How do virtually impermeable igneous rocks go from freshly crystallized to fully hydrothermally altered?
What is the role of hydrothermal solutions in the transport, concentration, and deposition of economically important elements (i.e., metals and REES) within the Bushveld Complex?
Can we use field data to improve model predictions of the alteration of igneous rocks and deposition of minerals?

How do the salinity and temperature of a hydrothermal solution affect its ability to transport elements? What is the volume of rock from which fluids must leach materials in order to produce the hydrothermal mineral deposits we observe?

What techniques do you plan to use?

Numerical simulators (equilibrium geochemistry as well as coupled fluid/heat/solute "reactive transport" models), X-ray Computed Tomography, (Ultra) Small Neutron Scattering, X-ray Diffraction (powder/microbeam), Optical and Scanning Electron Microscopy, electron microprobe, classic field geologic techniques (e.g., fracture counts and orientation), hydrothermal experiments

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

The major constraint for my study is that the rock has experienced significant hydrothermal fluid flow. I am primarily interested in two features: 1) hydrothermal deposition of economically significant ores; and 2) hydrothermal alteration of olivine-rich rocks. In the Ashwall, Webb, and Trumbull (2013) AGU abstract, mention was made of 2 short ~500 m boreholes, specifically sited to fill in stratigrapy missing from the Bellevue and Moordkopje cores. The 200 m thick Main Zone troctolitic horizon targeted in this proposed core particularly interests me because I have been studying hydrothermal alteration of troctolites as one of the main topics of my PhD thesis.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

I believe that my research questions can be answered in many of the geographic locations of the Bushveld complex. Ideal recovered core, however, would illustrate gradients in fluid-rock interaction, a variety of primary mineralogies, and several different fluid sources.

What comparable information or research exists already on other sections of the complex?

A significant number of fluid inclusion and isotopic studies have been performed on hydrothermally altered sections of the Bushveld, but there appear to be few or no studies that focus on the generation of porosity/permeability through tectonic and or reaction-driven processes. Additionally, relatively few studies have focused on using models of coupled fluid/heat/solute transport through the rocks of the Bushveld to elucidate the process of hydrothermal alteration and ore deposition.

Why can you not use existing outcrop or borehole material for this study?

I admittedly do not have a solid grasp on the current availability of samples from the Bushveld. However, some of the characterization techniques that I propose to employ, particularly (Ultra) Small Angle Neutron Scattering, are sensitive to porosity creation at the nanoscale, such as may be associated with chemical and physical weathering of surface-exposed outcrop samples.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

By applying coupled models of heat and fluid flow and chemical reactions to the problem of hydrothermal alteration and ore deposition within the Bushveld, I can attempt to produce a "big picture" idea of the processes that resulted in the hydrothermal mineralization that we see within the drill core. Additionally, by designing hydrothermal experiments to help to answer the research questions designated above, I will be able to provide constraints upon the theories proposed by myself and others over the course of our studies. My study will benefit from other researchers' constraints on cooling processes, fluid compositions (from fluid inclusion analyses), and horizon-scale interpretation of fracture spacing and mineralogies.

Please add suggestions or comments that might support the workshop success, thank you.

The proposed schedule looks like it includes two key features that will help to make the workshop a success: 1) short, individual presentations of research goals, and 2) free time for socialization. I strongly suggest that these two components are included in the final schedule.

Name	**JILL VANTONGEREN**
Institution	Rutgers University
Main Discipline	**Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

The scientific questions that I am most interested in pursuing in the Bushveld include the processes/dynamics of solidification and cooling, as well as the geochemical signature of extreme magmatic differentiation. Whether I will be able to address these topics with the ICDP borehole depends on where and through what horizons the community decides to drill. I am looking forward to discussing the pros and cons of various proposed drilling sites and intervals and will be open to working on a variety of different problems within the Bushveld.

What techniques do you plan to use?

Electron Microprobe
Laser-Ablation ICPMS for trace element concentrations
LA-ICPMS for in situ isotopic compositions
Ar-Ar geochronology

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

I am mainly concerned with the Upper Zone of the Bushveld Complex and would be interested in several different cores to provide high resolution (cm-scale) over a significant vertical distance (e.g. 3-4 km). But would also like to investigate the Lower Zone in greater detail as well.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

No, however, I think that a drillcore through the Eastern Bushveld might provide the best "new" information. The Western and Northern limbs already have drill core through significant portions, and having a core that could be compared directly to outcrop scale observations would be very beneficial (as can be done in the eastern Bushveld).

What comparable information or research exists already on other sections of the complex?

The studies of Ashwal et al. (2005) and, more recently, Tanner et al. (2014) on the Bellevue core through the Upper Zone and Upper Main Zone in the Northern limb demonstrate what can be done with a detailed core through the uppermost Bushveld. There also exists several boreholes through portions of the Upper Zone in the Western Limb (e.g. Tegner et al. 2006). To my knowledge no borehole through this portion of the stratigraphy has been drilled or studied from the Eastern Limb.

Why can you not use existing outcrop or borehole material for this study?

My existing sample suite is entirely outcrop data from the Eastern Limb of the Bushveld Upper Zone and Main Zones. There are several features that we've identified from these samples that would be greatly benefited by study at a finer resolution. Currently in the eastern Bushveld the erosional landscape makes sampling at the sub 20-50 m scale over large stratigraphic intervals very challenging in these critical regions. This is particularly the case for the section described by VanTongeren and Mathez (2012) in which an Fe-rich and a Si-rich horizon were proposed (e.g. the uppermost 650m of the eastern Bushveld Upper Zone).

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

Studies regarding the geochemical evolution of the Upper Zone will have potential benefit for those studying mineralization, particularly in the Fe-P2O5-REE system. Geochronology will provide important constraints on nearly all processes operating within the Bushveld.

Geochemistry and geochronology studies will significantly benefit from the work of the geophysists looking at paleomagnetics and gravity in order to place constraints on the longevity and volumes of the total magmatic system.

I am looking forward to a large community effort with significant overlap and collaboration on a variety of topics.

Please add suggestions or comments that might support the workshop success, thank you.

My biggest hope is that all voices are heard in the discussion of where to drill and the drilling strategy, so anything that the conveners might do to help diversify the discussion and the participants would be very appreciated. I would also strongly suggest that some concrete plan is discussed regarding the long-term storage and accessibility of the cores to the international community.

Name	**ILYA VEKSLER**
Institution	GFZ Potsdam German Research Centre for Geosciences
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

The origin of magmatic layering and the mechanism(s) of PGE concentration in chromitite layers. The origin of iron-rich ultramafic pegmatites (IRUP). Intercumulus crystallization.

What techniques do you plan to use?

X-Ray computer tomography (XRCT), Microanalytical techniques, melt- and fluid inclusion studies, experimental studies (for example, partial melting of cumulate samples combined with microprobe studies and XRCT before and after melting).

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Any stratigraphic intervals with well-developed layering

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Not really.

What comparable information or research exists already on other sections of the complex?

Trace element analyses of individual minerals in LZ and UZ by Barnes et al. and Mathez and VanTongeren. XRCT studies by Godel et al. More data of this kind is needed.

Name	**GERHARD VON GRUENEWALDT**
Institution	Science policy Consultant / retired
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

I am no longer active as a researcher, however as former director of the Institute for Geological Research on the Bushveld Complex at the University of Pretoria, I still retain an interest in the Complex and hope that through my presence at the workshop I will be able to add some value to the discussions and debates, based on my, albeit somewhat outdated, experience. At the time I was among others instrumental in the drilling of the 3000m Bellevue borehole in the Northern limb of the Complex. A second borehole was subsequently sited by the Geological Survey and drilled further north with the intention to intersect Bushveld rocks below the Waterberg. After more than 1000m the borehole was abandoned as no Bushveld rocks were intersected. To the best of my knowledge these were the last “stratigraphic” holes drilled in South Africa with Government funding.

I have some ideas where boreholes could be sited to clarify structure and petrology of the Complex, although am no longer in a position to participate in actively in any research on the core.

Name	**COREY J. WALL**
Institution	University of British Columbia (Vancouver, Canada)
Main Discipline	**Petrology-mineralogy-geochemistry** **Geochronology, radiogenic isotopes**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

- At the University of British Columbia, we have established a research group supervised by Drs. James Scoates and Dominique Weis that is investigating the timescales of crystallization and cooling of mafic layered intrusions worldwide (e.g., Stillwater, Muskox, Bushveld) and mafic to ultramafic cumulates from intrusions emplaced into a wide variety of tectonic settings (e.g., rift, arc, plume-related). We use high-precision U-Pb geochronology of zircon (and other U-Th-Pb-bearing accessory minerals), coupled with Hf isotopes and trace element concentrations in zircon, to constrain the age, duration of magmatism, and chemistry of the magmas related to the mafic-ultramafic rocks and how these magmas differentiate in the Earth's crust. We have published a large number of papers with dating results for mafic-ultramafic rocks (e.g., Bushveld, Muskox, Bird River, various intrusions associated with Proterozoic anorthosites, etc.). We have recently written an overview paper entitled "Geochronology of Layered Intrusions" for the new book on Layered Intrusions to be published by Springer at the end of 2014.
- We began a project on the age of the Bushveld Complex and associated rocks in the mid- to late 2000s when it became clear that published high-precision dates were lacking for this remarkable intrusion. We published the first high-precision date for rocks of the Bushveld Complex from the Merensky Reef (ca. 2054 Ma; Scoates & Friedman 2008) using the recently developed chemical-abrasion ID-TIMS technique where individual zircon grains are analyzed followed high-temperature annealing and chemical leaching to remove damaged zones and the effects of lead-loss. Since then, we have initiated a larger dating project of the Bushveld Complex in collaboration with colleagues at the American Museum of Natural History (New York) and have reported preliminary results at the Goldschmidt 2011 Prague and 2012 Montreal meetings and the AGU Fall 2011 meeting in San Francisco. We are currently working on finishing up this first phase of Bushveld dating for publication.
- The fundamental question to investigate with the Bushveld drilling project is: what is the age range, duration, and cooling history for the Bushveld Complex from a stratigraphic and lateral perspective, both within lobes and between lobes? Our work on mafic layered intrusions is beginning to show that there may not be a single age for a large intrusion, but a range of ages, perhaps as long as several million years. Whether or not magmatism is restricted in time or occurs over a million years or more has profound implications for how layered intrusions are constructed, the rates of mantle melting and ascent mechanisms, the relationship to associated ore deposits, and even potential environmental consequences related to eruption and degassing of magma at the Earth's surface. The cooling history of the Bushveld Complex, from liquidus temperatures down to ambient crustal temperatures, is critical for evaluating the thermal impact of emplacement of the Bushveld magmas into the Kaapvaal craton, for constraining the scale and extent of hydrothermal activity outside of, and within, the Bushveld Complex following crystallization, and for detecting subsequent thermal events related to regional orogenesis.
- We are also interested in assessing the significance and extent of radiogenic isotopic heterogeneity between minerals and whole rocks in the Bushveld Complex. Increasingly, there is evidence that coexisting minerals in layered intrusions (e.g., plagioclase, pyroxene) have different initial (at the time of crystallization) isotopic ratios, and this has profound implications for our basic understanding of how layered intrusions are assembled. At UBC, we have worked extensively on the Sr-Nd-Hf-Pb isotopic compositions of mafic layered intrusions and anorthosites, and we are currently investigating crystal-scale isotopic variations in the Kiglapait layered intrusion, coastal Labrador. Recent studies from the Bushveld Complex clearly demonstrate initial isotopic differences for select samples and specific stratigraphic sections. Our interest is in targeting stratigraphic levels that have not been assessed to date to allow integration with the existing studies and to constrain just how widespread this phenomenon is. Most studies use either coupled Sr-Nd isotope systematics or Pb isotope variations only, whereas our expertise is in application of combined Sr-Nd-Hf-Pb isotope compositions from minerals and whole rocks, a powerful multi-isotope approach. We are also in the early stages of developing in situ Sr-Pb isotope analytical capabilities in plagioclase by high-resolution laser ablation-ICP-MS.

What techniques do you plan to use?

- For geochronology, we plan to use high-precision isotope dilution-thermal ionization mass spectrometry (ID-TIMS) to determine the ages of crystallization (zircon, baddeleyite) and cooling (rutile, apatite, titanite); the chemical abrasion method is used for annealing and leaching individual zircon grains. We have two ID-TIMS instruments dedicated to U-Pb geochronology at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at UBC. All minerals to be analyzed will be characterized by cathodoluminescence (CL) imaging using a scanning electron microscope (SEM) to evaluate zonation patterns and possible inclusions.
- Laser ablation-ICP-MS will be use to determine the trace element concentrations of zircon and other U-Th-Pb-bearing accessory minerals, including thermometric information (e.g., Ti-in-zircon, Zr-in-rutile). High-precision multiple collector-ICP-MS and TIMS will be used to determine the isotopic composition of various minerals and whole rock samples. The facilities at the PCIGR house a large number of state-of-the-art mass spectrometers for this research.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

- Our study is concerned with the entire vertical distance of the Bushveld stratigraphy, including the roof rocks (Rashoop Granophyres, Lebowa Granite) and Rooiberg volcanic rocks. Our experience with high-precision dating of the Stillwater Complex, another major mafic-ultramafic layered intrusion that has been highly influential in developing our concepts of how magma chambers solidify, is that stratigraphic sample spacing may need to be less than 200 m to be able to identify all horizons where significant age gaps and changes occur – at Stillwater, we have identified a number of different magmatic episodes over an interval of several million years based on results from 20 samples over 6500 metres of cumulate stratigraphy (Wall, PhD work in progress).
- Given the samples we have already dated and that are in progress, we would target regularly spaced samples throughout (1) the Marginal Zone, Lower Zone, and Lower Critical Zone, (2) the Main Zone, and (3) the majority of the Upper Zone from the Eastern Lobe. The Upper Critical Zone is of particular interest given the variety of rock types, “reef” packages, and mineralization (chromite, PGE) present. There are no precise CA-ID-TIMS dates from the Northern Lobe and thus the existing drillcore and new drilling are excellent targets for evaluating the temporal relationship with the Eastern and Western Lobes.
- Granitic roof rocks that are drilled will be critical for evaluating the link between mafic and felsic magmatism in the Bushveld Complex. Two additional specific rocks are also of interest: (1) the troctolite horizon in the Northern Lobe, and (2) the newly identified Roof Zone rocks in the southeastern Bushveld Complex.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

- All targeted areas of the Bushveld Complex for drilling (continuous section across the Eastern Limb, sampling of the Roof Zone, middle section of the Northern Limb) will each yield important samples for dating (see above section) to test for age relationships with respect to stratigraphic and lateral position.

What comparable information or research exists already on other sections of the complex?

- The duration of magmatism and cooling of the Bushveld Complex and associated mafic-ultramafic rocks across the northern Kaapvaal craton remains a fundamental question in the origin of the world’s largest layered intrusion. Whether the duration is 1 Ma, 5 Ma, or 10 Ma or longer, directly impacts estimates for rates of mantle melting, melt extraction, magma transport, magma flux, and cooling, and even potential environmental impacts (i.e., degassing associated with eruptive equivalents) as noted above. Recent compilations of available geochronological data, combining in some cases published (analytical technique and data tables available) and unpublished (ages reported in abstracts with no associated data), suggest that most of the

products of Bushveld-related magmatism may have crystallized in the interval of 2054-2061 Ma (Mapeo et al. 2004; Scoates and Friedman 2008; Yudovskaya et al. 2013; Rajesh et al. 2013). Comparison of recently published ages filtered for apparent uncertainties of less than ±5-10 Ma, however, is problematic. The compiled ages include a wide range of minerals analyzed (e.g., zircon, baddeleyite, titanite, monazite, biotite), analytical techniques (e.g., TIMS [+thermal evaporation], CA-TIMS, SHRIMP, LA-ICP-MS), and age interpretations (e.g., upper intercept $^{207}Pb/^{206}Pb$ ages from discordant results, weighted average $^{207}Pb/^{206}Pb$ ages for concordant results, Pb-Pb evaporation ages, $^{40}Ar/^{39}Ar$ plateau or inverse isochron ages). Few studies involve common reference materials, reference values, and data reduction techniques. In the absence of a common technique referenced to the same standards, a true comparison of the published geochronological results for the Bushveld Complex and related rocks requires use of all external errors, including uncertainty in decay constants for the different isotopic systems, an exercise that will inevitably lead to significantly larger and overlapping uncertainty. Determination of the absolute and precise duration of Bushveld-related magmatism will require careful application of the single-grain CA-ID-TIMS U-Pb zircon method, referenced to EarthTime synthetic reference solutions and common data reduction protocols, to select samples of previously dated samples and intrusions and to newly targeted samples.

- There remain, as of yet, few published datasets for samples that directly date the timing of crystallization of mafic-ultramafic rocks from the Rustenburg Layered Suite. Our new CA-TIMS U-Pb zircon ages for the ca. 2057 Ma Merensky Reef (Scoates and Wall, in review), which are slightly older than those reported in Scoates and Friedman (2008) due to changes in data reduction, use of EarthTime spikes and reference solutions, and a revised and more precise lead standard value, establish the synchronous crystallization of this horizon within the uppermost Upper Critical Zone across the Bushveld Complex from the Eastern and Western Lobes. Olsson et al. (2010) report a U-Pb age of 2057.7 ± 1.6/6.4 Ma (±X/Z) for baddeleyite separated from a coarse-grained norite collected from the Marginal Zone (Eastern Limb). The date is an upper intercept $^{207}Pb/^{206}Pb$ age regressed through the slightly discordant (0.8-2.7%) U-Pb results of four multi-grain (n=10-23) baddeleyite fractions. This age is indistinguishable from the revised Merensky Reef ages within 2s uncertainty (internal errors only). Direct comparison between the two datasets, however, is not possible at this time as Olsson et al. (2010) use an “in-house program” for data reduction and do not report use of EarthTime reference synthetic solutions to allow for interlaboratory comparison and calibration. The Merensky Reef ages are now closer to that of Buick et al. (2001) for titanite that formed in a retrogressed xenolith in the Upper Zone (Eastern Limb). Their U-Pb age of 2058.9 ± 0.8 Ma (2s, weighted $^{207}Pb/^{206}Pb$ age, internal errors) from three large multi-grain titanite fractions (5-12 mg) provide an indirect age of crystallization for the uppermost part of the Bushveld Complex that appears to be older than the Merensky Reef ages by ~500,000 years assuming that there is no interlaboratory bias. Whether or not titanite growth in the calc-silicate protolith occurred during hydrothermal alteration related to Rooiberg magmatism with subsequent partial resetting during incorporation of the xenolith into the Bushveld magmas or that titanite growth indeed records the age of Bushveld magmatism remains to be tested.

Why can you not use existing outcrop or borehole material for this study?

- Our current study is based on existing outcrop, mine, and borehole material, and acess to this material has been incredibly important in helping us to begin to understand the timescales of crystallization and cooling of the Bushveld Complex. For the most part, however, the samples are from different parts of the intrusion such that the stratigraphic section is composite and not from a single slice through the Bushveld Complex. It is critical to evaluate lateral changes in age and cooling, but these need to be constrained by results from continuous sections through the intrusion as a key reference. This can only be accomplished from core from a series of continuous drill holes.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

- The results of our high-precision geochronological research, coupled with trace element variations in zircon and other U-Th-Pb-bearing minerals and radiogenic isotopic compositions of the main cumulus minerals, will provide key results to aid petrologists, geochemists, economic geologists, mineralogists, and paleomagnetism specialists to better understand the crystallization history of the Bushveld Complex with constraints on the chemistry and isotopic composition of the parent magmas and their source(s). A detailed temporal record of crystallization and cooling of the Bushveld Complex is required to assess the timescales of magma chamber processes and melt evolution, crust-mantle interactions and the origin of the Bushveld granitoids, and the origin of the many world-class ore deposits hosted by the Bushveld Complex. Our geochronological and isotopic studies will be highly influenced by careful core logging and geophysical borehole measurements, and the combined results of petrologic, geochemical, and paleomagnetic studies carried out on the same materials. Interaction and communication between the different teams of experts involved in the project will be essential in determining the overall success of this high-profile scientific endeavor.

Name	**QIN WANG**
Institution	School of Earth Sciences and Engineering, Nanjing University, China
Main Discipline	**Petrology-mineralogy-geochemistry** **Structural Geology, Rock Physics**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

We plan to investigate four questions as follows:
(1) What are the characteristic fabrics of the layered mafic and ultramafic rocks formed by magmatic underplating?
(2) What the relationships between magma intrusion, deformation and concentration of ore metals?
(3) How magmatic underplating causes discrepancies between seismic, electrical and petrological crust-mantle boundaries?
(4) What was the oxygen fugacity (fO_2) variation during formation of the Bushveld Igneous Complex and how it controlled PGE ore deposits?

What techniques do you plan to use?

To answer our main questions, we will apply the following techniques:
(1) For petrofabrics, we will determine the crystal preferred orientations (CPOs) of minerals using the electron backscatter diffraction (EBSD) technique;
(2) For seismic properties of core samples, we will analyze the EBSD data and calculate 3D seismic velocities of core samples using the MTex program, an open source MATLAB Toolbox for Quantitative Texture Analysis;
(3) We will measure electrical conductivity of core samples using a piston cylinder press and Solartron 1260 phase-gain analyzer, and compare the laboratory-derived results with calculated values using the Hashin–Shtrikman average;
(4) For the oxygen fugacity variation and its effects, we will perform Cu, Fe, and V isotope geochemistry.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

To constrain the deformation, element transfer and variation of fO2 during magmatic intrusion, we wish to focus on the boundaries of different stratigraphic zones, but some samples inside different layers are also needed. With a complete or systematic depth profile, we can know better about isotope variation along the depth.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

To apply our results to other regions subjected to magmatic underplating, we need to compare with geophysical observations. The Eastern Lobe has a seismic profile and structurally continuous, so it is the best region for us.

What comparable information or research exists already on other sections of the complex?

To the best of my knowledge, no research of Cu, Fe, and V isotopes on the complex has been published. An integrated petrophysics and geochemistry study of the complex is still lacking.

Why can you not use existing outcrop or borehole material for this study?

We need fresh samples and systematic sampling to decipher the relationship between fO2 and redox-sensitive isotopes, and combine with variations in fabric development and seismic velocities. Exiting outcrop or borehole material are good complementary to this study, but not enough. In addition, previous borehole material were not oriented during sampling, which cannot be used for fabric analysis.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others?

(1) The experimental results can be compared with the seismic and electrical data across the drilling site, to evaluate the reliability of using geophysical methods to trace large layered intrusion at great depths.

(2) The EBSD data will allow us to compare deformation of ultramafic to felsic rocks during intrusion and accumulation, which will provide a reference for magmatism-related deformation in large igneous complexes.

(3) Variation of fO2 during magma evolution is one of the key questions to understand how the layered mafic intrusion was formed and how the PGE ores were deposited. Our work will provide a unique geochemical aspect to the chemistry and physics of the complex.

Please add suggestions or comments that might support the workshop success, thank you.

We are open to any potential cooperation with other disciplines. Because Prof. Fang Huang cannot attend the workshop, I will present a poster to introduce his ideas. So besides oral presentations, a poster session will be appreciated.

Name	**ALLAN WILSON**
Institution	Wits
Main Discipline	**Mineralisation** **Petrology-mineralogy-geochemistry** **Heatflow**

Potential contributions to the science plan

What are the main questions (hypothesis) you plan to investigate?

Continue with the work I am currently involved with. That is the form and nature of the contact of the Marginal and Lower Zone sections. An evaluation of lateral variations in these units will be especially important.

What techniques do you plan to use?

Logging. XRF analyses. Probe analyses. ICP-MS. TIMs. LA.

What stratigraphic horizon(s) do you wish to study and over what vertical distance is your study concerned?

Lower Zone and below.

Is there a particular geographic region of the Bushveld complex that is essential for your study? If so, explain why and be specific about the location.

Any area would be ok.

What comparable information or research exists already on other sections of the complex?

Wilson several papers published and in press.

Why can you not use existing outcrop or borehole material for this study?

The whole idea would be to use new sections.

What does your research offer to other disciplines in the ICDP group and how will your study benefit from the results of others ?

I am sure the integrated data will be useful for petrologists.