MITT.ÖSTERR.MINER.GES. 161 (2015)

A GEOLOGICAL EXCURSION TO THE MINING AREAS OF SOUTH AFRICA

by

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1. Preface

Almost a year ago Aberra Mogessie planned to organize a field excursion for the students of the Institute of Earth Sciences, University of Graz. The choices were Argentina, Ethiopia (where we had organized past excursions) and South Africa. Having discussed the matter with Christoph Hauzenberger concerning geology, logistics etc. we decided to organize a field excursion to the geologically interesting mining areas of South Africa. We contacted Christoph Gauert from the University of Free State, South Africa to help us with the local organization especially to get permission from the different mining companies to visit their mining sites. We had a chance to discuss with him personally during his visit to our institute at the University of Graz in May 2014 and make the first plan. In September 2014 during the IMA2014 conference in Johannesburg we met again, this time also with Frank Melcher from the Montanuniversitaet Leoben who was interested to join our group with his students. We agreed to organize a joint excursion of the University of Graz and the Montanuniversitaet Leoben with the local support of the Department of Geology, University of Free State, South Africa. Although there were a large number of students who were interested to join the excursion, we decided to keep a maximum number of 40 participants which included 35 students and 5 staff members from both universities.

The excursion took place from 6 -20 April 2014 and it was a very successful one both from an academic point of view and the cooperation between the institutes from Austria as well as the Geology Department of the University of Free State, South Africa. The report that is presented here is compiled by Aberra Mogessie based on the report submitted by 10 different groups of students who were responsible for an excursion day each, and was edited by Christoph Hauzenberger, Frank Melcher, Walter Prochaska, Heinrich Mali and Christoph Gauert. The diagrams are drawn by Sara Raíc (Ph.D student of A. Mogessie and F. Melcher) also based on scanned figures and photos submitted by the excursion participants. The writing of the reports in the field was coordinated by Philip Schantl (MSc student of Christoph Hauzenberger).

2. Introduction to the geology of South Africa

Although the objective of the excursion was to visit specific mining areas it was necessary to have an idea of the general geology of South Africa. Below is a summary of the most important units from old to young (Fig. 1). This summary is based on the discussions in JOHNSON, M.R., ANHAEUSSER, C.R. and THOMAS, R.J. (Eds.) (2006): The Geology of South Africa and references therein.

The oldest rocks of South Africa are the granitoids of the Archaean Kaapvaal Craton (3.65 Ga). These cratons are characterized by infolded, extrusive mafic greenstone belts such as the Barberton Greenstone Belt. After the development of a stable craton, the deposition of the first sediments started, which are divided into the Pongola (3.1 Ga), Dominion (3.07 Ga) and Witwatersrand Supergroups (2.8.2.3 Ga). The "Wits" Supergroup contains valuable gold deposits in the conglomerates.

At 2.7 Ga the Limpopo Orogeny developed between the Zimbabwe Craton and the Kaapvaal Craton and is the oldest known transpressive orogenic event (VAN BREEMEN & DODSON, 1972). This orogeny enlarged the stable crust and generated the sedimentary basins of the Ventersdorp Supergroup and the Transvaal Supergroup on the Kaapvaal Craton. The Transvaal Supergroup represents the oldest carbonate platform successions with stromatolites and well preserved cyanobacterial evolution. Towards the top, massive banded iron formations, with substantial iron and asbestos deposits, and sedimentary to volcanic successions, with the world's largest manganese concentrations, occur. Structurally controlled gold deposits are also found in these units.

The Bushveld Igneous Complex (BIC) was emplaced into the Transvaal Supergroup sediments 2.06 Ga ago and covers an area of 65.000 km^2. The complex is divided into five limbs: The Northern, the Southeastern, the Western, the Far Western, and the Eastern Limb (Fig. 2a, b). It is the worlds´ largest layered mafic intrusion, known for its economically valuable chrome, platinum group elements (PGE) and vanadium mineralizations.
From bottom to top the complex comprises the Rooiberg Group, the Rustenburg Layered Suite and the Lebowa Granite Suite (as well as the Rashoop Granophyre Suite). Rooiberg Group rocks host basaltic andesite, dacites and rhyolites. The main part of the complex is represented by mafic volcanic rocks of the Rustenburg Layered Suite, characterized by a fully differentiated sequence of ultramafic, mafic and felsic rocks.

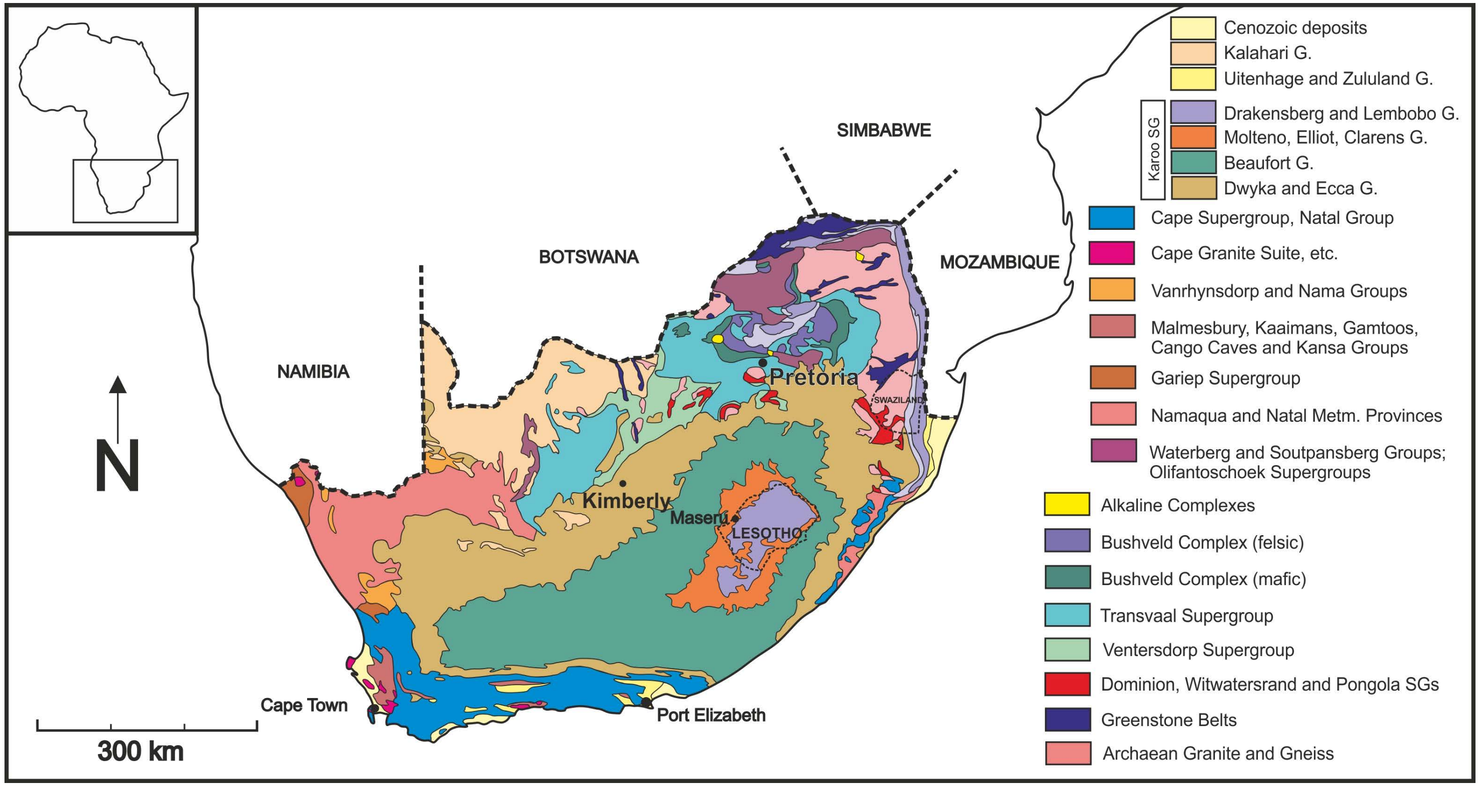


Fig. 1

Geological Map of South Africa (modified after N. Keyes, Council of Geosciences, 2006).

It can be subdivided into five zones: Marginal Zone (norite), Lower Zone (dunites and pyroxenites), Critical Zone (pyroxenites, anorthosite, norite), Main Zone (gabbronorites) and an Upper Zone (gabbronorite, anorthosite and magnetite- and apatite-rich diorite). Large platinum-group mineral-bearing ore bodies and chromite horizons are found within distinct layers of the Upper Critical Zone (e.g. UG2, Merensky Reef) and are being mined in the Eastern and Western Limbs.

During and after the emplacement of the BIC, alkaline complexes intruded in the northeastern Kaapvaal Craton. These are the Palabora Complex, in the eastern part of the northern province (2 Ga), and the well-known Pilanesberg Alkaline Complex, ENE of Pretoria (1.45 - 1.2 Ga; HARMER, 1992). They are economically important for their enrichment in Cu, Ni, U, Ag, Au, PGE, baddeleyite, REE, apatite and vermiculite.

During the Namaqua-Natal Orogenic event (1.2 - 1 Ga), a 1400 km long and 400 km wide belt developed, reworking older terranes (Khesian rocks; 2 Ga) and assembling younger crustal sediments along with plutonic rocks through collision tectonics and metamorphism. Nowadays most of these units lie under the massive Phanerozoic Karoo Supergroup. In the late Precambrian to early Cambrian, during the formation of the Pan-African Belt Saldania, the intrusion of the Cape Granite Suite started about 552 Ma ago. The Cape Granite suite intruded into the green-schist facies metasedimentary and metavolcanic rocks of the Neoproterozoic. In the early Paleozoic the formation of the Natal Group followed. This group consists of red-gray conglomerate, sandstones, siltstone and mudrocks, underlying the Dwyka Group and lying above the Archaean and Proterozoic basement. The siliceous Cape Supergroup was deposited in a passive margin basin after the Saldania orogeny, and the Pan-African deposition cycles in Gondwana ended in the late Precambrian to early Cambrian. Subsequently, the formation of the Karoo Supergroup took place from the Middle-Paleozoic to the Middle-Mesozoic. This group is well-known for their terrestrial vertebrate fossils, distinctive plant assemblages, thick glacial deposits and extensive flood basalts with dolerite dykes and sills. At the end of the Mesozoic Era, at 190Ma ago the Karoo Igneous Event started. It comprises thick successions of continental flood basalts, containing a significant number of siliceous, rhyodacitic and rhyolitic volcanic rocks.

After the Karoo Igneous Event, the Post Karoo Mesozoic deposition started. After the break-off of Gondwana, tectonic and volcanic activity in South Africa was at a minimum, producing one of the most stable regions in the world. The exception to this was the penetration of the lithosphere by kimberlite pipes on the subcontinent between 200-80 Ma ago. These kimberlite pipes are an important source for gem-quality diamonds. In general, the age of kimberlites in South Africa lasted from 1900 to 70 Ma. 90% of them have a Mesozoic age and are spread all over the country in at least 10 different provinces. The craters of the kimberlite diatremes are filled with early sediments of the Kalahari, which were then covered by younger sediments, in the Late Cretaceous. The deposits on the mainland are rather thin compared to the thicker deposits that have been formed offshore in the extensional rift basins and as sediment depositions in the major estuaries (JOHNSON et al., 2006).

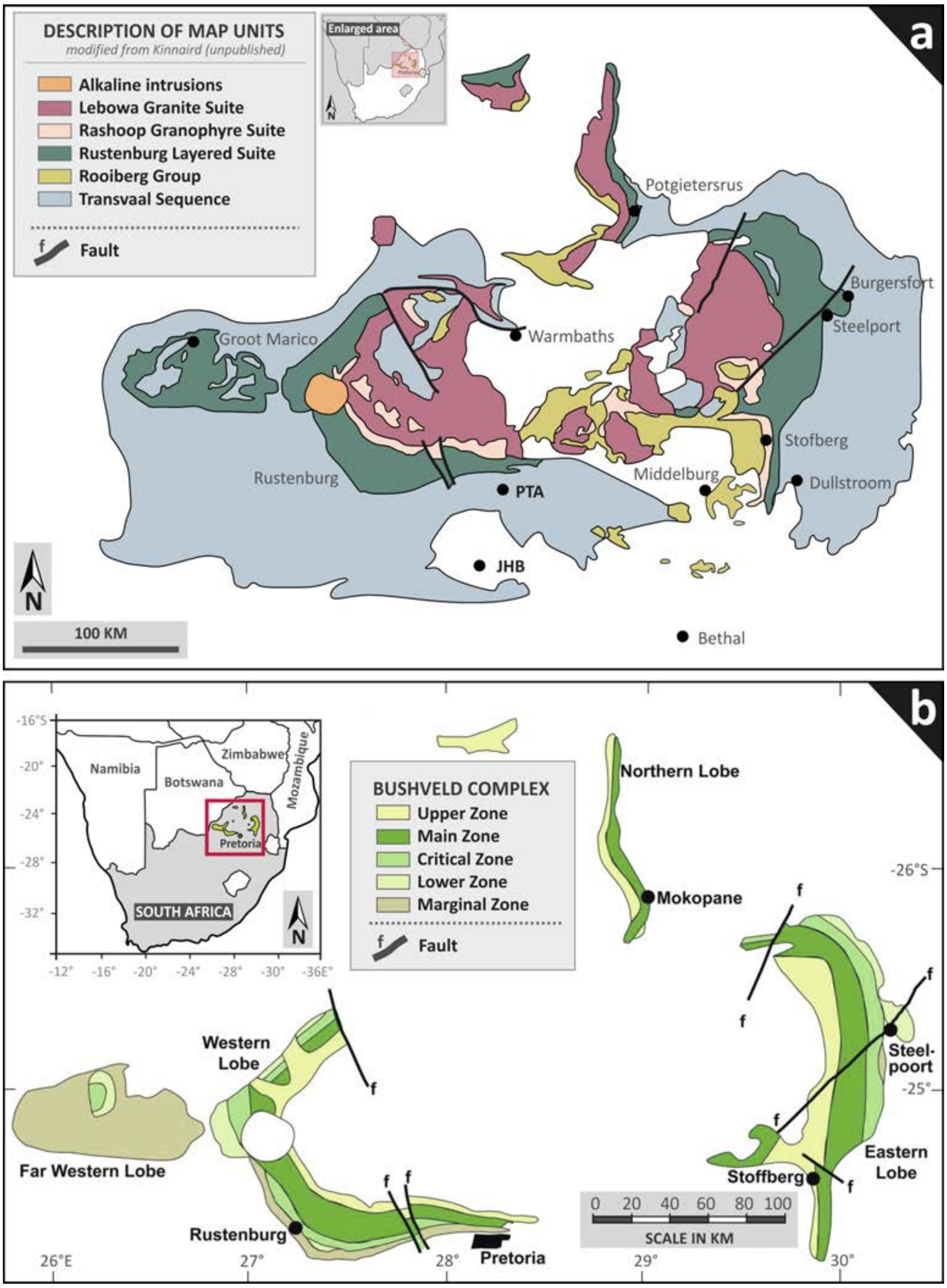


Fig. 2a, b

a) Geological Map of the Bushveld Complex, b) a map showing the mineralized zones of the Bushveld Complex.

Excursion Stops

Our field excursion (Fig. 2c) started in Pretoria on 8 April 2015 with a stop at the Vergenoeg fluorite mine followed by Karro coal Middelburg, Eastern Chrome, Dewars River UG1, Merensky Reef, UG3, UG2, Cameroon section Lower Zone-Critical Zone transition, Kumba Iron ore Thabazimbi mine, Andalusite Resources, Pilanesberg Alkaline Ring Complex, Big Hole Kimberley Diamond, University of Free State, Bloemfontein, Department of Geology, Vredefort Impact Crater and finally flew back to Graz from Johannesburg International Airport on 19 April 2015.

Fig. 2c
Excursion routes.

Excursion day 1

3. Geology of the Vergenoeg fluorite

The roof rocks overlying the Bushveld Complex (= Rustenburg Layered Suite) consist of the Rashoop Granophyre, the Rooiberg Group Lavas/Felsites and the Lebowa Granite Suite (Figs. 3, 4; VANTONGEREN et al., 2010). The whole sequence is overlain by the Waterberg Group sedimentary cover (clastics with minor volcanic intercalations) deposited conformably on the Rooiberg Group Lavas at 2,054 ± 4 Ma (DORLAND et al., 2006).

The Rashoop Granophyre discordantly overlies the Bushveld Complex and is geochemically very similar to the Rooiberg Group. Hence, vertical and lateral extensions of the granophyres are considered to have originated from partial remelting of Rooiberg Group by the Bushveld magma (VANTONGEREN et al., 2010).

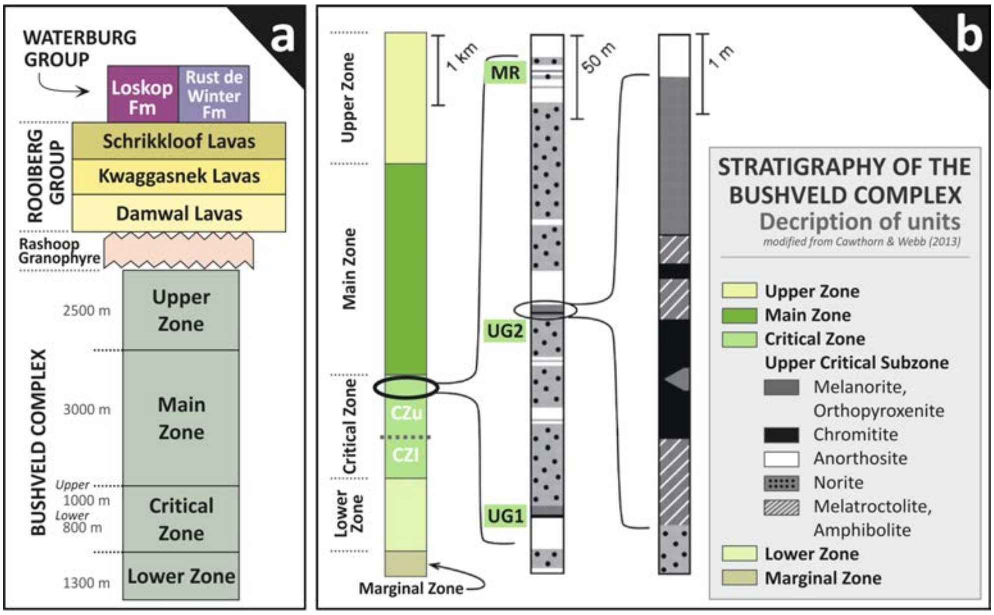


Fig. 3
Generalized stratigraphic relations of the Bushveld Complex and roof rocks (VANTONGEREN et al., 2010).

The Rooiberg Group is a bimodal lava sequence with a thickness of up to 3.5 km and covers an area of > 50,000 km² (SCHWEITZER et al., 1995). Extrusion ages of the lavas are given by a few authors (e.g. HARMER & ARMSTRONG, 2000) to range between 2,061 ± 2 and 2,057 ± 3.8 Ma, making them older than the Bushveld Complex. Economically, they host one of the second most important fluorite deposits in the world at Vergenoeg Mine (Fig. 4).
Finally, sheets and feeder dikes of the Lebowa Granites cross-cut the Bushveld Complex and the Rooiberg Group (2,052 Ma by HILL et al., 1996). The granites are generally alkali-feldspar granites but can be subdivided into 3 major facies by color and texture and further 4 geographically restricted facies. They also host economic tin mineralizations e.g. at Zaaiplaats, Rooiberg and Groenfontein.

3.1. Vergenoeg fluorite mine

(Location: ~ 80 km NE of Pretoria (Fig. 4; S25°15.307' E28°35.309')
We arrived at the mine site at 8:40AM and had an introductory presentation about the geology and the mining operation by Hennie Terblanche, the mine geologist at Vergenoeg.
Based on his presentation the fluorite (CaF_2) deposit was discovered by Wagner in 1928. In 1956 a first geological map was produced by Glatthaar and the first small mining activities started by Watercress Mining Company. Current owners are Minersa Group (85%) and Medu Capital (15%) since 2009.
Basic data: Vergenoeg, with an ore reserve of 162.8 Mt, comprises 10% of the world's esources of fluorspar and produces 70,000 tons of ore per month with a CaF_2 grade of ~38% which amounts to ca. ~16,000 tons of concentrate production.

Two major products are:

- Acidspar (> 97% CaF_2) → used for production of HF, glass industry, Al-fluoride
- Metspar (< 97% CaF_2) → used for local iron & steel industry (as it lowers the melting point)

Beside Vergenoeg there are 4 more occurrences of fluorite spread in different host rocks within the Bushveld Complex (e.g.Buffalo, Wallmansthal).

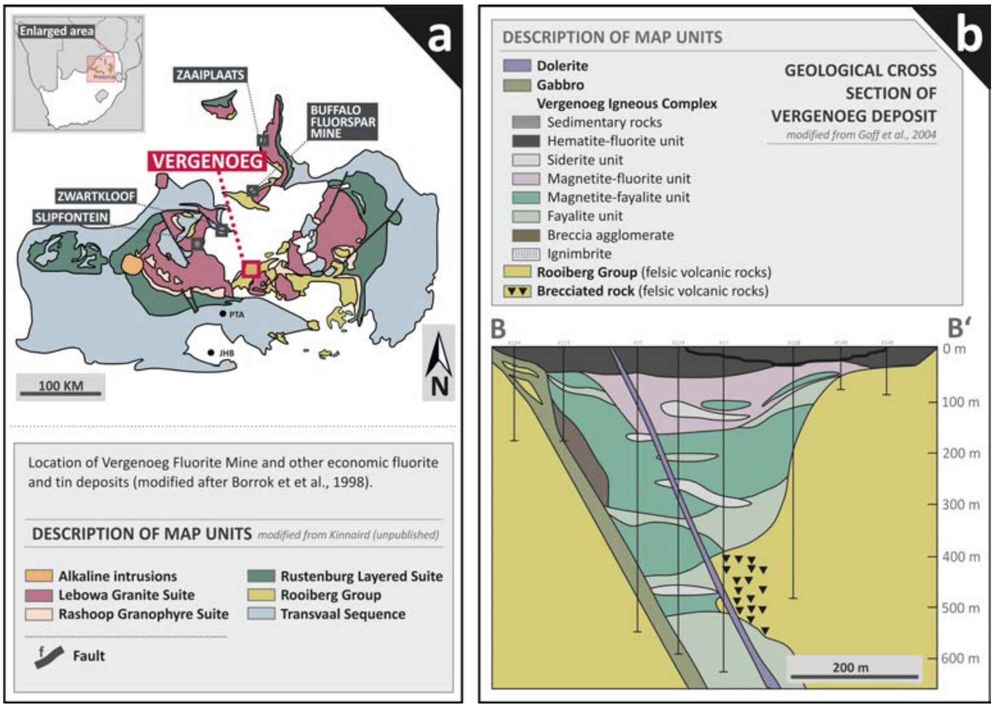


Fig. 4
Geological cross-section of the Vergenoeg fluorite deposit (GOFF et al., 2004).

Stop 1

Geology: Vergenoeg is a funnel-shaped breccia pipe with surface dimensions of 600 x 900 m and a diameter of 200 m in 600 m depth (GOFF et al., 2004). The host rocks of the pipe are Rooiberg Felsites (Figs. 3, 4, 5).

Within the pipe several vertical hypogene units can be distinguished: Surface gossan with hematite, goethite and supergene fluorite, magnetite-fluorite transition zone, magnetite-siderite-fayalite-fluorite zone and fayalite-fluorite zone. Additionally, massive, plume-shaped, siderite-fluorite lenses occur throughout the pipe (Fig.4; GRAUPNER et al., 2015).
Because of weathering and oxidation processes which produced the surface gossan with supergene fluorite, the CaF_2 grade can reach 40 - 60%, while it does not exceed 15 - 25% in units below 500 m (cut-off grade 28% CaF_2). S-content also increases with depth to about 1.5% occurring as pyrite, marcasite and pyrrhotite.

Other contaminants are phosphates and arsenates. Some aspects of the genesis of this deposit are still controversial especially concerning its possible link to the Bushveld Granites (exsolution of a F/Fe-rich magma from a parent granite magma; (GRAUPNER et al., 2015) or the idea of a separate pegmatoidal carbonatite intrusion (GOFF et al., 2004). Nevertheless two different intrusion phases can be distinguished with a first one producing a homogeneous simple mineralogy and a second one producing a complex mineralogy in random structures creating some difficulties during mining. On the other hand it is generally accepted that the mineralizations are derived from hydrothermal fluid alteration and precipitation. One age determination for the fluorite mineralization was reported by GRAUPNER et al., 2015 with 2,040 ± 46 Ma but because of a large error it has to be taken with caution.

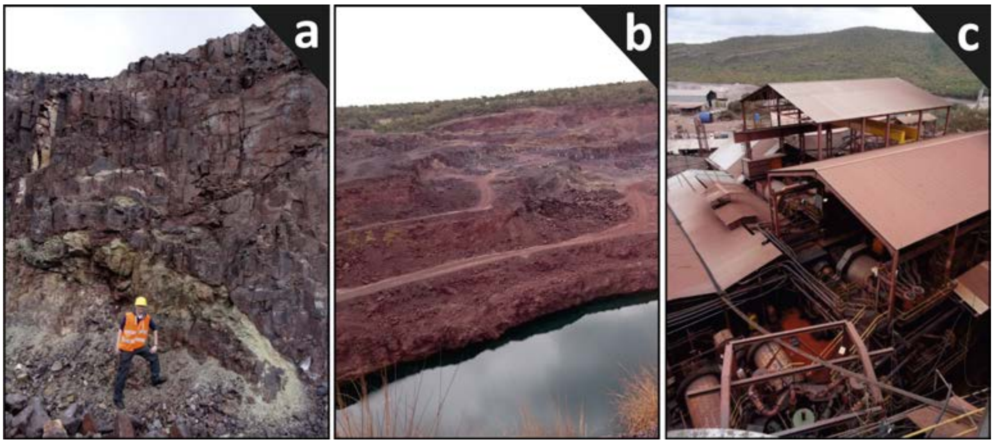


Fig. 5
Contact between the Rooiberg Felsites and the fluorite pipe. The building is the mine plant.

3.2. Mining
Mining is executed with standard open-pit mining (Fig. 5) including drilling and blasting in three different mining areas: plug (main pipe), spill area (where lava spilled out during the in-/extrusion of the pipe on the eastern side of the mine and dipping underground slightly towards E, representing highest CaF_2 contents) and flow area (the spilled out lava flow following an ancient valley).In this eastern mine area a special geological feature occurs called the "Neptunian dykes" which are sandstone dykes in shear zones but their genesis is still unknown.

3.3. Ore processing
Crushing, milling → flotation → magnetic separation (acidspar – metspar) → filtering → final concentrate. The recovery rate is 65 – 70% depending on the processing and product.

Stop 2

4. Premier Diamond Mine, Cullinan (Location: ~ 40 km ENE of Pretoria, GPS coordinates: S25° 40.213' E28° 31.011')

We left Vergenoeg around noon and arrived at Cullinan at1:40 hrs. Because of the large number of excursion participants, we only joined a normal surface tour starting with an introductory video followed by a short presentation by Anton Wollmerans, a mine official, and ending with a walking tour through the processing plant to Cullinan's big hole.

4.1. History of the mine

In 1905, the world famous and largest ever mined diamond – the "Cullinan-Diamond" - weighing 3,106 ct was found. After a few decades of surface mining to a depth of 320 m below surface, underground mining started in 1947 and is still active.

Basic Data: The Republic of South Africa produces 60% of the world's diamonds by value. The largest diamonds (25% of the world's +400 carat stones) come from the Cullinan mine with reserves of 26.38 Mct and resources of 200.81 Mct giving a life time-of-mine operation of at least another 50 years. The grade at Cullinan is 46.7 cpht (carat per hundred tons) or in other words, from 11,000 tpd of kimberlite mined, 4,500 ct of diamonds are produced from which 20% have gem quality. A specialty of Cullinan are blue diamonds, which derive their color from boron in the crystal lattice and which are very valuable with about 800,000 US$/ct.

4.2. Geology

The Cullinan kimberlite intruded into the Transvaal Supergroup 1,2-1.3 Ga ago and shows surface dimensions of 1.0 x 0.5 km (today represented by the big hole Fig. 6) and still an area of ~16 ha at 830 m depth below surface. With an inclination of 85°, the walls are nearly vertical. The intrusion of a gabbro sill 50 Ma after the kimberlite intrusion cross-cuts the kimberlite at 380 m depth and is nowadays the separating horizon between the former open-pit mine and the modern underground mine

Different types of kimberlites belonging to three different intrusive phases can be distinguished: Brown kimberlite in the eastern part of the mine (Type II); 2) Grey kimberlite (Type I) and 3) Black/hypabyssal kimberlite as the core.

A further phase, but not counted as separate intrusion, is represented by some carbonate dykes occurring at the transition zone between the grey and the black kimberlite and within the black kimberlite. Differences in diamond quality also occur between the phases: while small brown diamonds are abundant, the grey diamonds are large but rare.

4.3. Mining and processing

Underground mining is executed by block caving method. The material is crushed for the first time underground and hoisted to the surface. Secondary crushing reduces the size of the material to < 32 mm, meaning that also larger diamonds which cannot be sorted out optically before the second crusher are crushed. To separate the diamonds from the kimberlite, dense media separation (DMS) with ferrosilicon (ϱ = 3.2 g/cm^3) is applied ($\varrho_{diamond}$ = 3.5 g/cm^3; $\varrho_{kimberlite}$ = 2.7-2.8 g/cm^3).

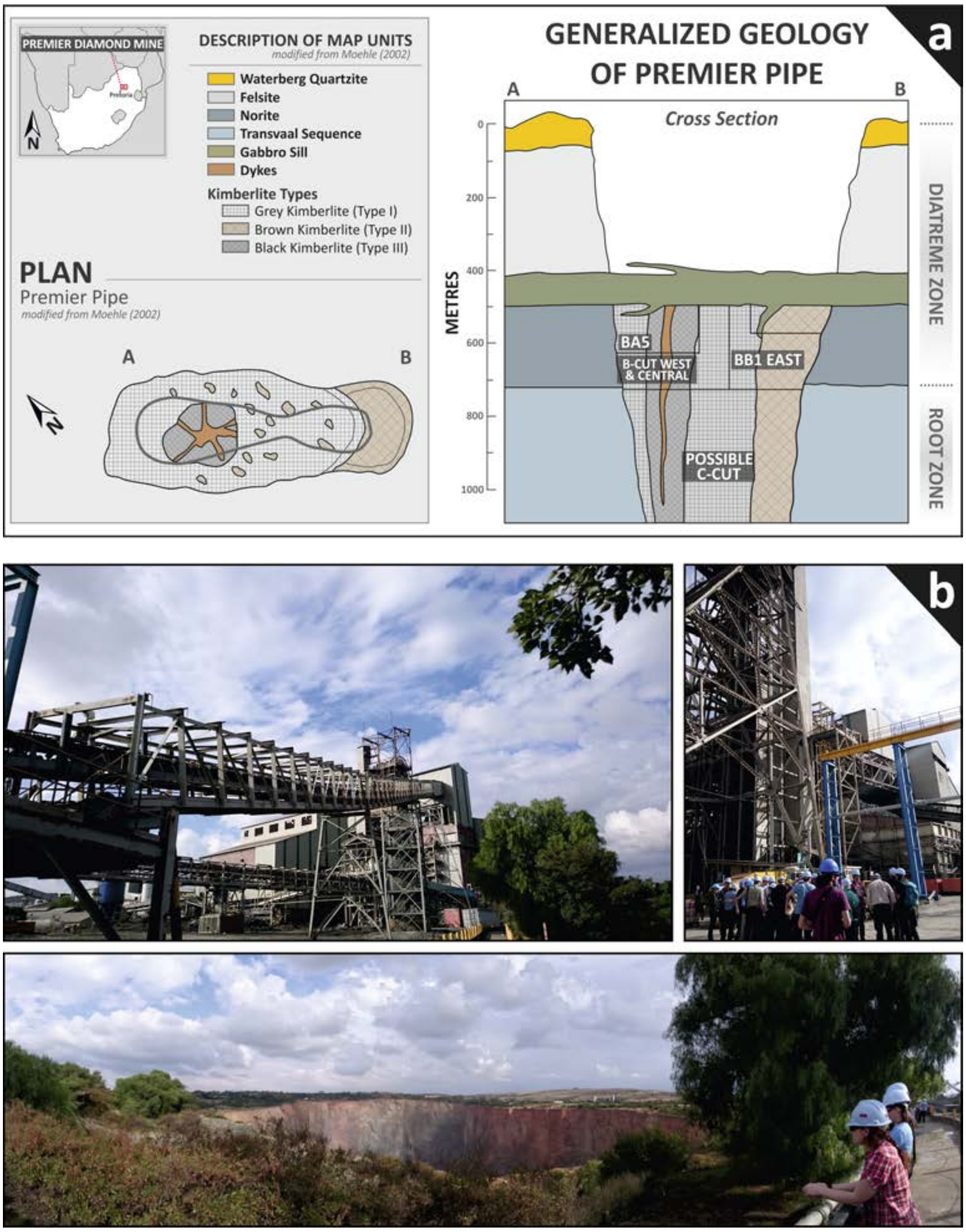


Fig. 6
a) Generalized geology of the Premier Mine, b) Cullinan Diamond Mine with the big hole.

Excursion Day 2

Stop 3

5. Leeuwpan Coal mine, Delmas, Mpumalanga, GPS S26° 08.617' E28° 47.359'

On the second day we visited the Leeuwpan Coal mine (LCM), one of the coal mines managed by the Exxaro group. It is located approximately 80 km south-east of Pretoria in South Africa's Mpumalanga province and is part of the Witbank Coal fields, currently the most important coal field in South Africa. It extends along the northern margin of the main Karoo Basin from Springs in the West through Belfast in the East and from just north of Witbank in the North to Rietspruit in the South. The basin is defined by the northern limit of the main Karoo Basin and a prominent pre-Karoo ridge in the South called the Smithfield Ridge. Out of the five developed coal seams four are economically exploited. The sediments of the Witbank Coalfield are laid down in a series of deltaic sequences each of which is capped by a coal seam. The sequence of deposition is postulated as follows: as the basin was the northern edge of a large basin that was continually subsiding, the rate of subsidence was reduced allowing accumulation of peat. There were major subsidence events with throws of between 20 and 30 m that were approximately 20 000 years apart. Above the number 5 seam (Fig. 7a) the whole regime changed with more marine type environments prevailing, and it is thought that at this time the main Karoo basin connected to the oceans and a more stable water level ensued.

At the LCM they have a quality variation in volatile content which is due to extent and positioning of the dolerite activity. This activity is induced by intrusions which are connected to the break-up of Pangea during the Jurassic. The dolerite intrusion devolatilizes the coal making it uneconomic.

The typical geological section in the visited north eastern part of the LCM (Fig. 7a) starts with approximately 40 m of overburden. Below, seam 5 has a thickness of 0.6 m. It is a bright coal with a raw ash content of lower than 16% but in this case it is totally weathered. In the footwall follows the so called BB-shale with a thickness of 1.5 to 2. 5 m, underlain by seam 4 upper, which is defined as a dull coal with interbedded bright coal and shale (Figs. 7a ,b). It has around 2 m thickness and 35 to 40% raw ash content. The X-shale, 0. 6 m thick, divides the seam 4 upper from the seam 4 lower. This shaley coal is interbedded with dull coal and shale layers and has a thickness of 2 to 5 m. The raw ash content is around 35 to 40%. It is underlain by the 0.6 m thick O-shale. Below this O-shale the seam 2 has a thickness of 7m with a raw ash content of around 25 to 32%. Below this seam is the 1m thick but uneconomic “floorcoal” which is also a shaley coal with raw ash contents from 35 to 40%. The footwall of the coal deposit is defined by the “Dwyka-tillite”. The seams 4 lower and upper with the seam 5 are considered to be “Top coal”. This coal is burnt in electric power stations and has a volatile content of around 22% and raw ash from 28 to 32%. The seam 2 is also called “Bottom coal” with a raw ash content of 18 to 24% and a volatile content of 5 to 20 %.

Fig. 7
a) Typical geological section in the NE part of the Leewpan coal mine (not to scale), b) coal samples.

LCM employs about 500 workers excluding contractors, and produces 3 Mt per year of metallurgical and power station coal. It is a conventional open-pit mine using modified terrace configurations and truck and shovel operations. Coal is processed using jigging technology for the top coal layer (seam 4 upper) and dense medium separation for the bottom coal layer (seam 4 lower). They also crush and screen bottom coal for power stations. LCM has a coal reserve base of about 143Million tons and a resource of about 160Million tons. In 2014 LCM had a record production of 4.106 Mt

Stop 4

6. Rooiberg rhyolitic felsite, Loskop Dam, Mpumalanga, GPS:S25° 25.077' E29° 21.721'

This stop was near the Loskop Dam where we visited an outcrop of Rooiberg Group lavas at the N11 (National Route) road cut. The volcanic Rooiberg Group represents the uppermost portion of the Transvaal Sequence (TWIST, 1983), nowadays called the Transvaal Supergroup and is the earliest phase of the Bushveld-related magmatism. (BUCHANAN et al., 2002) The felsite was erupted within the shrinking Transvaal basin during its final waning phase. (COERTZE et. al., 1977)
Noticeable is the general strike of the steeply dipping layering from WNW to ESE. At the bend (Fig.8) there is a tuff-layer with a thickness of approximately 10m parallel to the general strike. It is probably the ash-flow tuff which marks the top of the last unit in the hanging wall, as suggested by TWIST (1983). The tuff-layer is very fine grained and totally weathered. The layering of the massive felsite has a general thickness of 0.1 to 1 m (Fig. 8).

Fig. 8.
Layering of the Rooiberg felsites with the tuff layer at the far end (white).

Excursion Day 3

7. Samancor - Eastern Chrome Mines Bushveld Complex

On day 3 we moved to the Bushveld Complex proper to visit different mines and their geology. Our first visit was to the Samancor Company which is the biggest ferrochrome producer worldwide, involving mining as well as smelting of chrome ores. As shown in Figs. 9 and 10 the company consists of three plants and two chrome mining complexes in different locations in South Africa (SAMANCOR, 2015).

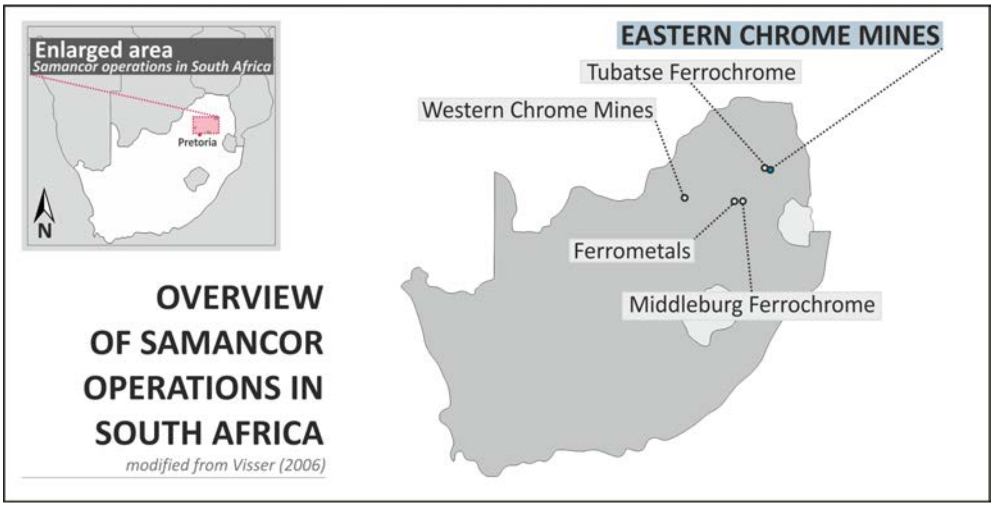


Fig. 9
An overview of the Samancor mine operations in South Africa (VISSER, 2006).

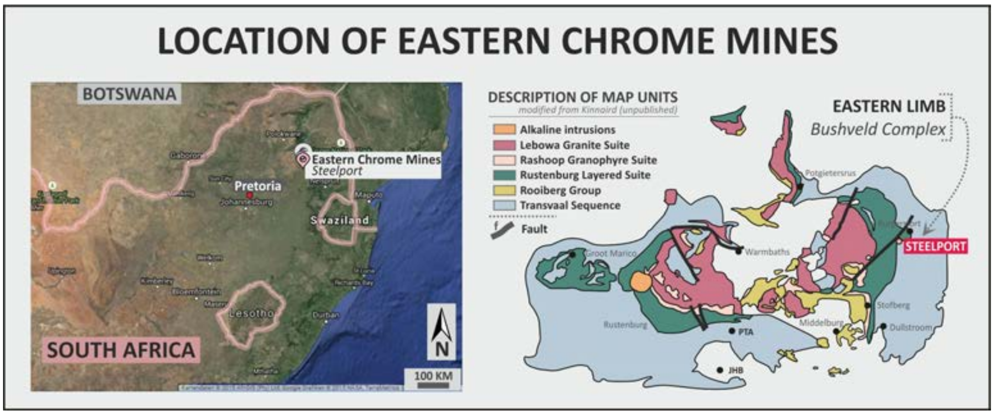


Fig. 10
Location of the Eastern Chrome mines, Bushveld Complex.

The outputs include on the one hand the chrome ore extracted by the mines and on the other hand chrome alloys produced by the plants (Fig. 11). Three different grades of ferrochrome are produced: 1) charge chrome, 2) intermediate carbon ferrochrome and 3) low carbon ferrochrome. All of them are used in different areas of the stainless steel smelting process (SAMANCOR, 2015). 80% of production is sold to companies within South Africa, whereas the rest is exported mainly to China but also to India, Europe and USA (SAMANCOR, 2015).
The Eastern Chrome Mines (ECM) are one of the two chrome mining areas of Samancor. They comprise of three underground operations (Doornbosch, Spitskop and Lwala) mining the Lower Group 6 (LG-6) chromite seam and two open casts (Lannex, Tweefontein, Fig. 9) extracting the Middle Group chromite seams (MG-1 to MG-4). Lwala represents a new mine with an expected operation life of 40 years (SAMACOR, 2015).
Underground mining takes place using the board and pillar mining method. The boards/panels are 10m wide established on breast. Pillars are 6m long and 4m wide, depending on the depth below surface. Drilling is done by hand held rock drills. Load haul dumpers are used for afterwards cleaning, where they bring the material to a strike conveyor belt that feeds onto a dip conveyor in a decline shaft. The average production rate for underground mining activities is around 80,000 to 100,000 tons/month. Open pit mining is mainly done by drill rigs using percussion drilling and load haul dump trucks for cleaning. The lumpy ore is processed in smelters. This ore must be low in aluminium.
ECM employs about 2,500 people. For open cast operations they have additional 1,000 contractors.

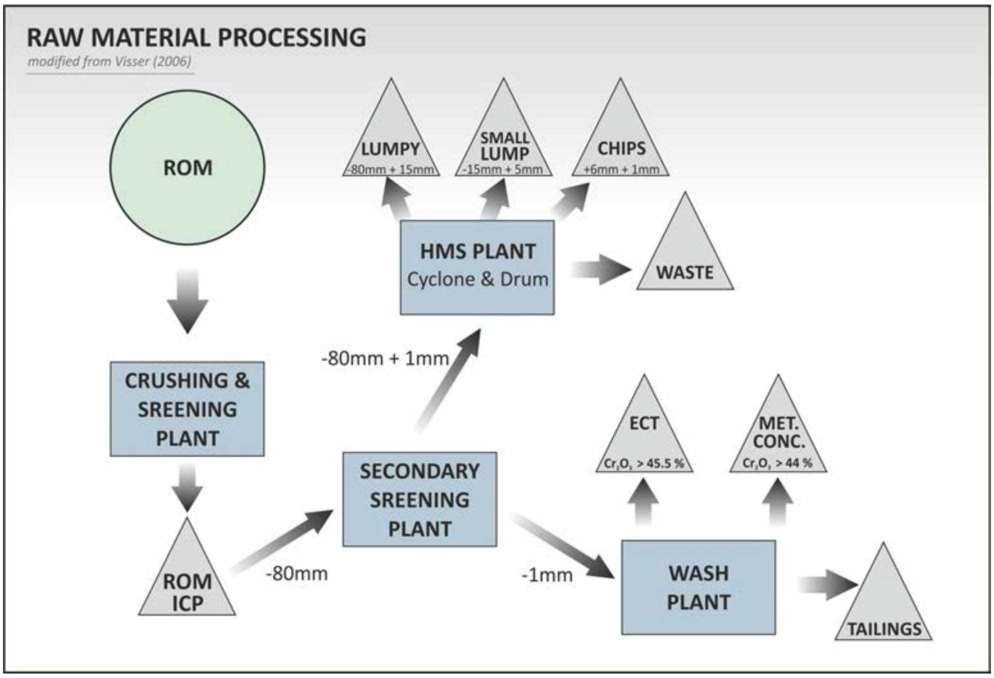


Fig. 11
The raw material processing scheme, Samancor, South Africa (VISSER, 2006).

7.1. Locality and Geology

The operations of Eastern Chrome Mines are located in the Mpumalanga Province of South Africa, close to the town of Steelpoort, which is approximately 300 km north-east of Johannesburg (Fig. 10).

The Critical Zone (CZ) of the Bushveld Complex crops out in the western and eastern limb (Fig. 2), whereas a cross section through the central part of the Bushveld Complex (Fig. 12), cutting N-S, shows the CZ at a depth of several km. It is assumed that the present dips were produced due to the high density of mafic rocks. After the emplacement, a down-buckling of the crust provoked an isostatic balance. The up to 1,500 m thick CZ is situated between the Main Zone representing the hanging wall and the Lower Zone representing the foot wall. It is further divided into a Lower Critical Zone (CLZ) and an Upper Critical Zone (CUZ), comprising mafic and ultramafic rocks. Chromitite layers occur in three stratigraphically delineated areas within those sequences each composed of several layers, all in all 29 (POHL, 2011), and numbered from the base upwards (Fig. 12). The Merensky Reef indicates the transition to the Main Zone (KINNAIRD, 2005).

Within the ECM, important chromitite orebodies occur within the Upper Group UG-6 and UG-6A also known as Steelpoort Chromite Seams, as well as in the Middle Group MG-0 to MG-4. The average thickness of the UG-6 is 2.15 m, whereas MG-1 is about 1.3 m to 1.6m thick and the MG-2 layer 1.89 m. The seams are hosted mainly in feldspathic pyroxenite and anorthosite as well as to a lesser extent in norite. In the Eastern Limb, in the vicinity of ECM, the strike of the ore body is nearly north-south, with a dip of approximately 10 degrees towards the west. No significant grade variation is present, especially not vertically in the ore seam. Small, insignificant regional variations do, however, exist. LG-6 for instance, shows an in situ grade of 45% Cr_2O_3 with a Cr:Fe ratio of about 1.24 and a 30.8% Cr_2O_3 cut-off grade.

Pipe-like dunite intrusions are evident in the area, as well as dolerite dykes that on average strike northeast-southwest. Other geological features, which can be found within the operations, are domes, dykes, faults (e.g. shear faults/zones), pegmatoids and potholes.

Stop 5

The Steelpoort Fault (Thabazimbi-Murchison Lineament) divides the northern sector (e.g. Doornbosch) from the southern sector (e.g. Tweefontein) of the Eastern Chrome Mine operations. According to NADINE & MAARTEN DE WIT (1997) the Thabazimbi–Murchison Lineament is a prominent tectonic feature extending for approximately 500 km in a NNE–SSW direction across the Kaapvaal Craton. The lineament has a tectonic history of more than 2.5 Ga, because it appears to form and/or influence: the boundary between the Archaean granite/greenstone terrain of the Kaapvaal Craton and the southern margin of the high grade terrain of the Limpopo Mobile Belt; the northern margin of the Archaean-Proterozoic Transvaal Basin; the southern margin of the Mesoproterozoic Waterberg Basin; and has probably also influenced the emplacement of the Mesoproterozoic Bushveld Complex. The lineament is cut by a Mesozoic dyke swarm associated with the break up of Gondwana.

The Steelpoort Fault which is part of this Lineament is a northeast – southwest striking shear zone, which caused a lateral movement of up to 100 km. It is suggested that at different times several magma pulses intruded/extruded in the south and in the north of the Steelpoort Fault, which could explain the fact that in the north of this fault the Lower Group is thick and the Middle Group is thin, whereas in the south the Lower Group rapidly disappears and the Middle Group layers become more prominent (SAMANCOR, 2015). It is still a matter of discussion if the Steelport Fault was a conduit for the magma of the eastern Bushveld Complex.

The Lower Group (LG) contains seven chromitite seams hosted in feldspathic pyroxenite. The LG-6 layer is the thickest one. The layers LG-1 to LG-4 are often associated with olivine, whereas all other layers are olivine-free.

The Middle Group comprises the boundary between the Lower Critical Zone and the Upper Critical Zone by convention with the first appearance of anorthosite at the MG-3 Layer.

The Upper Group contains two chromitite layers (UG-1 and UG-2), although in the Eastern Bushveld, UG-3 and UG-3a layers also occur.

The chromium content of the chromitite seams decreases constantly upwards (e.g.: LG-6 has a Cr_2O_3 content of 46–47%, MG 44–46%, UG-2 around 43% (SCHÜRMANN et al., 1998)). Due to a constant Fe content, the Cr:Fe ratio decreases in the same manner (e.g.: LG-6 layer has a Cr:Fe ratio of between 1.56 and 1.6, MG layers 1.35 - 1.5, UG-2 1.26 - 1.4).

Several models for the formation of thick chromitite layers have been suggested. These are:

1. Gravity-induced separation, crystal sorting and settling (EALES & REYNOLDS, 1986),
2. Immiscibility of Cr-rich liquid (EALES & REYNOLDS, 1986),
3. Increases in oxygen fugacity by country rock degassing (CMERON & DESBOROUGH, 1969)
4. Contamination by a siliceous component (IRVINE, 1975)
5. Mixing between resident and new magma (IRVINE, 1977)
6. Lateral growth within a stratified magma column (IRVINE et al, 1983)
7. Pressure changes (CAMERON, 1977)
8. Injection of a chromite-phyric magma (EALES et al., 1990

KINNAIRD et al, (2002) suggested that each chromitite layer is associated with a new influx of magma, referring to their strontium isotope data. Mixing between a primitive and evolved ultrabasic liquid may have resulted in the chromitite layers associated with olivine (LG-1-LG-4) but for thicker layers associated with orthopyroxene (LG-5-MG-1) or with orthopyroxene and plagioclase (MG-2 and above) mixing between two magmas of very different compositions may be invoked (IRVINEe, 1977, IRVINE et al., 1983). Generally the chromium content of the system seems very high compared to the total amount of magma found and compared to similar settings. The mechanisms that lead to such high contents are still not fully understood. It has been discussed that an additional, chromium depleted part of the original magma body has been removed by the deposition of a new one.

The Company mine geologists made an introductory power point presentation and we visited the drill repository, where we were able to see different sections of the CZ of the Bushveld Complex.

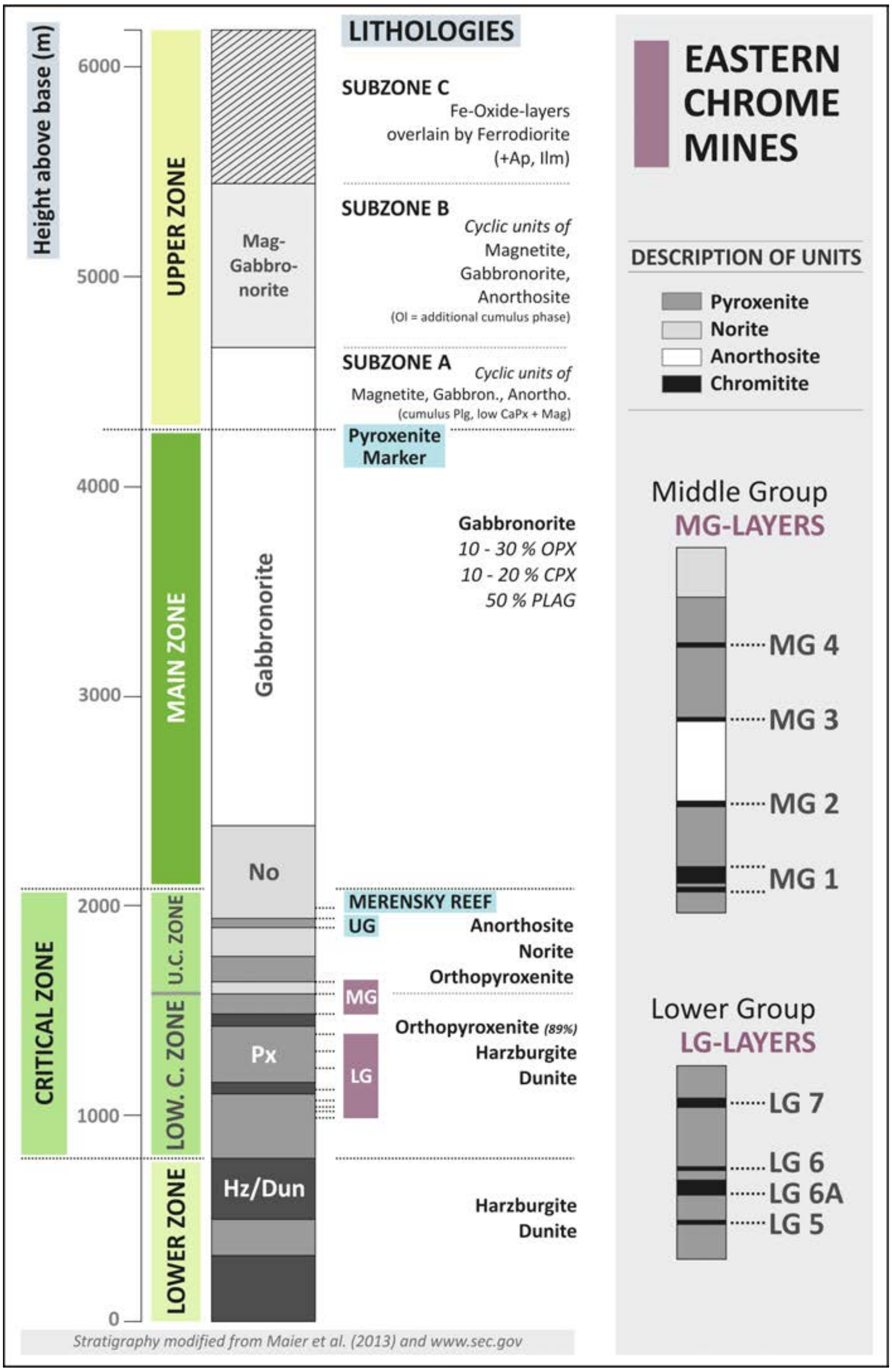


Fig. 12

Stratigraphic section of the Bushveld Complex with the Lower, Critical, Main and Upper Zones.

Stop 6

7.2. Tweefontein Processing Plant

We had a chance to see the different steps needed at the processing plant in Tweefontein to liberate the chromite from the chromitite layers. At the same time we were introduced to the different equipments used in the processing plant and the necessary procedures that should be followed (Fig. 13a, b)

Fig. 13

a) Drill core with anorthosite and chromitite seams of the critical zone of the Bushveld Complex; b) Conveyor belts and tailings; c, d) the Middle Group (MG) chromitiite seams.

7.3. Hoeggenoeg Open Cast (S24° 54.341' E30° 07.742' 1046 m)

We visited outcrops of the Middle Group chromitite seams and associated open pit mine with a monthly production of 50,000 tons of ore, and 30,000 tons of ore after processing. This operation deals with a stripping ratio of 1:8, an average Cr_2O_3 content of 38% and a cut-off grade of 28% (Fig.13c, d).

Excursion day 4

8. The Bushveld Complex

The Bushveld Complex is the world's largest layered mafic-ultramafic intrusion and covers > 60,000 km² of the northern part of the Kaapvaal Craton. It is known to host the bulk of global resources of PGE, Cr and V with significant Cu, Ni, Au, Sn and Fe. Furthermore the contact metamorphic aureole of the intrusion hosts the world's largest andalusite resources (MAIER et al., 2012).

The Bushveld large igneous province is the result of at least three distinct intrusions. The first event was the eruption of the Rooiberg Group with felsic volcanic rocks representing the uppermost part of the Transvaal Supergroup (discussed above). The overlying Pretoria Group consists of quartzitic to arkosic sandstone and mudstone with interlayered andesite and volcanoclastic sediments. The second major event formed the Bushveld Complex (Rustenburg Suite), at approximately 2060 ± 3 Ma (KRUGER et al., 1986). Magma intruded along the interface between the Pretoria Group and the Rooiberg Group. The intrusion of the Bushveld Granite (Lebowa Granite) between the Upper Zone of the Rustenburg Suite and the overlying Rooiberg Group represents the final event (HARDWICK et al., 2015; ZEH et al., 2015; WILLMORE et al., 2000).

The layered Bushveld Complex with outcrops subdivided into the western, eastern and northern limb, contains similar (but not identical) stratigraphy (from bottom to top): the noritic Marginal Zone, the Lower Zone consisting of peridotites and pyroxenites, the Critical Zone with units of harzburgites, pyroxenites, norites and chromitites, the Main Zone containing gabbronorites and anorthosites and the Upper Zone which consists of gabbronorites, anorthosites, magnetites overlain by diorites (BARNES et al., 2004).

Platinum group elements are mined from three layers located in the upper part of the Critical Zone: the Merensky reef and the UG-2 reef in the western and eastern limbs and the Platreef in the northern limb. Together these three deposits host over 70% of the world's platinum group element resources (HARDWICK et al., 2015; WILLMORE et al., 2000).

Stop 7

8.1. Dwars River Pass (S24° 56.994' E30° 10.709')

The outcrop is situated along the crest of the Dwars River Pass (Fig. 14 a). For about 200 meters there are about 10 m high walls along the road that expose the Marginal Zone of the Bushveld Complex. We found layered sediments in contact with a noritic intrusion. The norites seem to have internal flow structures (Fig.14b) and the contact to the sediments is sharp. The sediments are transformed by contact metamorphism to calc-silicate fels and are fine layered parallel to the intrusion.

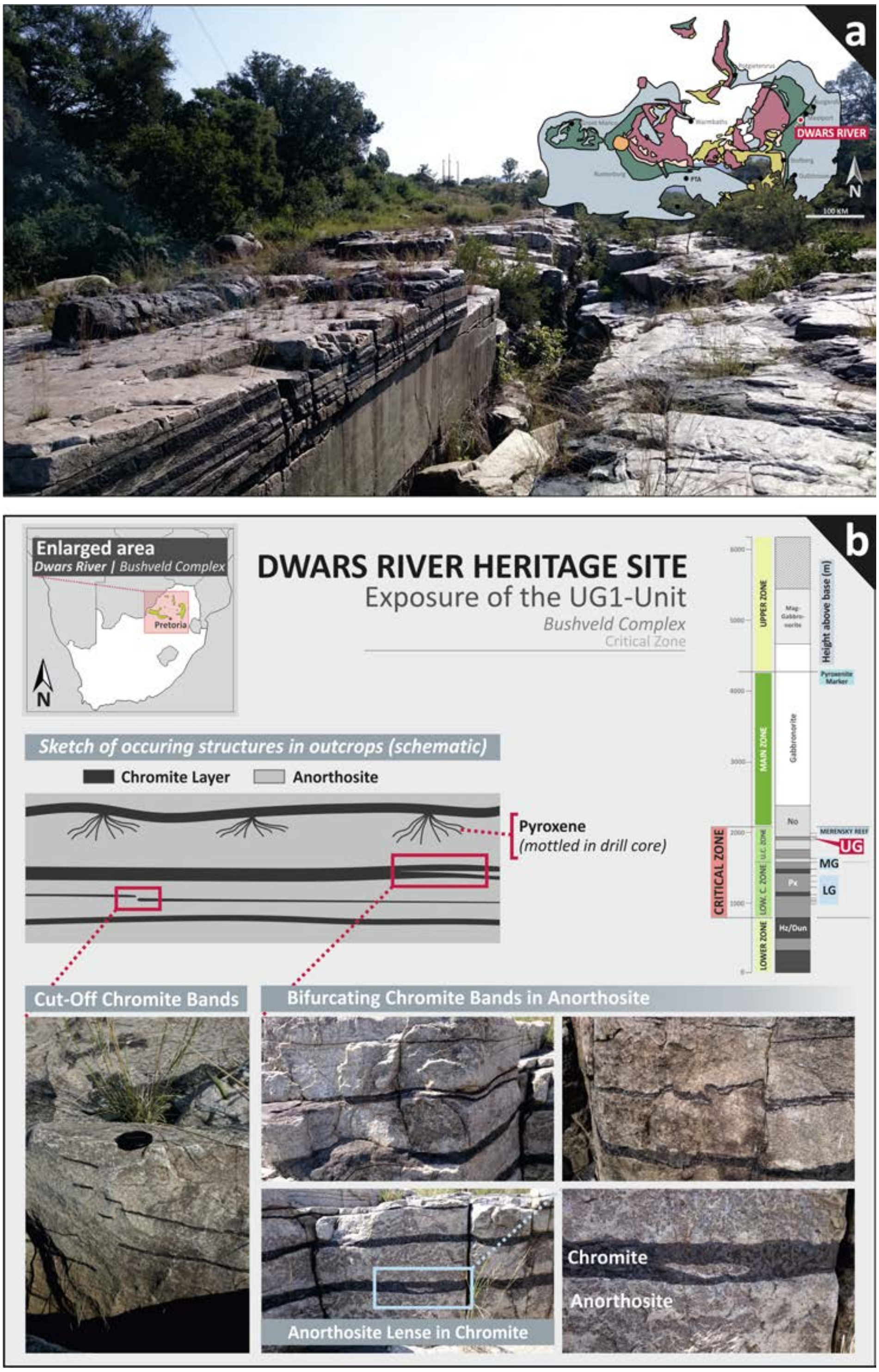

a
Pietersburg
Warmbaths
DWARS RIVER
PTA
Rustenburg
N
100 KM
b
Enlarged area
Dwars River | Bushveld Complex
Pretoria
N
DWARS RIVER HERITAGE SITE
Exposure of the UG1-Unit
Bushveld Complex
Critical Zone
Sketch of occuring structures in outcrops (schematic)
Chromite Layer
Anorthosite
Pyroxene
(mottled in drill core)
6000
5000
4000
3000
2000
1000
0
UPPER ZONE
MAIN ZONE
CRITICAL ZONE
U.C. ZONE
LOW. C. ZONE
LOWER ZONE
Mag-Gabbro-norite
Gabbronorite
No
Px
Hz/Dun
Height above base (m)
Pyroxenite Marker
MERENSKY REEF
UG
MG
LG
Cut-Off Chromite Bands
Bifurcating Chromite Bands in Anorthosite
Anorthosite Lense in Chromite
Chromite
Anorthosite

Fig. 14 [see left page]
a) The Dewars River UG1 Chromitite, b) Dewars River Heritage Site.

Stop 8

8.2. Dwars River Heritage Site

Here one observes exposure of UG-1 (Fig. 14 a) chromitite layers within mottled anorthosites of the upper Critical Zone of the Bushveld. The Dwars River locality is a narrow river gorge and is a preserved National Monument, so visitors are not permitted to hammer or take samples. Various UG-1 chromitite layers and stringers have very sharp contacts with the anorthosite host. The formation of the chromitite layers within the anorthosite is suggested to be due to cooling and related increase of the viscosity. A spectacular but enigmatic feature of this locality is the thin, bifurcating layers of chromitite. Most of them bifurcate to the south, implying the presence of more individual chromitite layers towards the south. However the total thickness of chromitite layers in any vertical section remains remarkably constant. Downstream the structures are more disturbed and there are features like potholes, updoming and cracks as well. In some cases there are pieces of broken layer, escape structures or displacement. The UG-1 is poor in PGE`s compared to the UG-2.

Stop 9

8.3.Tweefontein Pipe (S24° 53.220' E30° 07.064')

The outcrop of this pegmatoidal pipe along the road is located in the Critical Zone. Host rocks are spotted and mottled anorthosites and leuconorites. The difference is just the size of the pyroxene oikocrysts, which are distributed like dots all over the anorthosites with systematic vertical variations. An ultramafic pyroxenite pipe cuts discordant through this anorthosite with an extremely sharp contact. Chromitite xenoliths are also present in the pipes, assumed to be ripped out of chromitite layers beneath. Similar pipes (i.e., the Mooihoek, Driekop and Onverwacht pipes) were the first PGE mines in the Bushveld, because the PGE contents found in the ultramafic cores (“hortonolithic dunite”) of the pipes were unusually high.

Stop 10

8.4. Magneetshoogte (S24° 50.277' E29° 58.303')

The Main Magnetite Layer (MML) is located in the lower Upper Zone (Fig. 15). Along the stream one can observe the approximately 2 m thick MML and associated layers. The layers dip towards the west. Footwall outcrops are norites continuing upwards towards mottled anorthosites. The contact is again extremely sharp. At the footwall of the MML the plagioclase is orientated because of the weight of the overlying magnetite layer. Up the river one moves in the direction of the hanging wall. The MML is mined for its vanadium content, since the titaniferous magnetite layers comprise an enormous source of vanadium ore and host almost half of the world’s vanadium reserves.

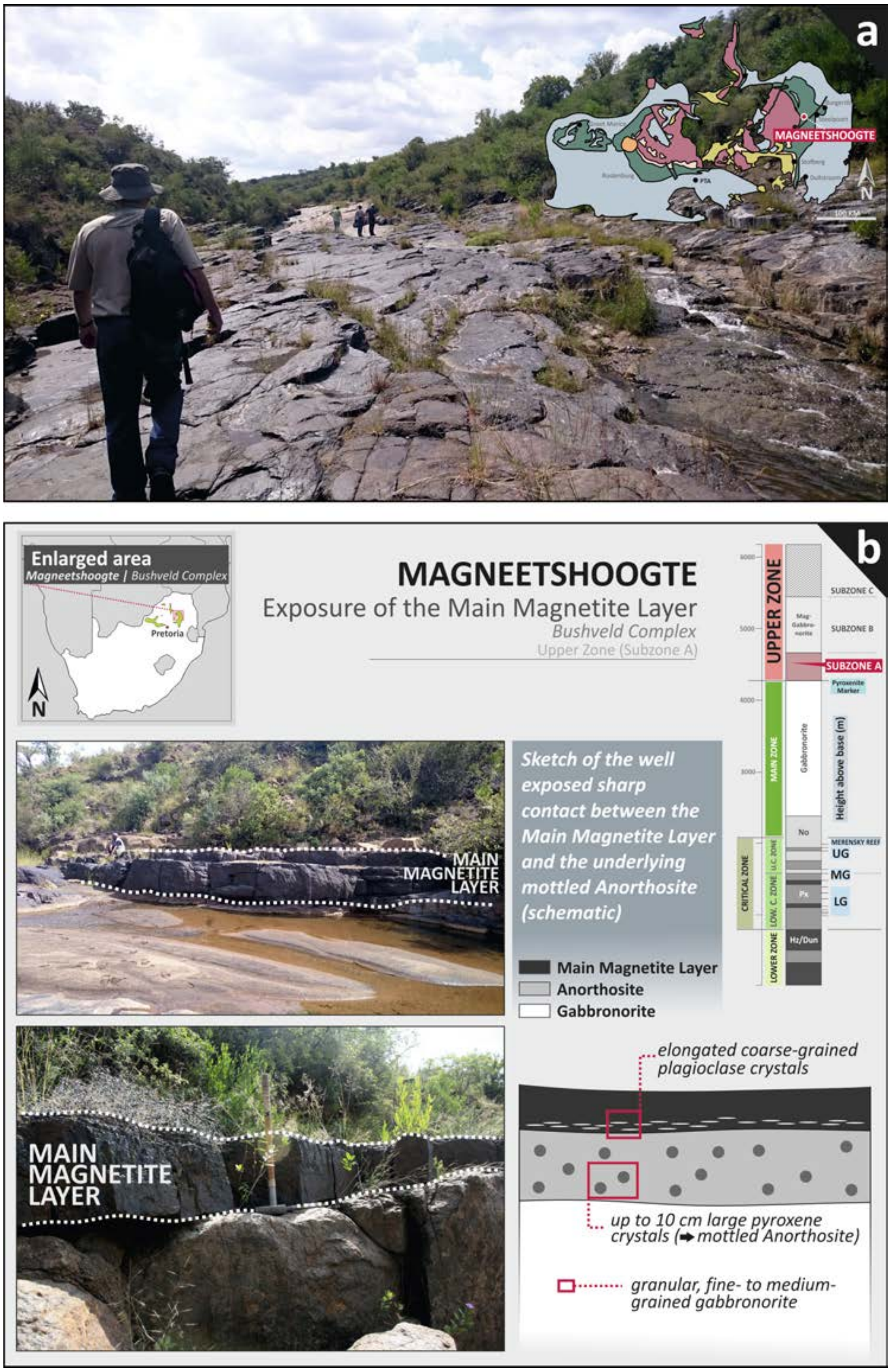

a
MAGNEETSHOOGTE
b
Enlarged area
Magneetshoogte | Bushveld Complex
Pretoria
N
MAGNEETSHOOGTE
Exposure of the Main Magnetite Layer
Bushveld Complex
Upper Zone (Subzone A)
UPPER ZONE
MAIN ZONE
CRITICAL ZONE
LOWER ZONE
SUBZONE C
SUBZONE B
SUBZONE A
Pyroxenite Marker
Gabbronorite
Height above base (m)
MERENSKY REEF
UG
MG
LG
Hz/Dun
MAIN MAGNETITE LAYER
Sketch of the well exposed sharp contact between the Main Magnetite Layer and the underlying mottled Anorthosite (schematic)
Main Magnetite Layer
Anorthosite
Gabbronorite
elongated coarse-grained plagioclase crystals
up to 10 cm large pyroxene crystals (➡ mottled Anorthosite)
granular, fine- to medium-grained gabbronorite
MAIN MAGNETITE LAYER

Fig. 15 [see left page]
a) Location of the main magnetite layer, b) field exposure at Magnethoote of the main magnetite layer and the respective position within the Upper Zone of the Bushveld Complex.

Stop 11

8.5. Driekop, Smoky Hills (S24° 33.733' E30° 06.329')
UG-2 and UG-3 layers are exposed along a small river bed. The outcrop quality is quite poor. Coarse –grained pyroxenite outcrops above the UG-2. Bright, weathered silicate spots (about 1 cm) in the chromitite display a spherical shape. The UG-3 layer is in between an anorthosite and a gabbro-norite layer with well-crystallized pyroxene. UG3 is too thin and the PGE content is too poor for mining. There are also deformed discordant diabase dikes cutting the chromitite and pyroxenite layers.

Stop 12

8.6. Ga-Manyaka (S24° 29.888' E30° 03.699')
The Merensky Reef is exposed on a hill slope along several old adits dug by Hans Merensky and his team. The old adits unfortunately cannot be visited but the mine dumps contain beautiful specimens of typical reef rocks. The basal layer of the Merensky Reef consists of fine- to medium-grained feldspathic orthopyroxenite. Large oikocrysts of postcumulus clinopyroxene give the rock a blotchy appearance. Pegmatoidal reef occurs at the top of the pyroxenite and often contains thin chromite layers at the top and bottom. In general the reef is composed of the following sequence from footwall to hanging wall: Pegmatoidal anorthosite, bottom chromite, norite. The Merensky Reef has been the world's most important source of platinum since exploitation commenced in 1928.

Excursion Day 5

This was the last day of our excursion in the Eastern Bushveld Complex. Therefore the first stop was at Jachtlust, an important location to summarize and discuss the outcrops of the critical zones and its chromitite layers, which were visited during the previous days in the different localities. In the hills surrounding Jachtlust almost all the chromitite layers outcrop (UG, MG and LG layers). The second outcrop in the Olifants river valley shows how the rocks of the Lower Zone were altered by secondary fluids. The locations of the stops are marked on Fig. 16a. The adjacent street R37 is given as a reference.

Stop 13

8.7. Jachtlust (S24° 16.135' E29° 53.311')
Jachtlust is located North-West of Burgersfort. From there one should follow the road R37 and drive for about 70 km to reach Jachtlust. The outcrop is located south of the road.

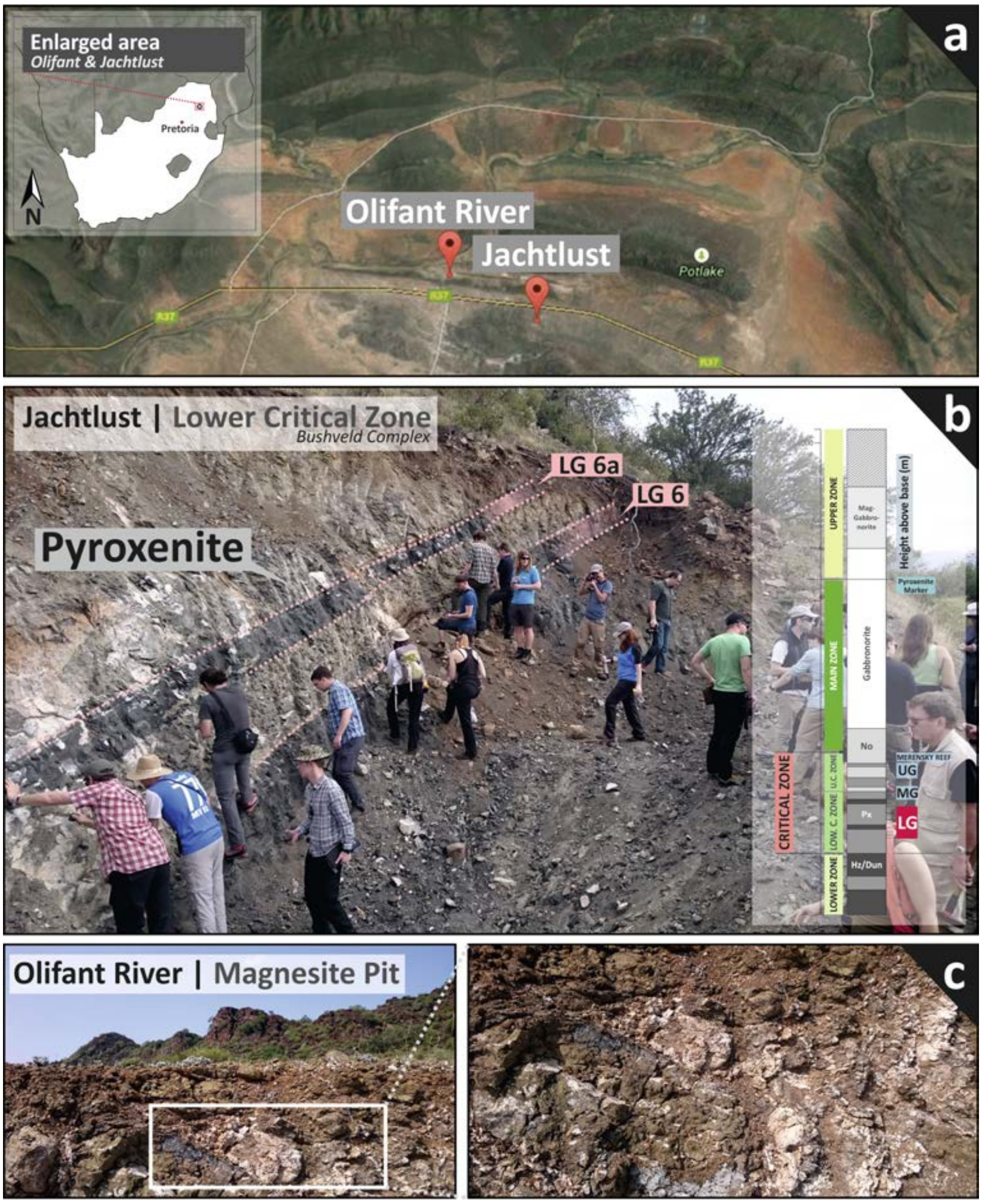


Fig. 16

a) Location of the stops at Jachtlust and Olifants River within the Bushveld Complex b) Outcrop of the Critical Zone of the Bushveld Complex and the LG-6 with the Leader seam at Jachtlust, c) magnesite outcrop at Olifants river,

Up the hill one observes the chromite layers of the Critical Zone of the Bushveld Complex. The first exposed layers are those of the LG-6, which belong to the Lower Critical Zone (Fig. 16b). As shown in Figure 16b the leader seam, sometimes also referred to as LG-6a, lies above the LG-6.

They are separated by a pyroxenite layer. These layers, among others, are mined at the Eastern Chrome Mines (discussed above) at the same stratigraphic level. The LG-5 is not well exposed on the surface but is known to be present below the LG-6 at this location. Further up the hill the MG-2 can be recognized as a very thin seam. It is only a few centimetres thick, which stands in strong contrast to the MG-2 outcrops visited during the previous days. Only a few meters above, there is the boundary between the lower and the upper critical zone marked by the first anorthosite layer. This is the so called mottled anorthosite, which consists of green clinopyroxene in the inner part and brownish orthopyroxene (bronzite) in the outer part. The MG-3 layer crops out directly above the mottled anorthosite followed by the UG layers towards the top of the hill where there is a platinum mine (Lebowa mine, previously known as the Atok mine).

Stop 14

8.8. Olifants River trough (S24° 15.356' E29° 51.680')

Only a few minutes drive away from the first stop there is the Olifants River and its magnesite deposits (Fig. 16a). There is a small dirt road north of the R37 which leads directly to the site. In the past there were some small magnesite mines but at present they are not economical. Some of the small pits are still visible and are nowadays used as waste disposal sites. The location is the second ultramafic layer within the Lower Zone, which consists of pyroxenites and harzburgites, mainly composed of orthopyroxene and olivine. There are two big pyroxenite sequences with a layer of harzburgite and dunite in-between. Both the upper and the lower pyroxenites are very similar, except the differences in grain size, which resulted in specific layering. While the orthopyroxene composition is more or less constant in the whole Lower Zone with a range of En_{84-87}, the magnesium content increases in the harzburgite, where it occurs together with olivine Fo_{85-87} (CAMERON, 1978). Magnesite is found as lenses and veins within harzburgite (Fig. 16 c). Chromite is absent in these layers. The fine-grained “Kraubath-type” magnesite is assumed to have formed by reaction of the ultramafic rock with low temperature secondary CO_2-rich fluid.

After these two stops we had a long drive to Thabazimbi towards the western limb of the Bushveld Complex.

From the MG-3 layer at Jachtlust turning to the NE into the valley, one can observe a panoramic view of the Bushveld Complex (Fig. 17). Far in the back there are the basement rocks and in front the sediments of the Transvaal Supergroup dipping underneath the Bushveld. The small hills at the very front are the rocks of the Lower Zone of the Bushveld Complex. These ultramafic rocks are olivine rich and weather easily and therefore show a specific relief.

Fig. 17
Panorama view of the Bushveld Complex from the Jachtlust outcrop.

Excursion Day 6

Stop 15

9. Kumba Iron ore mine, Limpopo Province (S24° 37.517' E27° 19.970')

Kumba is a business unit of the mining company Anglo American and operates three mines in South Africa with a capacity of 50 million tons per annum (Mtpa): These are Sishen and Kolomela, which are situated in the Northern Cape, and the Thabazimbi mine (Fig. 18a).

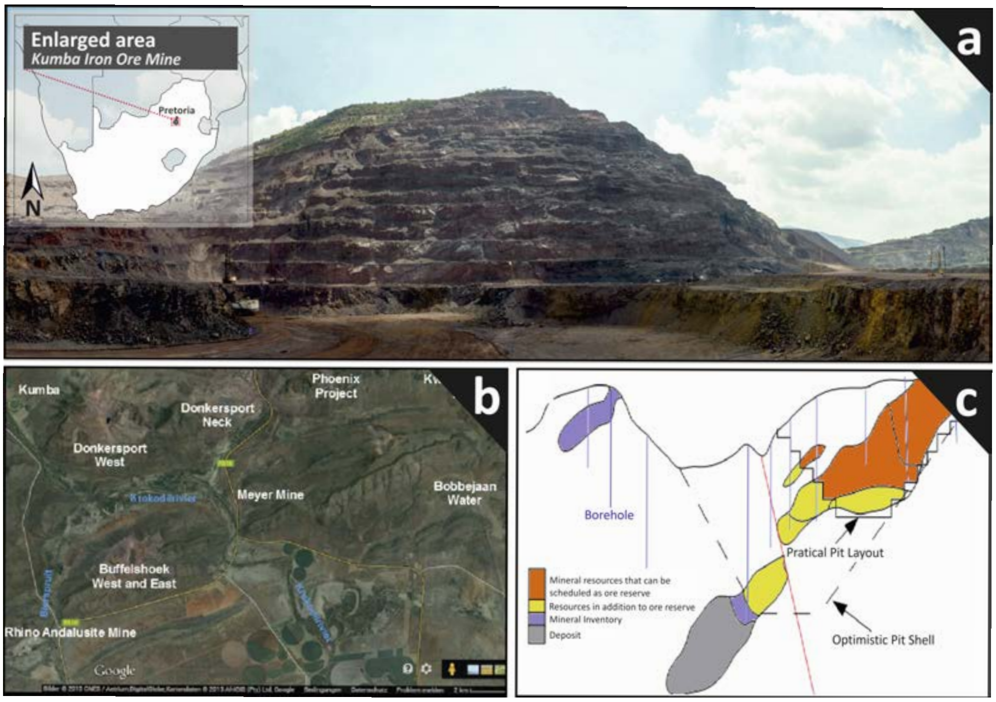


Fig. 18

a) Location of the Kumba Iron mine at Thabazimibi and the field outcrop b) Locations of the pits at the Kumba Iron Ore mine in Thabazimbi, and c) a cross-section through the different iron ore resources of Kumba Iron Ore Mine.

The Thabazimbi iron ore mine is in the Limpopo Province 220 km north-west of Johannesburg. Sishen mine is one of the largest open-pit mines in the world and was opened in 1952. Kolomela mine is the latest mine of the Kumba group and was opened in 2012. In 1919 the prospection started in Thabazimbi and in 1931 the mine officially opened as an underground mine. Surface mining started in 1942 and in 1997 the underground mining stopped but the surface mining continued. The mine has a total of 447,4 km underground tunnels and has produced 174 Mt ore and 859 Mt waste since it started operation.

Thabazimbi has five pits, 800 employees and 1 Mtpa production capacity. The Thabazimbi iron ore is located on the northern margin of the lower Transvaal basin, within the Penge formation. It is a Banded Iron Formations (BIF) which is highly thrusted and separated into three blocks (northern, middle and southern block). In the northern block are the Kwaggashoek-East, East Mine, Vanderbijl, Donkerpoort, -Nek and -West ore bodies. The Buffelshoek-East, -West and Meyer Mine ore bodies are located in the southern range and Bobbejaan Water ore body in the central range. Figures18b, c display the positions of the different pits. The ore bodies strike N-S and dip with 40° to the south. They extend over 80 km with a thickness of about 350 m. However, the ore bodies are not continuous. Lenses of unmineralized rocks occur in the ore, or vice versa. The unmineralized layer contains carbonates, is quartz-rich and in some cases diabase dikes cut through the layer. Beneath the dikes the concentrations of K and Al are higher than in the rest.

The genetic model for the formation of the BIF is that fluids from the Bushveld Complex moved upward and came in contact with the iron oxides at the base of the formation and interacted with the silicates. The rocks beneath the dykes are still anoxic and therefore have a different mineralogy. The upper ore bodies have a Fe concentration of more than 62% in contrast to 35% of the banded-ironstones (Table 1).

	Thabazimbi Specification for 2014-2015							
	Lumb Ore							
	Fe%	SiO_2%	Al_2O_3%	K_2O %	P%	Moisture%	Oversize%	Undersize%
Specification	61.0	7.9	1.4	0.16	0.04	3	5(+32mm)	10(-8mm)
Upper/Lower limits	>60.4	<8.5	<1.6	<0.18	<0.055	Maximise Phosphorus to between 0.055 and 0.068		
Rejection Levels	59.8	9.1	1.8	0.2	0.07	At and beyond this value AMSA will not accept product		
	Fine Ore							
Specification	Fe%	SiO_2%	Al_2O_3%	K_2O %	P%	Moisture%	Oversize%	Undersize%
Upper/Lower limits	>62.5	<6.5	<1.57	<0.23	<0.055	Maximise Phosphorus to between 0.055 and 0.060		
Rejection Levels	62.0	7	1.74	0.26	65	At and beyond this value AMSA will not accept product		

Table 1
Chemical parameters of the Kumba Thabazimbi iron mine.

The mine is operated by conventional open cast methods, including blasting, drilling, loading and hauling. Samples are collected from blast blocks and drilled cores are analyzed for the elements Fe, Si, K, P and Al contained in deleterious minerals. Depending on the chemical compositions, the different qualities are mixed to get a constant high quality product. The cut-off grade is 53% and the ore is beneficiated by dense medium separation.

The mine produces two kinds of products: lump ore and fine ore. Lump ore has a grain size of 30 mm and a Fe content of 62% and fine ore has a grain size of 8 mm and 62.5% Fe content. The lump to fine ratio is 42:58. Thabazimbi mine ore is low in contaminants like sulphur and therefore good for the steel industry.
The mine has reserves of about 11.3 Mt high grade ore. Based on this Kumba plans to process stockpiles and banded-ironstones to extend the lifetime of the mine by more than 20 years compared to 7 years projected at the moment.

Stop 16

10. Andalusite Resources, Andalusite open pit mine, Limpopo province (° 46.725', E27° 12.661')

Andalusite Resources mines and processes the LP- aluminosilicate polymorph from contact metamorphosed high-Al shales (Figs. 19 a, b). The extracted idioblastic chiastolite crystals range in size from about 0.1-4 mm (Figs. 19 c, e) and are used in a variety of refractory applications. This is due to the characteristic physical properties like resistance to high thermal shock, creeping, chemical attack and due to low volume expansion on heating (http://www.andalusite-resources.com). Products for the chemical industry must have an Al_2O_3-content ≥ 57% and an Fe_2O_3-content ≤ 1%. The production involves a number of critical steps like crushing (Fig. 19d) and washing, dense media separation (DMS), magnetic separation and packing.

The Mine lies within the contact aureole of the Western Limb of the prominent BIC. This 2,06 Ga structure intruded into the Transvaal Supergroup (WALRAVEN et. al., 1990) and superimposed an inverted thermal gradient upon the regional metamorphic geotherm producing a metamorphic contact aureole of ~4 km orthogonal thickness (JOHNSON et al., 2003).

PT-estimates infer 3.0 ± 0.5 kbar & ~760°C (ENGELBRECHT, 1990) at the intrusion-country rock contact. A migmatitic front that extends up to ~2 km from the intrusion (corresponding to an orthogonal thickness of about 400-700 m) marks partial melting (JOHNSON et al., 2003). The contact metamorphic grade decreases with distance from the intrusion following the temperature-gradient (heat is assumed to be transported via conduction).

Several andalusite mines lie within the Timeball Hill formation which consists of three major units: the lower phyllitic/shale unit (~1400m), the Klapperkop quartzite member (~100m) and the upper phyllitic/shale unit (~180m) (NELL, 1984; UKEN, 1998).

The increasing metamorphic gradient is represented in the lower shale unit by the assemblage andalusite-staurolite-biotite, although the mined lithology is a strongly altered, mostly brittle sericite-andalusite bearing shale. This assemblage indicates high-alumina content, although other phases could not be identified in the field. Local hydrothermal alteration forms carbonate-bearing veins; in combination with the arid climate calcrete crusts form.
Ideally andalusite has 62.9% Al_2O_3 and 37.1% SiO_2. In nature however it hardly ever occurs pure, but with various impurities.

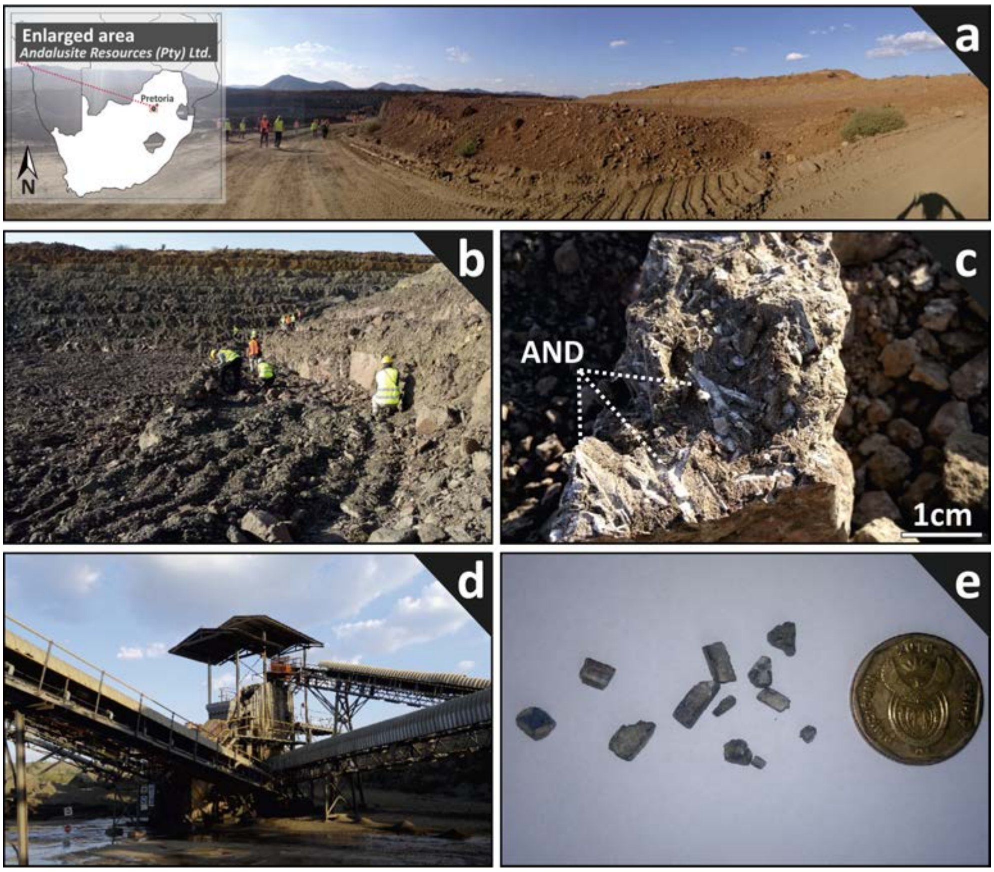


Fig. 19
a) The mining site of the andalusite bearing shales, b) a close up image of the shale horizon with c) andalusite and chiastolite crystals, d) shows the treatment process and the DMS plant, e) separated andalusite grains with 10 South African Rand cent as a scale.

Excursion day 7

Stop 17

11. The Pilanesberg Alkaline Ring Complex

The Proterozoic (1390Ma) Pilanesberg Alkaline Complex is one of the biggest ring complexes of the world. Its shape is nearly circular with a north-south-diameter of 24 km and an east-west-diameter of 28 km (Fig. 20a, b, c). Located in the North West Province of South Africa, where it rises from the topographically plain Western Lobe of the BIC, the Pilanesberg area covers about 540 km^2 (LURIE, 1973).

It is built up by diverse plutonic rocks, situated at the border between the acidic (Granophyre, Granite) and mafic (Rustenburg Layered Suite) Bushveld formations. With respect to the Bushveld stratigraphy the intrusion is located at the border between the Main and the Critical zones of the BIC. The plutonic rocks of the Pilanesberg Complex occur mainly as five rings which are composed of Nepheline Syenite (Foyaite), Syenite and several smaller arc shaped intrusions (VERWOERD, 2006). The highest point of the crater lies at 1685 m above sea level, while the surroundings show a topographic height of around 1100 m. The biggest fault in the area is the Vlakfontein Fault.

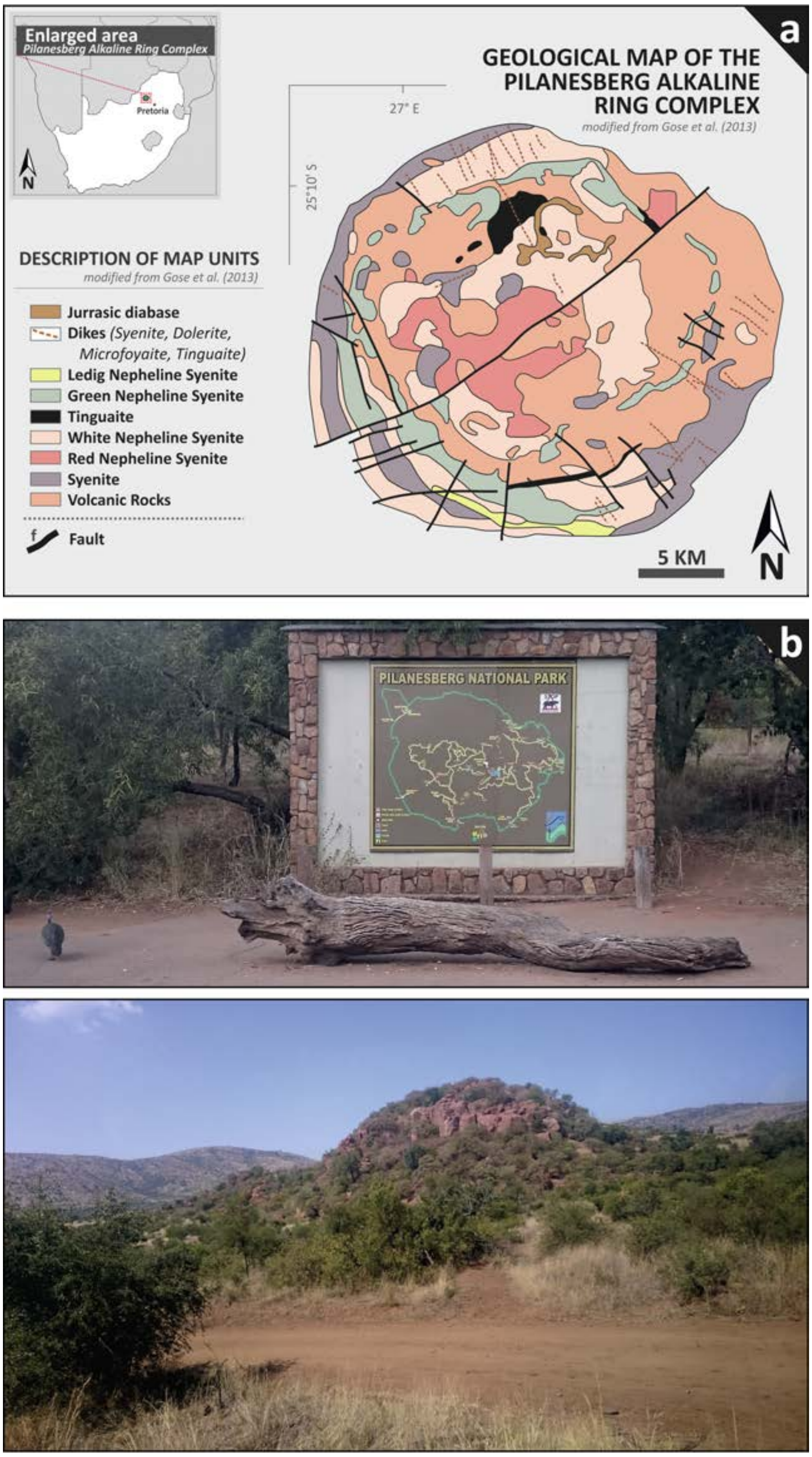
11.1.Formation of the Pilanesberg Ring Complex

The different stages of the formation of the Pilansberg Ring Complex as summerized by LURIE et al., 1973) are as follows: 1) Volcanic activity, formation of pyroclastics; 2) Formation of concentric fractures around the core accompanied by red syenite intrusion; 3) deposition of red foyaite in the centre; 4) 2nd stage volcanic activity; 5) Caldera subsidence and deposition of the major Pilanesberg facies (white foyaite, tinguaite and green foyaite, Ledig foyaite); 6) syenite dyke intrusion; 7) compressive stage, tilting of the whole complex and 8) displacement of southern semi-circle due to fault tectonics.

11.2. Geology

Red Foyaite: forms the centre of the complex. It is pink, coarse-grained, highly weathered and contains microcline (50-70%), liebenerite which is an alteration product of nepheline and some times albite. It shows the lowest content of rare elements. Accessories are fluorite and magnetite.
White Foyaite: is widely distributed in the complex. It occurs in 3 ring structures (the outermost is only a quarter of a ring). It is white or light grey and dominated by white minerals. There is no preferred orientation. The grain size is variable. Dark aegirine-rich zones occur.
Tinguaite: is a green-grey porphyritic rock occurring as an incomplete thin ring and in form of a layer covering the highest point of the area. It consists of alkalifeldspar, nepheline, aegirine-augite-phenocrysts in a fine-grained zeolite-bearing matrix. Accessories are fluorite and eudialyte.
Green Foyaite: is spatially related with tinguaite. Also the REE-pattern of both rocks is similar. Green foyaite lies between the 2nd and the 3rd ring of white foyaite. It is mostly porphyric, medium-coarse grained and dark green. It contains 25-40% kalifeldspar, 10-45% pyroxene (aegirine-augite) as well as eudialyte and fluorite as accessories.
Ledig Foyaite: is a transition between the White and the Green Foyaite. Typical samples are distinguished easily from these foyaites, but some can be very similar to them. Ledig Foyaite is quite similar to the Green Foyaite concerning the REE-pattern and mineralogy, but it shows the highest REE-content occurring in the complex.
Further rocks are Red Syenite, which forms the outer ring of half of the area, isolated intrusives, minor intrusions of dyke like habit and volcanic rocks.

Fig. 20 [see right page]
a) Geological map of the Pilanesberg Ring Complex, b) Pilanesberg National Park and a field outcrop.


a
GEOLOGICAL MAP OF THE PILANESBERG ALKALINE RING COMPLEX
modified from Gose et al. (2013)
Enlarged area
Pilanesberg Alkaline Ring Complex
Pretoria
N
27° E
25°10' S
DESCRIPTION OF MAP UNITS
modified from Gose et al. (2013)
Jurrasic diabase
Dikes (Syenite, Dolerite, Microfoyaite, Tinguaite)
Ledig Nepheline Syenite
Green Nepheline Syenite
Tinguaite
White Nepheline Syenite
Red Nepheline Syenite
Syenite
Volcanic Rocks
f Fault
5 KM
N
b
PILANESBERG NATIONAL PARK

11.3. Petrology and Geochemistry of the Pilanesberg Ring Complex

The element distribution is characteristic for alkaline complexes. Only K and Ca are a little higher and Na is a little lower compared to related complexes like the Lovozero complex. Na/K ratios range from 0.32 to 2.04 (Red Foyaite: 0.32, White Foyaite: 1.48, Green Foyaite: 1.94, Ledig Foyaite: 2.04. (LURIE, 1973)). The Pilanesberg Complex shows high values in F, Sr, Nb, Ta, Zr, Hf, Th, U and REE. Ledig Foyaite shows the highest enrichment of trace elements followed by Green Foyaite. Both are located in the outer rings. The Th/U proportion is about five for the Pilanesberg Complex.

Compared with the Lovozero Complex in Russia and the Ilimaussaq Complex in Greenland, the Pilanesberg shows the highest content of LREE, Sr and Th (LURIE, 1973)

The rocks of the Pilanesberg Complex show significant fluorine content – on the average 0.45%. Fluorite occurs in nearly all rocks of the Pilanesberg. The contact between volcanics and the Red Foyaite contains small deposits of fluorite (LURIE, 1973).

Excursion Day 8

Stop 18

12. Impala Platinum Mine and Visitor's Centre

This took place at the Impala Platinum Mine in Rustenburg (Fig. 21a), located about 115 km to the west of Pretoria.

12.1. General overview of the Impala Mine

Because of the large number of excursion participants it was not possible to visit the underground Platinum mines. The mining geologist (Mr. Bennie Cilliers) instead made power point presentations about the geology, mineralization and the mining operations conducted by Impala Platinum .

According to this presentation the Impala Mine started mining platinum from the Bushveld Complex in 1968. At the moment, the Impala Mine, together with a joint venture with Royal Bafokeng Resources, holds contiguous and prospecting rights over a total area of 33.562 hectare and not only includes mining, but refining and marketing of PGMs (platinum group metals), nickel, cobalt and copper.

In 2014 the group produced about 2.370 million ounces of PGMs, including 1.178 million ounces of platinum. Therefore, it holds approximately 22% of the world's supply of primary platinum. Impala Mine drilled about 8.000 boreholes (Figs. 21b, c) and is mainly mining the Merensky Reef and UG-2 Reef. They also mine the MG-1 due to the chrome content.

Impala has 33.000 employees at two main resources – at the BIC in South Africa and at the Great Dyke in Zimbabwe. More specifically, the operations can be divided into the following: The BIC in South Africa in the Western limb – Impala and Leeuwkop and in the Eastern limb – Marula and Two Rivers as well as the Great Dyke in Zimbabwe – Zimplats and Mimosa. All operations include mineral resources of 212 million ounces of platinum.

Fig. 21
a) Main entrance to the Impala Visitors Centre, b & c) Bushveld Complex Critical Zone drill cores.

12.2. The geology of Impala Mine

The main resources are located in the Merensky Reef and the UG-2 Reef of the BIC. Vertical separation of the Merensky Reef and the UG-2 reef varies between 125 metres in the south to 45 metres in the north. Platinum content increases from bottom to the top. The shafts of Impala can be divided into three groups: 1) old shafts, 2) mature shafts and 3) new shafts. In total, the Impala Mine has 13 shafts.

The Merensky Reef in the mining area has a thickness of about 100 cm. It is sulphide rich (pyrrhotite, pentlandite, chalcopyrite and pyrite) and contains about 6 to 9 g/t platinum and contains PGMs such as braggite (Pd, Pt, Ni)S, cooperite (Pt, Pd, Ni)S, moncheite (Pt, Pd)(Te, $Bi)_2$ and laurite (Ru, Os, Ir, $Fe)S_2$). The UG-2 Reef has an average thickness of about 65 cm and is rather sulphide poor but chromite rich, has about 7 g/t platinum concentration and contains Pt-Fe alloys as well as braggite, laurite, cooperite and additionally stibnides, tellurides and bismuthinites.

The Bastard Unit overlies the Merensky Reef, and contains mottled anorthosite. In Figures 21b and c, some of Impala's drill cores are shown with the mottled anorthosite in white. The black dots are pyroxenites.

Excursion Day 9

13. Mantle xenoliths, xenocrysts and mantle processes

This is primarily focused on hotly debated processes affecting chemical composition of the Archean subcontinental lithospheric mantle (SCLM) (GRIFFIN et al., 2003). The main mantle rocks to characterize the SCLM evolution are mantle xenoliths predominantly sampled in kimberlites, e.g. Kaapvaal peridotites from Kimberley. The South African kimberlites can be divided into two major groups, group I kimberlites (80-95 Ma) and group II kimberlites, also named orangeites (120-150 Ma) (SMITH, 1983).

13.1. Mantle affecting processes

One of the most common applications of peridotitic mantle xenoliths is their usage as "window into the mantle" which means their key role is to reconstruct the mantle evolution. The chemical variation and composition of the Earth's upper mantle is mainly determined by two processes, which are known as melt extraction and mantle metasomatism. These two mechanisms are different in their contrary effects on the upper mantle and stand in relative time relation. These days, melt extraction from the uppermost mantle occurs in several tectonic settings like oceanic and continental spreading centers such as "hot spots", and subduction zones whereby the largest melt extraction appears at mid-ocean ridges (e.g. WILSON, 1989). However, melt extraction from 4.5 to 3.5 Ga in Earth's history was a complex process and resulted in the depletion of the upper mantle from lherzolite to dunite (WALTER, 2003). In contrast, mantle metasomatism leads to a secondary refertilization of the refractory protoliths in several localities (e.g. LE ROUX et al., 2007; TANG et al., 2008). The different chemical consequences of both predominant processes are archived in today's SCLM.

Stop 19

13.2. The Big Hole in Kimberley (S28° 44.34167‘, E24° 45.36133´)

It is a Cretaceous (~90 Ma) kimberlite pipe (type I) erupted into the Archean granitic basement covered by Karoo sediments (Fig. 22a). For a historical overview a large volume of literature and discarded mining equipments were presented in the Big Hole museum. In 1871, Fleetwood Rawstorne found a handful of diamonds in kimberlitic rocks and established the beginning of mining history in this area. The end of mining operation in 1914 was caused by economic unprofitability due to the First World War. The mine, owned by "De Beers", produced in total 14.5 Ma carats of diamonds corresponding to 2722 kg. The Hole has a diameter of 450 m, an original open pit depth of 240 m and is currently filled with 40 m deep water.

Additionally, the diamond bearing volcanic rocks contain mantle derived peridotitic xenoliths ranging in composition from garnet lherzolithes (Fig. 22b) to garnet harzburgites (Fig. 22c). Furthermore, phlogopite (up to 5 mm in size) lherzolithes (Fig. 22d) can be observed, which may have been influenced by mantle metasomatic processes. The main macroscopically observed phases of the lherzolites are olivine (partly serpentinized), orthopyroxene, dark green clinopyroxene and red garnets whereby clinopyroxene is missing in the harzburgites.

Stop 20

13.3. Roberts Victor Mine (S28° 29.265‘, E25° 33.813´)

It is located about 30 km east of Boshof at an altitude of 1259 m. At the Roberts Victor Mine locality, a diamond bearing type II kimberlite (JACOB et al., 2009) (120-150 Ma in age) has been emplaced within the Ventersdorp lava. The majority (95-98%) of the mantle xenoliths enclosed within the kimberlite are eclogitic in composition, whereas harzburgites, garnet harzburgites and garnet lherzolites are subordinate (VILJOEN et al., 1991). Sampled hand specimens of eclogite xenoliths, show an elliptical shape and are composed of green omphacite and ~6 mm sized dark red garnet (Fig. 22e).

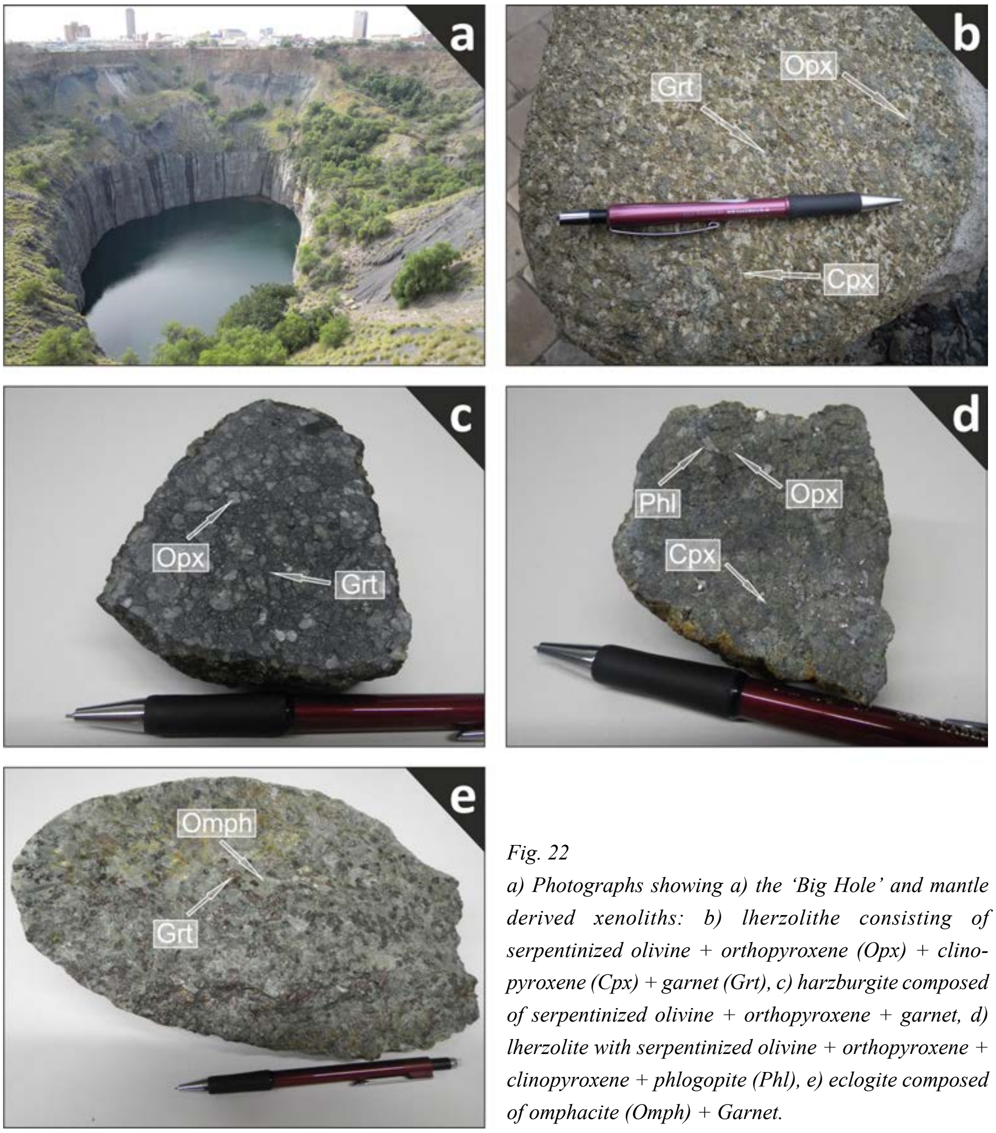


Fig. 22

a) Photographs showing a) the ‘Big Hole’ and mantle derived xenoliths: b) lherzolithe consisting of serpentinized olivine + orthopyroxene (Opx) + clinopyroxene (Cpx) + garnet (Grt), c) harzburgite composed of serpentinized olivine + orthopyroxene + garnet, d) lherzolite with serpentinized olivine + orthopyroxene + clinopyroxene + phlogopite (Phl), e) eclogite composed of omphacite (Omph) + Garnet.

Excursion Day 10

Stop 21

14. Bloemfontein – Department of Geology; Univ. of the Free State (S29° 06.638' E26° 11.067')

The tour on Friday the 17th led us from Kimberley (Northern Cape) about 162 km eastwards to Bloemfontein (Free State). On our way we crossed the lithological units of the Dwyka and Ecca Groups (deposited during the upper Palaeozoic). Our destination was the University of the Free States (UFS) where we headed towards the Department of Geology. Prof Christoph Gauert (at the UFS), who already had been part of our group during the last few days as academic advisor during the excursion, gave us a brief overview of the department´s laboratories. Finally we met Prof Marian Tredoux (UFS) who made a power point presentation of her model about the development of the Vredefort meteorite crater which lies further north of Bloemfontein. According to her presentation there is enough evidence to prove that the spectacular Vredefort structure formed due to a meteorite impact about 2 By ago. This evidence is provided among other things by special rock occurrences, which are typical for meteorite impacts like breccias, shatter cones, psedotachylites etc. All in all she gave us a hint what we will observe in the field the next day. For detailed information about the Vredefort crater refer to the field report below.

15. The Vredefort Dome impact structure in South Africa

The Vredefort Dome structure is known as the world's largest and oldest visible impact structure. It is located 100 km SSW of Johannesburg in the middle of the Witwatersrand basin (Fig. 23a). At first the Vredefort Ring structure was determined to be the result of an endogenic event like a gas explosion or a tectonic happening. Daly was the first who thought that this could be a large impact structure, being the origin of the Vredefort Ring (DALY, 1947). Also Dietz suggested that the shatter cones represent definitive evidence for an exogenic event (DIETZ, 1947). Today the structure is known as the Vredefort Dome and it is definitely proven to be a meteorite impact structure. Some parts of the Vredefort Dome were also inscribed as a World Heritage Site by UNESCO in 2006 (REIMOLD & KOEBERL, 2014). A number of research projects have been conducted during the last 20 years in fields like regional geology, metamorphic history of the region, structural mapping, detailed investigations of shatter cones and the pseudotachylitic breccias and microdeformations in quartz and zircon. These data were used to interpret and describe the appearance of the Vredefort Dome structure and to understand the influence of the impact on the ore deposits of the Witwatersrand basin.

15.1. The central dome structure and the wave-shaped foreland

The Vredefort dome structure is the result of the central uplift of a meteorite impact event nearly 2.023 Ga ago. The present surface lies approximately 10 kilometres lower than 2 Ga ago which is caused by a long time of erosion. Formations located in the centre of the dome (Archean basement rock) consist mainly of granulites and some granite greenstone series. Further away from the centre there is granite gneiss which is in contact with the volcanogenic Dominion group that is the first rock-formation of the collar-structure (Fig. 23a). Stratigraphically upwards the collar consists mainly of the Dominion group, Witwatersrand Supergroup and the Ventersdrop volcanics.

At the collar zone the stratigraphic layers were overturned up to angles of 90° to 120° and in the centripetal direction the layers flat out to their original sub horizontal bedding. Not only the central area of the Vredefort dome is marked by the meteorite impact, the foreland outside the collar structure also was influenced by the massive shock wave of the explosion of the meteorite and of the central uplift event. Evidence for this massive event is the widely occurring pseudotachylite breccia (Fig. 23b) and the circular wave-shaped stratigraphic layers which are also found in the foreland. For example there is the Potchefstroom syncline that has a circular shape and located at a 50 km radius from the centre of the dome, and the Rand anticline that has a radius of approximately 80 to 90 km and lies westwards of Johannesburg (REIMOLD and KOEBERL, 2014).

15.2. Vredefort Granophyre, pseudotachylitic breccia and shatter cones

A series of nine large dikes appear in Archean Gneisses in the centre of the Vredefort Dome structure. This rock is called the Vredefort Granophyre. Some of these dikes occur in a line as far as 9 km from the collar contact of the central Archean basement within the Lower Witwatersrand Supergroup (Fig. 23a). The other dikes can be found much closer to the centre of the structure and are oriented NW-SE or NE-SW. The granophyre gets its name from the micro-pegmatitic groundmass texture. It is mainly composed of plagioclase and hypersthene clasts embedded in a microphyric groundmass of feldspar and quartz. The very homogeneous chemical composition leads to the assumption that the source of the melt was the same for all dykes. All these dykes contain more or less clast components which are mainly from the Archean basement but also a distinctive portion comes from the Witwatersrand formation. Because of the content of the Witwatersrand clasts the dykes are seen as downward-intrusions of impact melted rock, but the meteorite portion of the melt is approximately only 0.2%. (KOEBERL et al., 2002). The granophyre is obviously not deformed, and considered to be an impact-based rock and used for dating the impact age of 2023±44 Ma (SHRIMP single zircon U-Pb) (REIMOLD & KOEBERL, 2014).

Another evidence for a large impact event is the pseudotachylitic breccia (PTB) (Fig. 23b). In structural geology pseudotachylite is synonymous with friction melt. Many examples are known from fault and shear zones. But the PTB's in the Vrederfort dome and in the surrounding area are structures generated not only by friction but also due to high compressive and decompressive forces during the impact process and the uplift event. It should be noted that the Vredefort dome is also the type locality for pseudotachylite. Additional evidence for a meteorite impact are the shatter cones found in the crater. These structures appear as cone-shaped with striations on the surface. Shatter cones occur within a circular space within the crater, having a distinct width, which can be correlated to the energy of the impact (Fig. 23a).

15.3. Shock metamorphism and post-shock metamorphism

In the 1960s geologists began to study the Vredefort rocks for evidence of microscopic mineral deformation that could have been caused by intense shock pressure. Finally they found planar deformation features (PDFs) in many quartz grains in plenty of rock types. The only problem was that in the deformation zones (in the lamellae) there was no glass phase which normally is typical for shock metamorphism. It was only in the 1990s that PDFs without glass phase were regarded as evidence for impact.

It was considered much later that an ongoing thermal metamorphism after the impact caused the recrystallization of the glassy quartz phases. The effect of the post-shock metamorphism can be observed in an overprint of the fully equilibrated Archean granites which after the impact shows a diffusion-controlled replacement of garnet by corona reaction to a partial equilibrium state (REIMOLD and KOEBERL, 2014).

Excursion Day 11

Our last day in the field in South Africa was a rather busy one. We visited several key sites of the Vredefort impact structure around Vredefort and Parys (Fig. 23a).

Stop 22
(S26°56.620', E27°24.840')
After just a 5.5 km drive on the main road southwest from the centre of Parys, adjacent to the closed „outlaws bar" lies the Vredefort Charnockite.

Stop 23
(S26°59.290', E27°22.310')
The next stop was situated at the northern border of the town of Vredefort, the „Vredefort Interpretation Centre". Unfortunately, what was meant to be a tourist magnet and a center of study of the Vredefort structure, had been closed (or never really opened) and the buildings are in a state of decay. We were allowed to get inside the centre and had the chance to look at the beautiful outcrops of orthopyroxene-bearing dark charnockite embedded in reddish granite gneiss. Small pseudotachylitic veins penetrate the charonickite lenses and the granitic gneiss. Sometimes the veins crosscut the dark orthopyroxene-bearing lenses. Mostly they outcrop at the borders between the charnockite and the granite gneiss. One can also observe a few large K-feldspar crystals in the host rock.

Stop 24
(S26°56.860', E27°22.450')
Starting at the entrance of the interpretation center, and a 4.5 km drive NNW on the road until the crossing, then 1.9 km ENE, we parked our bus at the gate of an agricultural field. After the gate, it was just a 750 m foot walk SSW until we reached the outcrop of the Vredefort granophyre. The outcrop from the distance appears as few rocks laying randomly in a gentle slope of grass covered background. But as one reaches the outcrop, it is a large horizontal dyke structure, a few meters in width and a few hundred metres in length. The rock is very fine-grained with greyish ground mass. Enclosed are numerous clasts of centimetres to decimetres size. The clasts are not easy to describe macroscopically, but according to the literature they may be mostly granite gneisses and lesser amounts of overlying sedimentary rocks of the Witwatersrand basin. It is also suggested that the early settlers in this area recognised the fine grained granophyre and used them for making prehistoric artwork that one can observe on the outcrops.

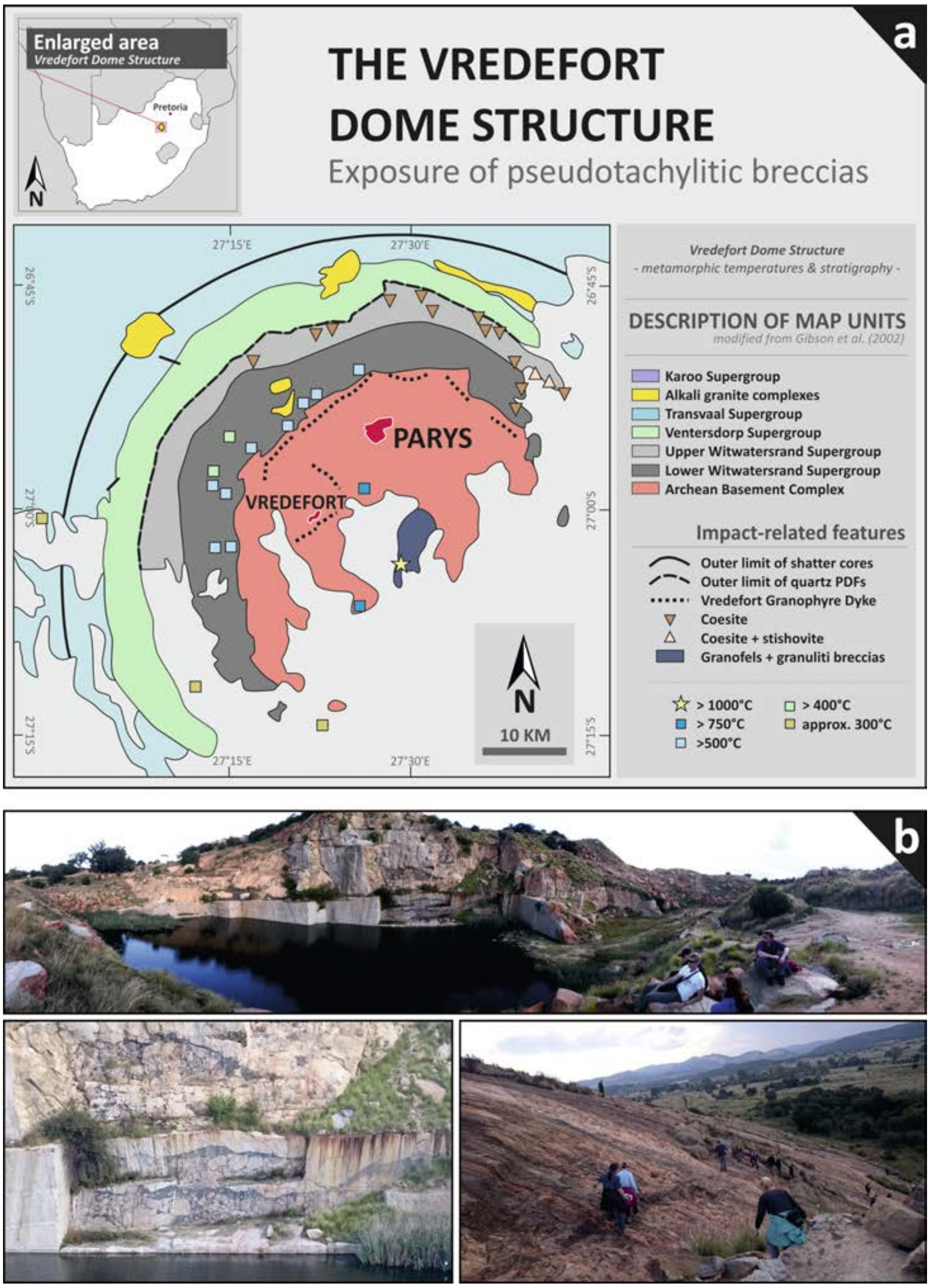


Fig. 23

a) Geology of the Vredefort dome structure with metamorphic temperatures, stratigraphy and location of the Vredefort Granophyre dikes (GIBSON et al., 2002), b) abandoned quarry with outcrop of the Vredefort pseudo-tachylitic breccia.

Stop 25

(S26°53.830', E27°24.460')

This stop was at an abandoned quarry, where one can observe blocks of the famous Vredefort pseudotachylite breccias (Fig. 23b). The Quarry lies just northwest of Parys. The unsealed access road we had to walk starts at [S26°53.850', E27°23.930']. It had been an easy walk of 1.25 km on the unsealed road around half the quarry, but if one does not mind some simple climbing, one can take a shortcut of 0.85 km total length. From a distance one can see the spectacular pseudotachylitic breccia (PTB). A thick irregular vein of black glassy rock with large clasts outcrops above the base of the quarry. The host-rock is central granite gneiss, which is supposed to be the source of the clasts in the PTB. Within the PTB two massive veins with approximately 4 meters in height and nearly 20 metres in length were observed. This is an abandoned quarry with an artificial pond which made it difficult to reach the outcrop. It is a protected area and one is not allowed to use geological hammer.

Stop 26

(S26°52.910', E27°21.510'),

The last stop was an outcrop of the overturned Vredefort quartzite. It is just a 20 m walk from the nearby unsealed road and 9.2 km from the Vredefort city center. The outcrop is directly located in the Vaal-River. After a few metres off the road in the direction towards the river we walked on overturned quartzite outcrops of the Witwatersrand formation. One can clearly recognise the cross-bedding structures of the sandstone, and the area where the former horizontally deposited sediments were overturned by more than 90°, due to the meteorite impact. After further few metres, standing on the bank of the river one can observe the overturned quartzite in the middle of the stream, rising up a few metres above the water-surface. In the background the vertical sandstone layers outcrop on a curved ridge extending towards the southwest.

Acknowledgements

We would like to thank Sara Raic, Philip Schantl, Christoph Gauert, Marion Tredoux and Freddie Roelofse, the Head of the Geology Department, University of Free State, South Africa for their academic support in the field and during the compilation of the report. Sylvia Umschaden, Secretary, Institute of Earth Sciences, University of Graz and Brigitte Mang, Secretary (Lehrstuhl für Geologie und Lagerstättenlehre) Montanuniversitaet Leoben and Juergen Neubauer are thanked for all the administrative support in organizing the excursion. We would also like to acknowledge the support of the Council of Geosciences of South Africa (Fhatuwani Ramagwede and Bisrat Yibas) for providing us geological maps of the areas visited during the excursion. The managers and geologists of the different mining companies (Anton Wollmerans, Cullinan mine; Michelle Steenkamp, Geologist at Delmas; Harry Leicester, Geologist; Pieter Lategan, Manager Mining; Ruwaida Mohideen, Production geologist at Andalusite Resources: Piet Kolbe, Herman Penyenge, from Kumba/Thabazimbi iron mines; Bennie Cilliers from Rustenburg Platinum Impala) are thanked gratefully. Last but not least, we thank the Bus Company Robin quality touring service, South Africa and our driver Douglas for the efficient service which was very important for executing all what we planned to do during the excursion period.

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received: 25.06.2015
accepted: 30.06.2015