The Centenary of the Discovery of Economic Platinum Deposits in the Eastern Limb of the Bushveld Complex

Field Guide August 2024 by R N Scoon

The discovery of an economic platinum deposit in the dunite pipe at Mooihoek, by Hans Merensky and his Lydenburg Platinum Syndicate on 15 August 1924, is one of the most significant geological events in South Africa

Hans Merensky (third from right) prospecting on the farm Onverwacht in 1924. From Lehmann (1955)

doi.org/10.25131/PMTX5734

Itinerary and Field Stops

Thursday 15 August: Johannesburg-Steelpoort

- **EL-1 Views of the Eastern Limb**
- **EL-2 IRUPs at Kennedy's Vale and Spitskop**
- **EL-3 Burgersfort trough**

Friday 16 August: Steelpoort

- **EL-4 Onverwacht pipe, Modikwe Platinum mine**
- **EL-5 Mooihoek pipe**
- **EL-6 Driekop pipe**
- **EL-7 Merensky Reef, Maandagshoek**
- **EL-8 De Grooteboom Chromite mine**

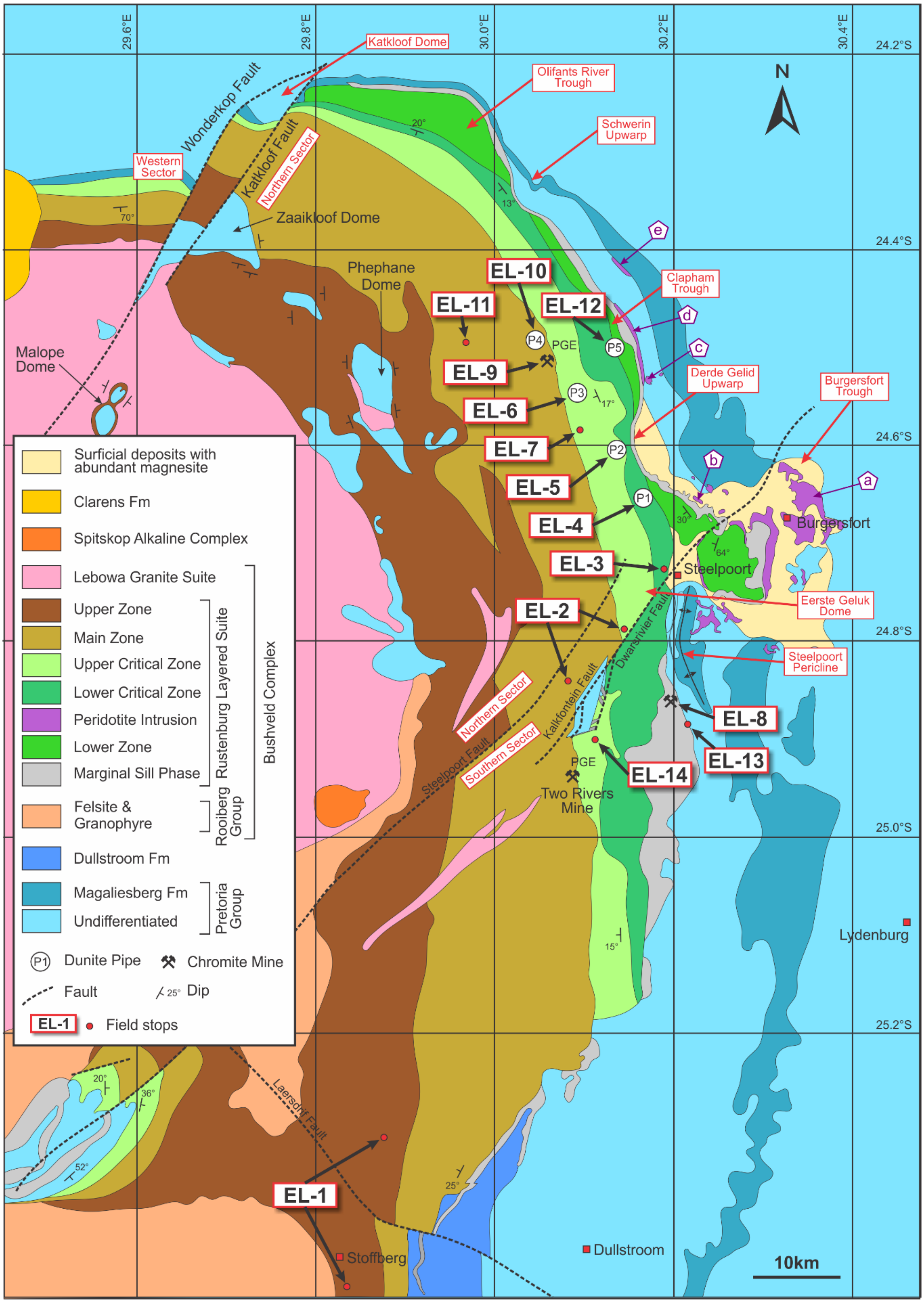
Saturday 17 August: Steelpoort

- **EL-9 Merensky Reef, Winnaarshoek (surface outcrops and old mine workings)**
- **EL-10 UG2 and Winnaarshoek Pipe, Marula Platinum mine (core shed)**
- **EL-11 Tsate Cultural Centre and views of the LMZ**
- **EL-12 Magnesite quarry and Twyfelaar Pipe**

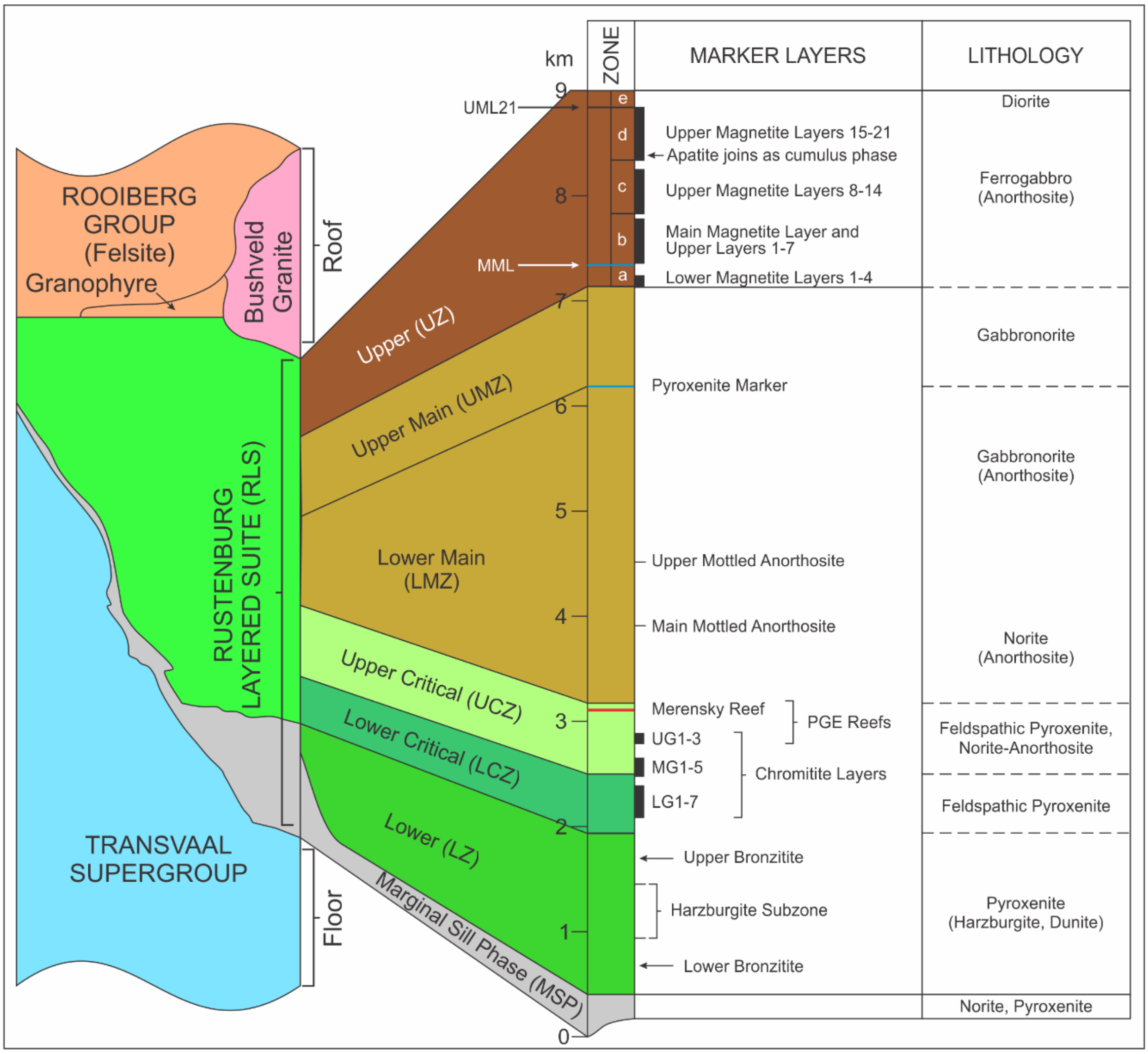
Sunday 18 August: Steelpoort-Johannesburg

- **EL-13 MSP, De Grooteboom**
- **EL-14 UG1, Dwars Rivier**

"The Bushveld Igneous Complex is a vast treasure ground which for many years to come will provide the mineralogist, the petrographer, and the geologist with a rich field to dig over" **(Hall, 1932)**



Simplified map of part of the Eastern Limb showing the field stops



Subdivision of the RLS into zones and subzones showing marker layers and broad details of the igneous stratigraphy

The **three components of the Bushveld Complex** have been awarded formal status by the South African Committee for Stratigraphy (1980), in part as they define a stratigraphic order.

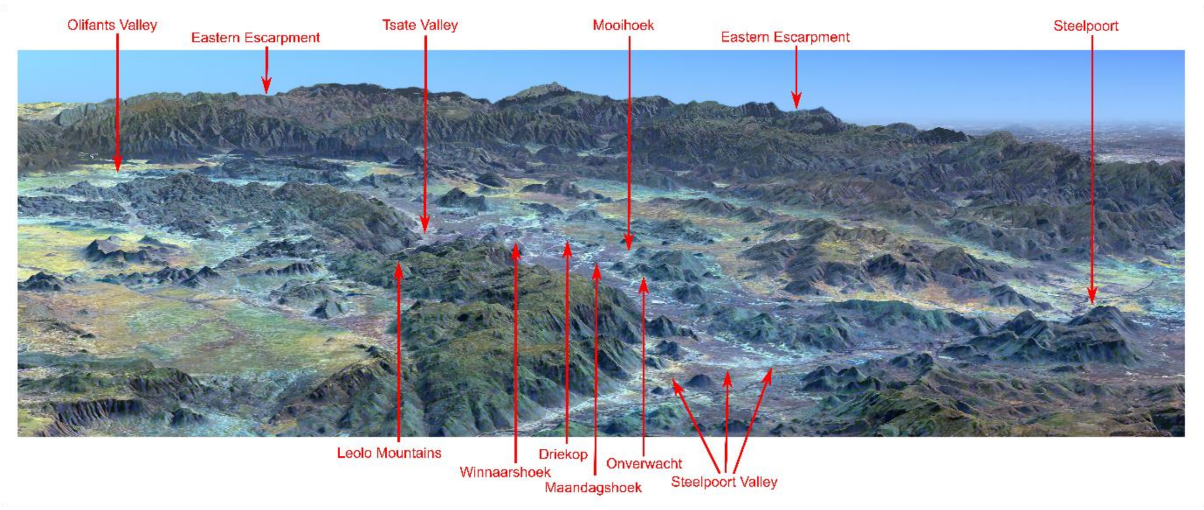
Rooiberg Group (oldest): sheets of rhyolite lava (felsite) ±subordinate granophyre flooded the centre of the Transvaal Basin. The Rooiberg is part of the Bushveld Complex, as proposed by Hall (1932) (not part of the Transvaal Supergroup). The thickness is estimated at 6 km.

Rustenburg Layered Suite (intermediate): the layered mafic-ultramafic rocks were intruded beneath the Rooiberg Group into the uppermost part of the Transvaal Supergroup. The maximum thickness is 10 km.

Lebowa Granite Suite (youngest): thick sheets of granite ±subordinate granophyre were intruded mostly between the RLS and the Rooiberg Group. The maximum thickness is estimated at 4 km.

Usage of "Rashoop Granophyre Suite" is avoided as the granophyre sheets of the Rooiberg and those associated with the younger granites should not be conflated.

A three-dimensional satellite image (two times vertical exaggeration) of part of the Eastern Limb looking north from Die Berg with the deeply-incised valleys of the Groot and Klein Dwarsrivers in the foreground. The irregularity of the basal contact, particularly between the towns of Steelpoort (S) and Burgersfort (B) contrasts with the planar nature of the roof. The platinum discoveries were made in the Motse Valley and subsidiary tributaries that occupy a broad valley at the foot of the Bushveld Escarpment. (Landsat 7 image for the year 2000 sourced from the University of Maryland Global Land Cover Facility and processed by Philip Eales of Planetary Visions)



Location of the platinum deposits in the area north of Steelpoort

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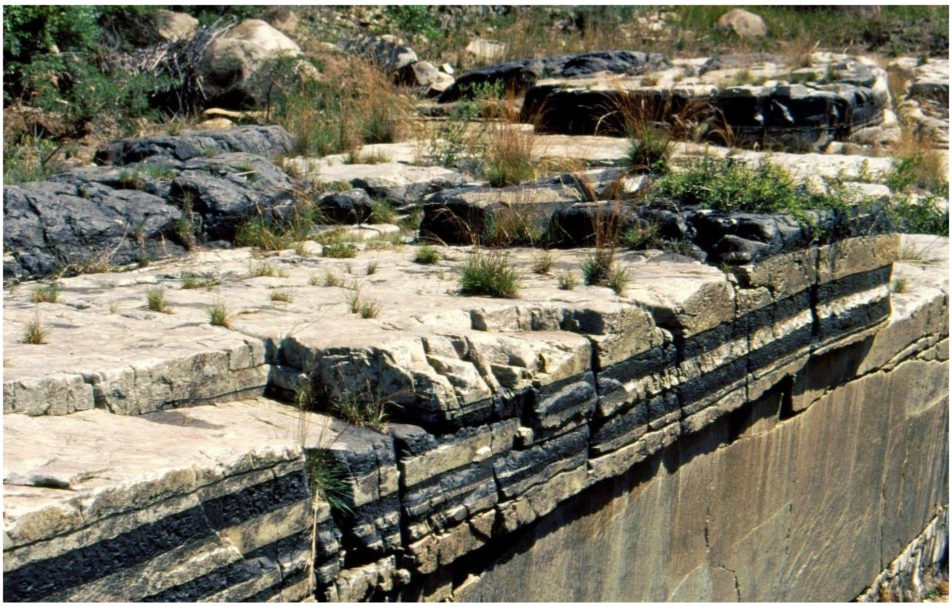


The thin chromitite layers (dark) located in the anorthosite (white) have split from the base of the metre-thick UG1 chromitite (top), Dwarsriver National Monument. Photograph: Morris Viljoen

1. Location and Naming of the Bushveld Complex

The Bushveld Complex occupies an area covering more than 65,000 km^2 and measuring 400 km east-west and 350 km north-south (Hall, 1932; Willemse, 1969a). The layered mafic-ultramafic rocks outcrop in three principal limbs (or lobes), together with minor adjuncts and satellite bodies, whereas the felsites and granites are mostly restricted to the centre of the Transvaal basin.

Limbs
The three limbs which constitute the main outcrops of the layered mafic-ultramafic rocks are isolated by their position on the fringes of the Transvaal Basin. This has resulted in usage of geographical names being awarded formal status in the scientific literature. The formal status of the limbs offers a logical basis for describing the layered rocks but is less than satisfactory for the felsites and granites.

Eastern Limb
The Eastern Limb occurs in the Limpopo and Mpumalanga provinces. Regional towns include Burgersfort, Lydenburg, Roossenekal and Steelpoort.

Early Reports
The first reports of the occurrence of igneous rocks now known to be part of the Bushveld Complex were from expeditions into the interior of South Africa, by German explorers including Mauch (1869-1872), Hübner (1869-1871), Cohen (1883), and Wülfing (1888), as described by Burke (1969), Molengraaff (1903), and Hall (1932).

Naming
The name "*Bushveld*" is translated from the Afrikaans "*bosveld*" and has arisen due to overlap between the geological terrane and the bushy savannah that covers large parts of the interior. Molengraaff (1901) introduced the descriptor "*Plutonic Series of the Bushveld*" for the mafic-ultramafic rocks. The widely spaced outcrops of the intrusive rocks, i.e., in the southern part of the Eastern Limb and in the Western Limb were interpreted as sections of a giant laccolith. The extensiveness of the igneous layering caused Molengraaff (1901) and Hall (1903) to refer to the widely spaced outcrops as part of a large igneous complex. Kynaston and Mellor (1905) identified similar outcrops in the northern part of the Eastern Limb, at Ga-Mphalele (near Lebowakgomo,), as well as in the Northern Limb near Polokwane.

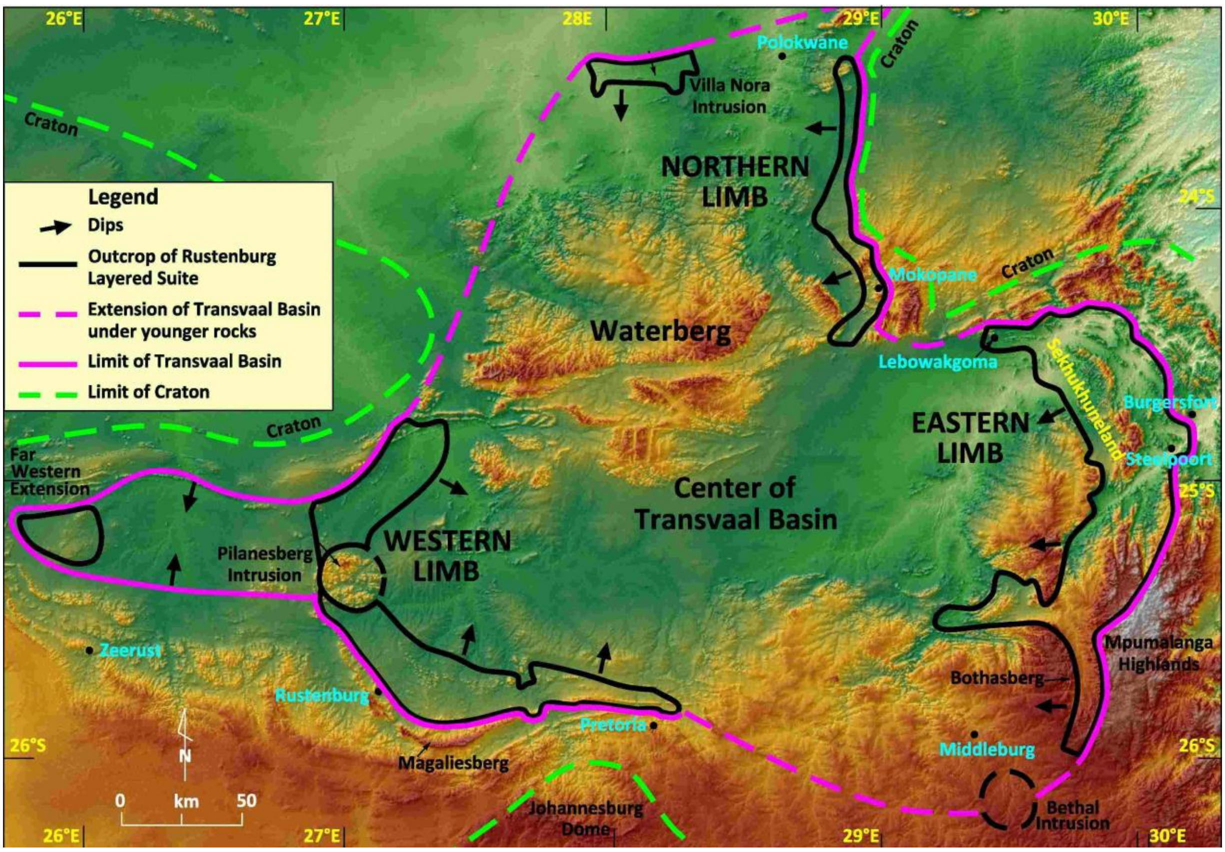
The descriptor "*Bushveld Igneous Complex"* was proposed by the Geological Survey) to incorporate the extrusive and plutonic components into a single system, i.e., inclusive of the felsites (Hall, 1932).

The current format is "***Bushveld Complex**,"* as defined by the South African Committee for Stratigraphy (1980).

Geological Mapping
The first geological map of the northeastern part of South Africa, i.e., the region formerly known as the Transvaal, was compiled by the explorer Carl Mauch in 1869-1871 (Harger, 1934). The map depicts outcrops of gabbro, granite, norite, and pyroxenite between Rustenburg and Pretoria (Western Limb), as well as in the Bothasberg locality (Eastern Limb). Mauch also commented on the outcrops of chromite and magnetite in the Hex River Valley, near Rustenburg.

Carl Mauch was assisted in some of his earliest travels and map making endeavours by Alexander Merensky, the father of the famous geologist Hans Merensky. Alexander Merensky, a German missionary who established the Botshabelo mission station near Middelburg (see below), had developed an interest in geography which may have influenced Hans in his chosen profession.

Detailed geological mapping was subsequently undertaken by the Geological Survey of the Transvaal (1903-1910), and by the Geological Survey of South Africa (1910-1993) (the forerunner of the Council of Geoscience). The 1:250,00 scale maps cover the entire complex.



Topography of the northeastern part of South Africa portrayed by a digital terrain image with areas of high relief (shades of yellow and orange) and low relief (shades of green). The three main limbs of the Rustenburg Layered Suite, together with the adjuncts, are interpreted to constitute separate magma compartments which outcrop (or subcrop) on the inner perimeter of the inward-dipping Transvaal Supergroup. The Northern Limb has cut down into the cratonic basement. The Eastern Limb is situated in the Middleveld where erosion of the interior plateau has created a localised geomorphological region. The traditional area of Sekhukhuneland in the Eastern Limb contains many of the most spectacular outcrops. The felsites and granites are found in the centre of the Transvaal Basin

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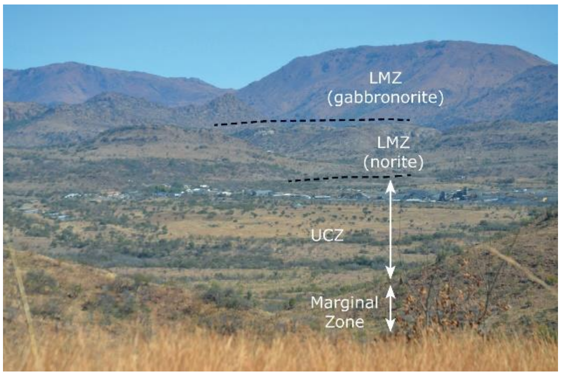
2. Geomorphology

The geomorphology of southern Africa was shaped to a considerable extent by break-up of the ancient supercontinent of Gondwana (Burke 1996; McCarthy and Rubidge 2005). The African Plate was uplifted in response to the major thermal event that triggered rifting of the Atlantic and Indian oceans (180-35 Ma) (Begg et al. 2009; Moore et al., 2009; Dirks et al. 2015). The uplift initiated intense cycles of erosion which formed the African Erosion Surface (70 Ma), i.e., the interior plateau, as well as several younger surfaces (Partridge and Maud 1987).

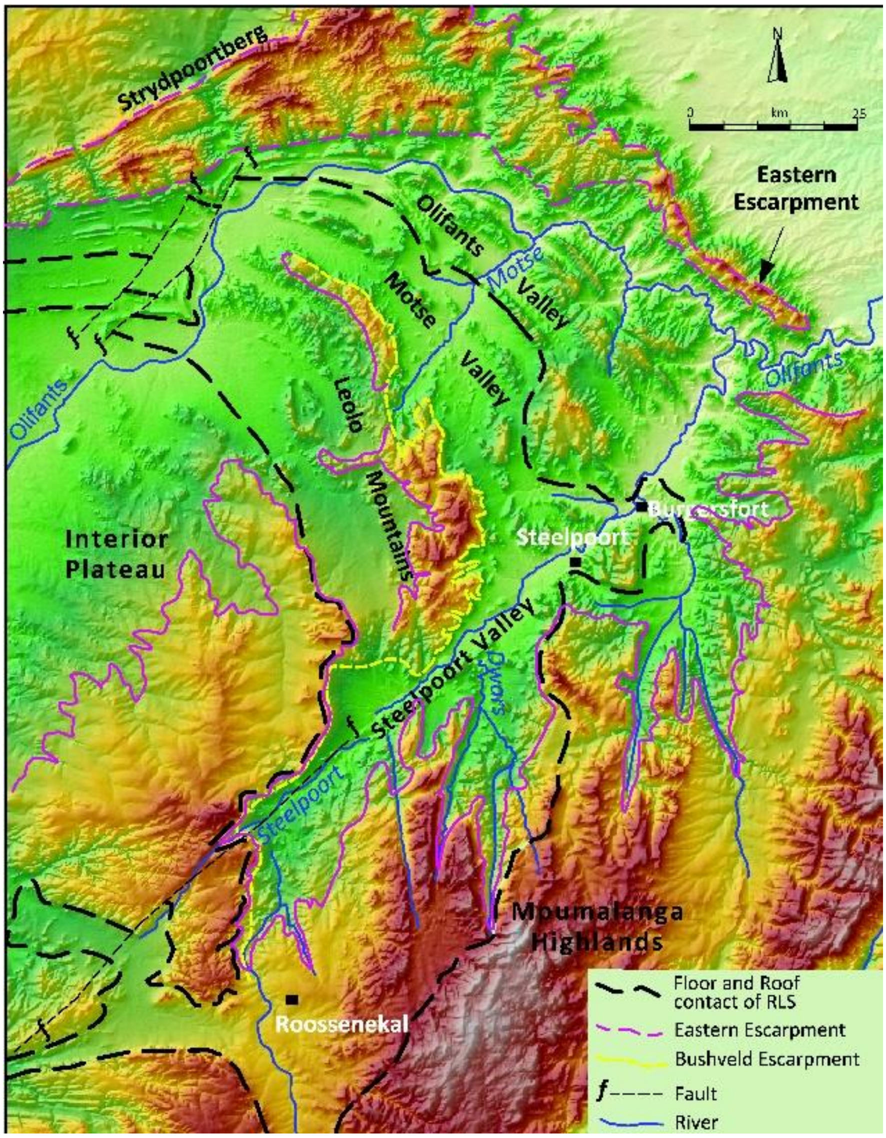
The interior plateau in the region of southern Africa described here is divided from the coastal lowlands by the Great Escarpment, known as the Eastern Escarpment, or the Northern Drakensberg in the Eastern Limb. The regional nature of the Great Escarpment was commented on by Du Toit (1933).
In the Eastern Limb, a secondary escarpment has been identified associated with the resistant nature of the gabbronorite in the RLS (Hall, 1932; Scoon and Viljoen, 2019). The "Bushveld Escarpment" forms the eastern extent of the Leolo Mountains. Between the two escarpments, headward erosion of the Olifants River has carved out a system of arcuate ridges and valleys, in an area traditionally known as Sekhukhuneland. The Motse River is a prominent, eastward flowing tributary of the Olifants River.

In the area to the south of Sekhukhuneland, major tributaries of the Olifants River include the Steelpoort River and the Groot and Klein Dwarsrivers. The reivers here have retreated along linear, structurally controlled valleys into the interior plateau. The isolated areas of high relief that project from the Middleveld, such as the Mpumalanga Highlands, are underlain by metasedimentary sequences associated with the Transvaal Supergroup.
The interior plateau of southern Africa supports a grassy and bushy savanna. The relatively high elevation moderates the subtropical, monsoon climate, and cold, dry winters alternate with wet, hot summers. The position of the Middleveld in the area between the Bushveld and Great Escarpments has resulted in a mild climate, tempered by the modest elevation. Endemic species of grasses and aloes, together with pockets of indigenous forest and bushy savannah are recognized. Some of the earliest settlements in the Middleveld can be traced to Tsate where a broad valley has been carved in the mountainous terrain by the Motse River.

Rugged topography in the northern part of the Eastern Limb



Erosion of the Middleveld has created a series of stepped ridges, or cuesta topography in which the different zones of the RLS can be identified, as seen here in a view point at De Grooteboom looking west towards the Dwarsrivier valleys



Topography of the Eastern Limb portrayed by a digital terrain image shows the retreating scarp faces of the Olifants and Steelpoort River systems, Middleveld. Areas of high relief are shown in shades of yellow and orange, low relief in shades of green. From Scoon and Viljoen (2019)

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3. Human Habitation and Cultural Features of the Middleveld

Indigenous peoples have occupied the Middleveld for extended periods of history. The mountain ranges remain remote wilderness areas, but the valleys and plateau are densely populated. Intense cycles of erosion occurred during the wetter climatic conditions of epochs prior to the Holocene and large areas of "badlands" reflect erosion of transported soils from the interior plateau.

The earliest humans in southern Africa, the Khoisan, may have lived and hunted in this region for tens of thousands of years. Rock art attributed to the Khoisan has been found on the flanks of the Tsate Valley (Spencer, 1910a). Habitation of the Middleveld by Bantu-speaking peoples, later migrants into the region, dates to the African Iron Age (1600-1000 AD) and includes the site of an ancient copper mine in the Tsate Valley (Spencer, 1910b). The source of the copper has not been traced but there is a possibility ore may have been obtained from the Merensky Reef, which outcrops on the adjacent farms.

In the period 1830-1879, King Sekwati (1775-1861) and his son, King Sekhukhune (1814-1882), united a group of the Bantu-speaking peoples, the Bapedi, in this region into the formidable Marota Empire. They established their capital at Thaba Mosega, in the Tsate Valley. A memorial and interpretive centre has been established here. In 1861, Alexander Merensky of the Berlin Missionary Society was granted permission to build a mission station at Garatouw, approximately 10 km south of Tsate. The ruins of the mission station can be seen west of Maandagshoek. In 1864, the Sekhukhune uprising caused Alexander Merensky, together with his wife and daughter, to flee southward, across the Steelpoort River, the then boundary between Sekhukhuneland and the Transvaal Republic. The flight of the Merensky family from Garatouw, described as an epic piece of history (Lombaard, 1945), has been well documented. After fleeing the uprising, Alexander Merensky initially sought safety at Roossenekal, but in1865 established a new mission station at Botshabelo ("place of refuge"), near Middleburg.

Fort Merensky (or Fort Wilhelm) was built in 1869 at the Botshabelo Cultural Centre, Middleburg

The Sekhukhune warriors at Tsate initially defended their remote mountain fortress against attacks from tribal groups, as well as from European settlers, but in 1879 a combined assault from British troops and Swazi warriors forced their subjugation. The battlefield is commemorated by a memorial in the Tsate Valley.

Mapoch's Caves near Roossenekal is a provincial heritage site of archaeological significance. The caves were constructed in resistant outcrops of gabbronorite by Mapoch, one of the earliest leaders of the Ndebele peoples. Extensive stone walling was constructed to join small cliffs and large boulders.

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4. Introduction to the Geology of the Bushveld Complex

The Bushveld Complex is a giant magmatic province situated within the northeast of South Africa (Hall, 1932; Wager and Brown, 1968; Willemse, 1969; Tankard et al., 1982; Von Gruenewaldt et al., 1985; Eales, 2014; Cawthorn, 2015). All three components, i.e., the felsites ±granophyres of the Rooiberg Group, the Rustenburg Layered Suite (RLS), and the Lebowa Granite Suite can be linked to a single thermal event with an approximate age of 2.055 Ga.

Mineral Deposits
The mineral deposits of the Bushveld Complex have been described in several review articles, including by Lee (1996) and Viljoen (2016). The stratabound nature of many of the ore deposits is a prominent feature. Many of the chromitite layers (sources of chromite ore), and the magnetite layers (sources of vanadium ore) constitute important marker layers (Figs. 7 and 8). Dimension stone (slabs of grey and black gabbro) are quarried from specific parts of the Main Zone. Industrial minerals (magnesite, andalusite, asbestos) are exploited from either peridotite intrusions and sills in the floor rocks or from the metamorphic rocks in the thermal aureole. The Lebowa granites host deposits of tin and fluorspar.

Zones
The RLS is subdivided into laterally persistent zones, i.e., Marginal Sill Phase (MSP) or marginal zone; Lower Zone (LZ); Lower/Upper Critical Zone (LCZ: UCZ); Lower/Upper Main Zone (LMZ; UMZ); Upper Zone (UZ). Zones may be further subdivided into subzones and units. Marker layers can be traced over tens of km of strike.

Chromitites
The nomenclature defining the chromitites was developed by Cousins and Feringa (1964) for the Western Limb. Attempts at incorporating the chromitites in the Eastern Limb into this system is not straightforward, in part due to the multiple nature of the layers. Layers 1-17 of Cameron (1977; 1980; 1982) are categorized within the Lower Group on a unit-by-unit basis. The LG1-LG4 are assigned to the B, C1, C2, and C3 units, respectively. The LG5, LG6, and LG6a occur in the D2 unit. The LG7 occurs in the E unit. Layers 18 and above are assigned to the Middle Group. The MG1 and MG2 occur in the LCZ (E unit). The MG3-MG5 occur in the UCZ. The Upper Group layers (UG1-UG3) and UG2 chromitites are laterally more persistent than the LGs and MGs.

Petrogenesis
The petrogenesis of layered mafic-ultramafic rocks is uncertain despite more than a century of research. Moreover, the classic cumulus theory of Wager and Deer (1939) as applied to the Bushveld Complex by Wager and Brown (1968) is not universally accepted. After critical appraisal of the role of crystal settling in tholeiitic magmas (Bottinga and Weill, 1970; McBirney and Noyes, 1979), the significance of *in situ* growth of crystals on the temporary floor of the Bushveld magma chamber was recognised as an alternative mechanism (Eales et al., 1986; Naslund and McBirney, 1996). There is, however, currently no consensus on the relative roles of crystal setting and *in situ* growth of crystals.

New Hypothesis
As the existence of a shallow crustal magma chamber, despite this being widely accepted, is not compatible with the field relationships, a new hypothesis has been proposed (Mitchell and Scoon, 2007; Scoon and Costin, 2018; Mitchell et al., 2019a; 2019b). Key field relationships include the overlapping nature of zones, presence of basal discordancies (intrusive hiatuses), and lack of fractionation trends in some of the zones. The igneous layering is thought to have developed from successions of intrusive events. The boundaries and geochemical discontinuities within the igneous stratigraphy are explained by radical switches in the composition of the parental magma. Magma was emplaced either in batches, incrementally beneath the Rooiberg Group, or as syn-magmatic sills.

Parts of the igneous stratigraphy are non-sequential.

The identification of successive intrusive events may account for the transitory and planar nature of the roof, as preserved by the contact between the UZ and the felsites. Each intrusive pulse functioned as a “shim” which progressively uplifted the roof. This process seems far more plausible than intrusions of tens of cubic kilometres of magma in single events. Inflation of the RLS by emplacement of multiple magma sheets may have followed a similar pattern to the growth of granitic plutons as discussed by Miller et al. (2011).

Parental Magmas

Broad lineages of parental magma are identified rather than attempting to quantify the composition of each and every magma increment. The “B1 magma”, as defined by Harmer and Sharpe (1985), is not a specific magma-type (this is a popular misconception), as the noritic and pyroxenitic sills in the floor rocks and in the MSP have a broad range of compositions. The heterogeneity of this lineage is consistent with tholeiitic magmas having been fed from deep, fractionating staging chambers in the lower crust that were episodically replenished and tapped, as described by Cox et al. (1979). The switch from the tholeiitic magmas of the MSP to the ultramafic magmas of the LZ has been widely recognized (Teigler and Eales, 1996; Eales, 2000; Wilson, 2015; Maier et al., 2016). The ultramafic magmas have been conflated with the B1 lineage (Harmer and Sharpe, 1985) but this has little support.

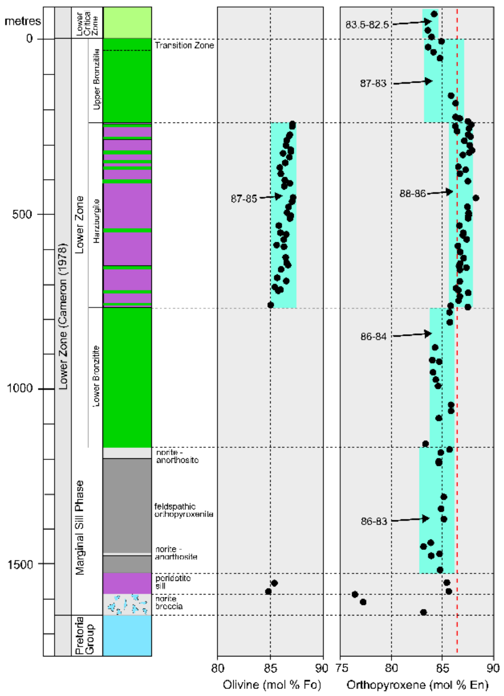
Where we differ from the mainstream view, however, is that we identify two lineages of ultramafic magma, orthopyroxene-saturated and peridotitic (Scoon and Mitchell, 2023). Evidence of the latter is found in the occurrence of peridotite intrusions and sills in the floor rocks (Cawthorn et al., 1981; Sharpe, 1981; Sharpe and Hulbert, 1985; Clarke et al., 2009b; Wilson, 2015). The ultramafic magmas are mantle-derived melts that intruded through a separate system of feeders which developed after formation of the MSP.

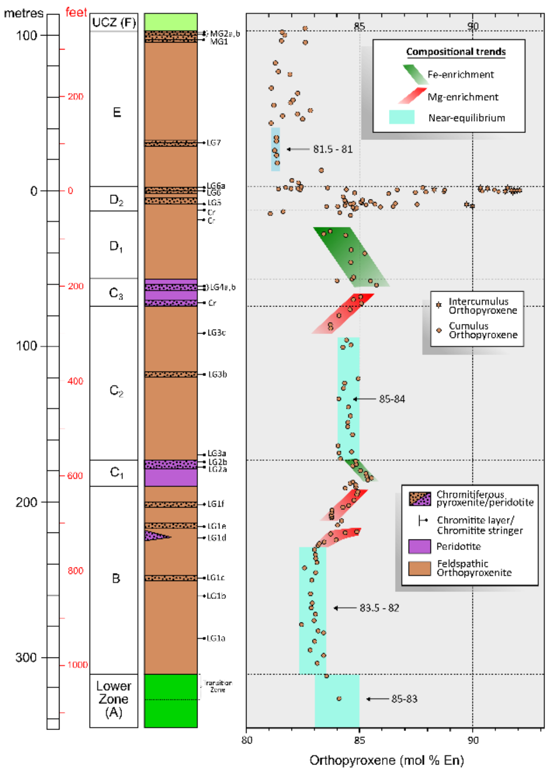
Development of Igneous Layering

The zones of interest to the field excursion can be envisaged as having built up incrementally, from successive intrusive event. The **MSP** is a stacked sequence of noritic and pyroxenitic sills, rather than the chilled carapace of a magma chamber. The **LZ** developed in isolated subchambers (Cameron, 1978; Scoon and Mitchell, 2023). Chemical equilibrium was maintained as the orthopyroxene-saturated magma was intruded as thin magma laminae. The increments matched the rate of batch crystallisation. After formation of the pyroxenitic sequences in the LZ, peridotite magma was injected into the floor rocks forming complexly layered **peridotite intrusives** with their anastomosing groups of sills. Some peridotite sills stepped up through the thermal aureole and intruded the earlier-formed MSP and LZ, crystallising as syn-magmatic sills, i.e., in an analogous manner to the peridotite sills in the Rum Intrusion, Scotland (Bédard et al., 1988).

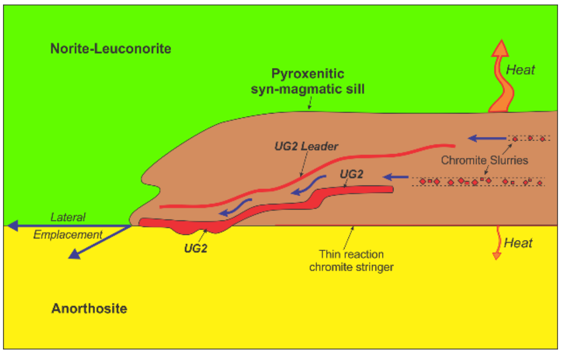
The pyroxenitic units in the **LCZ** accumulated from increments of the B1 (pyroxenitic) magma (Scoon et al., 2024). The peridotitic units in the LCZ are syn-magmatic sills. The chromitite layers are linked to the intrusion of chromite slurries (Eales, 2002; Eales and Costin, 2010). Slurries consisting of xenocrysts of Cr-spinel were transported from depth by the pyroxenitic magma.

The **UCZ** reflects **a** two-stage process. First, intrusion of the B1 (noritic) magma and development of the norite and leuconorite stratigraphy. Partial melting events were induced by the intrusion of thin magma increments. Layers of mottled anorthosite reflect a particularly complex petrogenesis in which the oikocrysts of pyroxene developed from the migration of late-stage melts (Mitchell and Manthree, 2002). Second, the B1 (pyroxenitic) magmas, some of which contained chromite slurries, were intruded into the earlier formed igneous stratigraphy as sills (Mitchell and Scoon, 2007; Voordouw et al., 2009: Mitchell et al, 2019b). The sills exploited competency contrasts between the layers of norite and anorthosite.





Vertical sections of the MSP/LZ and LCZ, Olifants River, showing electron microprobe analyses of Cameron (1978; 1980). The absence of fractionation trends in the is not compatible with fractional crystallization of a large magma reservoir and is explained by the intrusion of thin increments of magma. The fluctuating nature of the vertical trends is indicative of successions of intrusive events



Syn-magmatic pyroxenitic sill injected between earlier-formed layers of leuconorite and anorthosite. The sills are composite and may contain chromite slurries. The slurry associated with the UG2 disaggregated the footwall anorthosite. A "reaction" chromite stringer may occur on the contact with the anorthosite

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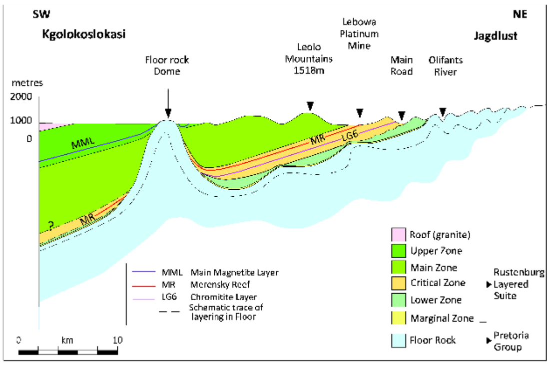
5. Eastern Limb

The Eastern Limb is comprised of three intrusive compartments, or sectors (Schwellnus et al., 1962; Cameron, 1978; Hatton and Von Gruenewaldt, 1978; Sharpe and Snyman, 1980; Scoon and Teigler, 1995; Scoon and Mitchell, 2023). Sectors are separated by structurally complex regions demarcated by floor-rock domes and regional faults. The MSP is laterally persistent in the region, but the LZ is restricted to three trough-like bodies (subchambers) in the Northern Sector, i.e., Burgersfort, Clapham, Olifants River. The LCZ and UCZ reach their thickest development in the Northern Sector and are thinned considerably in the area south of Steelpoort. Complexly layered peridotite intrusions with their anastomosing groups of sills occur in the floor rocks, e.g., the Aapiesdoorndraai Intrusion (Sharpe and Hulbert, 1985; Clarke et al., 2009a).

Floor Rock Domes

The intrusion of the layered mafic-ultramafic rocks in the Eastern Limb deformed and thermally metamorphosed the floor rocks (Transvaal Supergroup) (Hall, 1932; Willemse 1964; Button, 1977; Sharpe and Snyman, 1980; Cawthorn, 1998; Clarke et al., 2009b). The most obvious manifestation of this is regional uplift of the floor rocks, which in turn induced an inward tilt to the igneous layering (into the centre of the Transvaal Basin). Localized areas of uplift generated floor-rock domes (Marlow and Van der Merwe, 1977; Sharpe and Chadwick, 1982; Uken and Watkeys, 1997; Clarke et al., 2005).

Domes are concentrated in sector boundaries but also occur in the interior of the Northern Sector, e.g., the Phephane and Zaaikloof domes which have been active throughout the intrusive history of the Eastern Limb (Scoon, 2002). Domes constrain the three trough-like bodies that contain the LZ, i.e., Derde Gelid and Schweirin upwarps.



Simplified cross section of the RLS in the Olifants River Trough, Eastern Limb, showing the gentle dip into the interior of the Transvaal Basin and the impact of floor-attached domes

Igneous Stratigraphy

The MSP reveals a broad stratigraphy in the Northern Sector, e.g., the Hendriksplaats norite and the Clapham pyroxenite but these units are not recognized in the Southern Sector. Three subzones may be identified in the LZ (specifically at Olifants River), i.e., Lower and Upper Bronzitites and the Harzburgite Subzones. Cameron (1980) identified seven lithological units in the LCZ, i.e., B, C1-C3, D1-D2, and E. (Note that in Cameron's system the LZ corresponds to the A unit). Five of the seven units are pyroxenitic and two are peridotitic. The UCZ consists of multiple units labelled by Cameron (1982) as the F through M units, together with the UG1, UG2, Merensky Reef.

Cameron's approach in defining units based on lithology is preferred to the use of chromitites as basal markers (South African Committee for Stratigraphy, 1980). One reason for this is that many of the chromitites occur in the centre of the lithological units.

A key difference between the Northern and Southern Sectors is In the occurrence of the LGs and MGs (Cameron, 1964; Cameron and Desborough, 1969; Worst, 1986; Schürmann et al., 1998). Both groups are developed in the Northern Sector, although the MGs are subordinate. In the Southern Sector, however, the LGs are absent, and the MGs occur as thick, mineable layers.

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6. Discordant Bodies

Discordant bodies are a significant part of the RLS. In the Eastern Limb, these features may outcrop in koppies, i.e., small, conical hills. This assisted with the discovery of the mineralized pipes. The three-dimensional shapes of the discordant bodies are variable, and in addition to subvertical pipes, they occur as subconcordant sheets, dikes, veins, and pods. Cameron and Desborough (1964) described occurrences of subconcordant sheets that cap entire hillslopes in localities south of Steelpoort, e.g., at Annex Grootboom, Grootboom, and Dwarsrivier.

The first discordant body to be described from the Eastern Limb was at Zwartkoppies, by participants of the 1922 Shaler Memorial Expedition, as reported by Hall (1932). The dark, lustrous crystals of iron-rich olivine were observed to constitute a transgressive body in layered norites. The unusual mineralogy resulted in this rock-type only being named several years later, i.e., after the discovery of the platiniferous dunite pipes. The descriptor "hortonolite dunite/wehrlite pegmatites" was proposed by Wagner and Mellor (1925) to describe the mineralized core-zones at Mooihoek and Onverwacht. The anomalous occurrence of discordant bodies comprised of both iron-rich dunite (±wehrlite) and normal (or magnesian) dunite accounts for the unorthodox nature of the terminology.

Categorization of Discordant Bodies

The methodology proposed Viljoen and Scoon (1985) has been incorporated into the mining industry and applied to independent verifications of ore resources for stock exchanges. One reason for this is that the discordant bodies can sterilize layered orebodies over large areas and the identification of the diverse types of bodies is significant.

Iron-rich ultramafic pegmatites (IRUPs)

IRUPs are the most abundant of the distinct categories (Viljoen and Scoon, 1985; Scoon and Mitchell, 1994). The coarse-grained texture and dark coloration of the ferromagnesian minerals (olivine <Fo_{50}; augite Mg number <66), together with the presence of abundant Fe-Ti oxides, is diagnostic. Plagioclase is absent from the core-parts of the IRUPs, although recrystallized grains and aggregates occur in contact zones.

The IRUPs incorporate the aforementioned hortonolite dunite/wehrlite pegmatites together with the magnetite-bearing pegmatites described by Cameron and Desborough (1964), and the Ti-magnetite pipes. The inclusion of the Ti-magnetite pipes follows the approach of Willemse (1969). The latter is consistent with the envelopes of IRUP (+disseminated Fe-Ti oxides) which enclose the massive oxides, e.g., at Kennedy's Vale (Scoon et al., 2017).

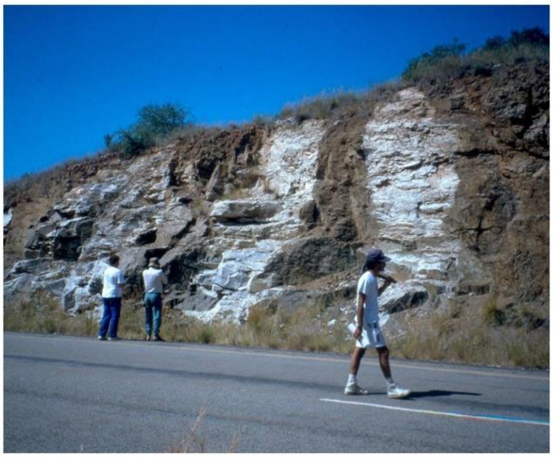
The IRUPs form highly irregular bodies, including satellites of large disk-like features, and subconcordant sheets. Field relationships demonstrate that the IRUPs formed by the passive replacement of the host stratigraphy, on a near volume-for-volume basis (Wagner, 1929; Cameron and Desborough, 1964; Viljoen and Scoon, 1985). The passive replacement of the host wall rocks by the IRUP may impact mining of the layered reefs. This includes the phenomenon known as "Replaced Merensky Reef," first recognized at Eerste Geluk (Wagner, 1929).

Magnesian Dunite Pipes

This category of the discordant bodies is dominated by a non-pegmatitic assemblage of olivine (Fo_{85-82}) and accessory Cr-spinel (Wagner, 1929; Hall, 1932; Viljoen and Scoon, 1985). The magnesian dunites generally form pipe or stock-like bodies (diameters 100-300 m) aligned perpendicular to the primary layering. The pipes are deep-rooted and may be enveloped by irregular masses of harzburgite or pyroxenitic pegmatites. The presence of outer envelopes may increase the diameter to >1 km. The pipes are disruptive as wall rocks may be catastrophically downwarped, leading to the dismembering of layered orebodies.

Pyroxenite Pegmatites

These are a poorly understood category of the discordant ultramafic bodies, and several types or associations may be recognized. The clinopyroxenite pegmatites (or "diallagite pegmatites" of Wagner, 1929) are found in association with the magnesian dunites. Clinopyroxenite pegmatites at Tweefontein emanate outwards from a small body of harzburgite (Tegner et al., 1994). The orthopyroxenite pegmatites are less common but have been reported in association with the magnesian dunite pipes at Maandagshoek (Gain, 1985).



Discordant clinopyroxenite pegmatites, Tweefontein

Platiniferous Dunite Pipes

This is a specialized category of the discordant bodies. The spatial association of magnesian dunites and IRUPs has resulted in large pipes with a well-defined, semi-concentric zonation. The IRUPs are constrained to small, carrot-shaped bodies (they peter out with depth) contained with magnesian dunite pipes. Large irregular outer envelopes are also recognized. They are restricted to four occurrences: Driekop, Mooihoek, Onverwacht and Twyfelaar.

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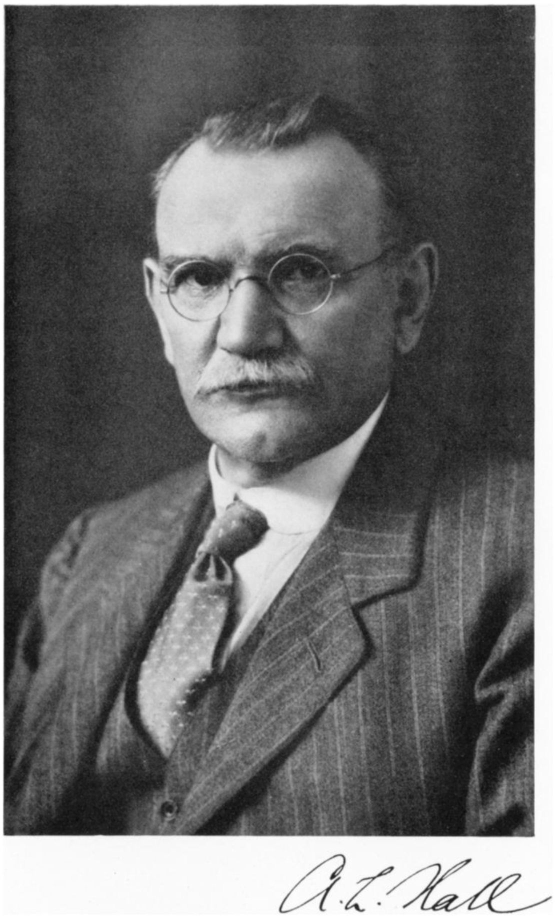
7. Three Famous Bushveld Geologists

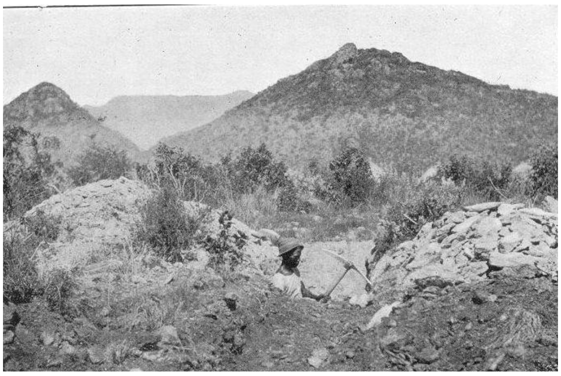


Arthur Lewis Hall (1872-1955) was born in England, partly educated in Germany, but spent most of his life in South Africa at the Geological Survey (Haughton, 1956; Anhaeusser, 1997; Scoon and Viljoen, 2019). The mapping undertaken by Hall over a period of 29 years, much of it in the remote Eastern Limb was a major achievement. The Memoir of the Geological Survey compiled by Hall (and published in 1932) is a significant publication. Descriptions of the field relationships remain unsurpassed. The following quotation is from the Memoir:

Percy Albert Wagner (1885-1929) was born in Richmond, South Africa, and educated in Cape Town. Wagner was described in obituaries as South Africa's greatest mineralogist and geologist (Bateman, 1930; Du Toit, 1930; Rogers, 1930; Spencer, 1930). Primarily, an economic geologist with the Geological Survey, Wagner had access to the opening up of many of the mineral deposits in the Bushveld. Wagner had a particular interest in the pipe-like deposits of platinum (Wagner, 1926a-b) and of tin (Wagner, 1927). Wagner's book "*The Platinum Mines and Deposits of Southern Africa*" (1929) remains the only comprehensive description of the platinum deposits in the Bushveld Complex.

"Panning platiniferous ground close to the fabulously rich platinum pipe at Onverwacht. Dr Merensky is third from the right" (Caption and photograph: Lehmann, 1955). The Onverwacht pipe occurs on the western slopes of a low, bushy ridge to the east of the Moopetsi Valley (view looking north).

Hans Merensky (1871-1955) was born at Botshabelo, a mission station established by Alexander Merensky. The meaning is "Place of Shelter" or "Sanctuary." The German explorer Carl Mauch was reported to be a regular visitor. In 1882, the Merensky family resettled in Germany where Hans qualified as an economic geologist and mining engineer. Hans returned to South Africa to follow a career which included discovering numerous major ore deposits, both in the Bushveld Complex and in Namibia (Lehmann, 1955). Hans Merensky is probably most well-known for his role in the discovery of the economic platinum deposits in the Eastern Limb. The details are recounted below. An unusual sequence of events can be added to the story as the discoveries occurred in the same locality where Han's parents had fled the Sekhukhuneland uprising. Whilst fleeing south-eastward from the mission station at Garatouw, Alexander Merensky and his family would have traversed Maandagshoek.



Historical photograph of trenching on the Merensky Reef at Winnaarshoek (from Wagner, 1929)

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8. Discovery of the Platinum Deposits in the Eastern Limb

Chromite
The discovery of economic deposits of platinum in the Bushveld Complex was preceded by the identification of chromitites in Sekhukhuneland (Wagner, 1923). The discoveries in the Eastern Limb were assisted by the outcrops of the orebodies. Moreover, the completion of the geological map of the region, by Hall in 1911, played a key role. The chromite mines in this area exploit the metre-wide LG6 chromitite, or "Steelpoort seam", described by Cameron and Desborough (1969) as "one of the world's great orebodies". The earliest surface workings on the LG6 have ben dated to Goudmyn (1916) and Mooihoek (1917) (Gräbe, P-J., 2003). The first underground workings on the LG6 are traced to the Winterveld Chromite mine, which started in 1931 (adjacent to the Onverwacht pipe). The mining at Jagdlust, despite the deposits being known since at least 1918, commenced in 1936.

Platinum: early reports
The earliest report of platinum in the Bushveld Complex is from the Rustenburg area, where William Bettel, in 1906, reported the presence of 1.8 g/t Pt in an olivine gabbro (as recounted by Bettel, 1925). This was followed by the recognition of Pt in chromitites from Sekhukhuneland (Hall and Humphrey, 1908). The maximum assay reported was 2.3 g/t Pt. Hans Merensky obtained the samples, possibly at Jagdlust. The fineness of the platinum minerals in the richest of the two chromitites – which may have included the UG2 - was not amenable to beneficiation.

During the period when the chromite deposits were being evaluated, many geologists, including Hall, Humphrey and Wagner, were convinced substantial deposits of platinum would be discovered in the Bushveld Complex, as discussed with supporting references by Lombaard (1945) and Scoon and Mitchell (2004a). This was in part based on similarities with the geology of the Urals, Russia, the primary source of PGE prior to opening up of the Bushveld deposits.

Lydenburg Platinum Syndicate
Many of the platinum discoveries in the Eastern Limb are accredited to Hans Merensky and his "Lydenburg Platinum Syndicate" (LPS) (Wagner, 1925a-d; Lehmann, 1955; Worst, 1991; Cawthorn, 1999; Scoon and Mitchell, 2004a). The sequence of events is relatively well established although there is some debate as to exact dates and the methodology applied by Merensky (Scoon and Mitchell, 2005). The details summarised here are supported by reports from the popular mining press of the time, including by Hans Merensky (1925a; 1925b), as well as editorial commentary (e.g., Anonymous, 1925a; 1926b).

The events commenced in mid-1924 when Andries Frederik Lombaard, a local farmer and experienced gold prospector panned an ephemeral stream at Maandagshoek. The date of the panning has not been established but is liable to have been early June (Lombaard, 1945). A. F. Lombaard was born in the nearby town of Lydenburg, in 1877, but had settled at Maandagshoek in 1920 after marrying Sara Maria Schoeman. The streams, or spruits, at Maandagshoek are part of a braided river pattern in a broad valley associated with the Moopetsi River. The valley attests to an earlier, far wetter climatic regime when the rivers draining the Leolo Mountains carved out the less resistant strata of the upper part of the UCZ and the LMZ. The river systems have altered in recent years due to the changing land usage and exploitation from drill holes. The streams in the southern part of Maandagshoek, rather than flowing northward as part of the Moopetsi and Motse system, flow southward to join the Steelpoort River. Merensky's 1925 map, as well as the map prepared by B. V. Lombaard in 1935, indicates the stream panned by A. F. Lombaard was located in the southern part of Maandagshoek, close to the farm house.

The "heavy, silver-coloured stuff in the pan" was identified by A. F. Lombaard as platinum.

This was tentatively confirmed several days later by a local attorney, H. C. Dunne, in Lydenburg. Dunne dispatched the sample Dunne (accompanied by a letter dated 4 June 1924) to the consulting offices of Hans Merensky in Johannesburg (Lombaard, 1945). Merensky obtained an assay that reported native Pt and Au, together with iron oxide and traces of Rh and Ir.

After receiving the analysis, Merensky visited Maandagshoek – an area he was already familiar with - together with a colleague, F. P. Holleman on 12 June 2024. The confirmation of the regional geology as being part of the "norite belt" of the Bushveld Complex was encouraging. Merensky requested A. F. Lombaard, together with his cousins Schalk and Willem Schoeman, to continue panning the river beds and soils in the area. On his return to Johannesburg, Merensky formed the LPS with private funds from his close friends. The objective was to locate alluvial and hard-rock PGE ores in the area (Lehmann, 1955).

Discovery of the Dunite pipes

After acquiring some mineral rights titles, Merensky returned to Maandagshoek on 12 August 1924 to find that the Schoeman brothers had panned Pt in soils to the east of the stream. Lombaard (1945) intimates one of the panning sites was close to the boundary of the adjacent farm, Mooihoek. Three days later, on **15 August 1924**, Merensky located Pt in rock chip samples of "dark, lustrous crystalline pyroxenites and ultrabasic rocks" (Lombaard, 1945; Lehmann, 1955). The ultramafic rocks were part of a small koppie situated proximal to the watershed of the Moopetsi Valley. The mineralization was found to be concentrated in a discordant body, rather than a layer. The pipe-like shape of the dunites and wehrlites was, however, ascertained at a later stage, as discussed by Scoon and Mitchell (2004a). The pipe was originally named the "Merensky pipe" but the name was subsequently changed to the

Mooihoek pipe.

The high grade of the orebody at Mooihoek was determined by panning and weighing the concentrate. The assays were sufficiently encouraging as to cause Merensky to travel to Barberton to register a claim with the Mining Commissioner. The laws covering mineral rights in South Africa at the time were complex, and Mooihoek was a government-controlled title on which claims had previously been acquired for the chromite deposits. The LPS took out claims over the pipe.

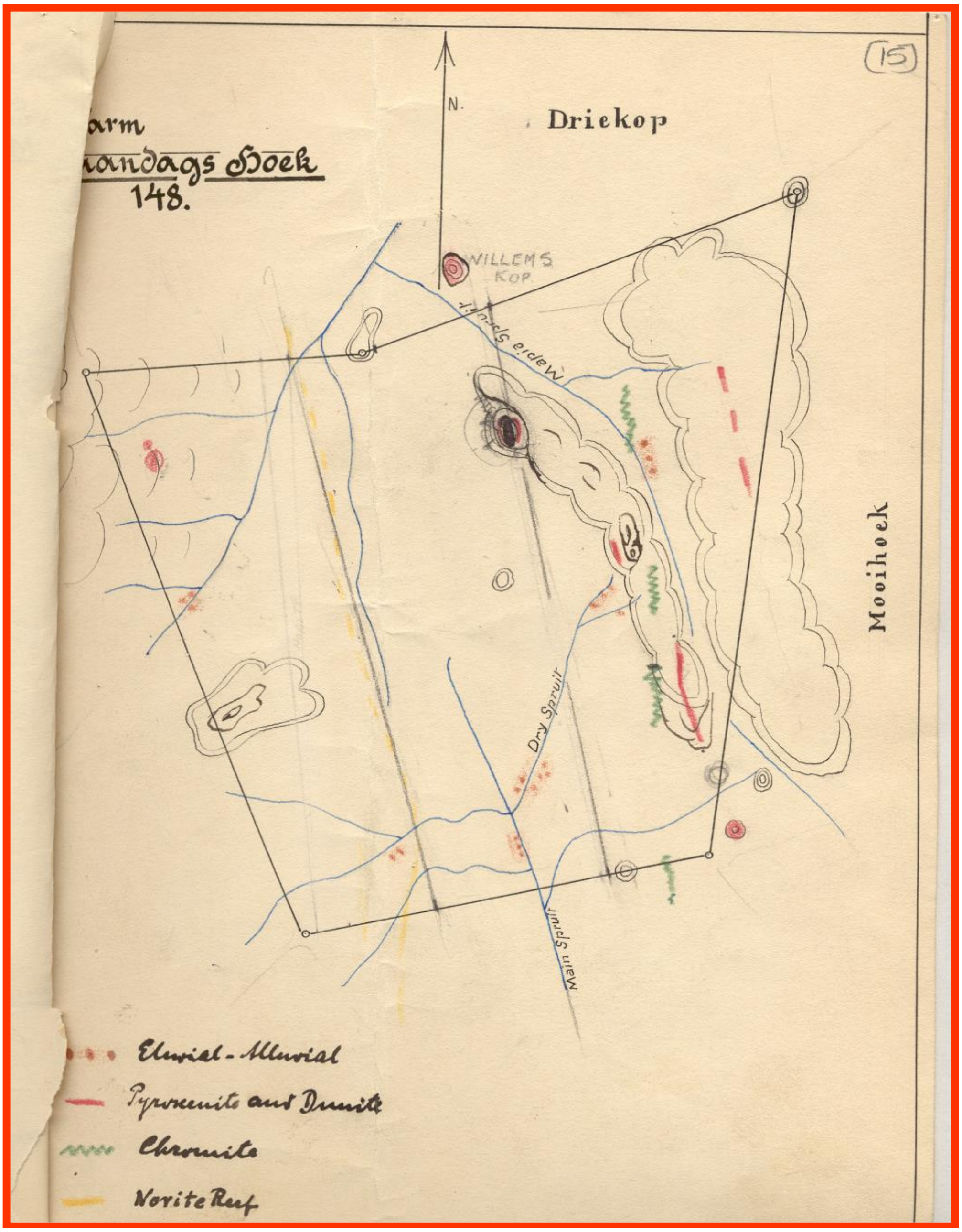
The **Driekop pipe** was discovered by Willem Schoeman, on behalf of the LPS, on 18 August 1924. This was based on recollection of observing similar rocks on the slopes of Khubetswane, a rounded koppies situated to the north of Mooihoek. The koppie was temporarily named "Willemskop." At approximately the same time, the LPS located the low-grade **Twyfelaar pipe** (Scoon and Mitchell, 2004b).

The **Onverwacht pipe** was discovered by geologist Frederick W. Blaine of Rand Mines. The date of the discovery has generally been established as 10 October 1924. Lombaard (1945) questioned this, in part based on evidence of the Mining Commissioner as quoted in the article. There is a suggestion all of the discoveries in the region occurred in August 1024 and there had been attempts to change the dates to ward off rivals. The discovery of the dunite at Onverwacht was based on a field program which included panning of concentrates and identification of small nuggets in the ephemeral stream located west of the pipe.

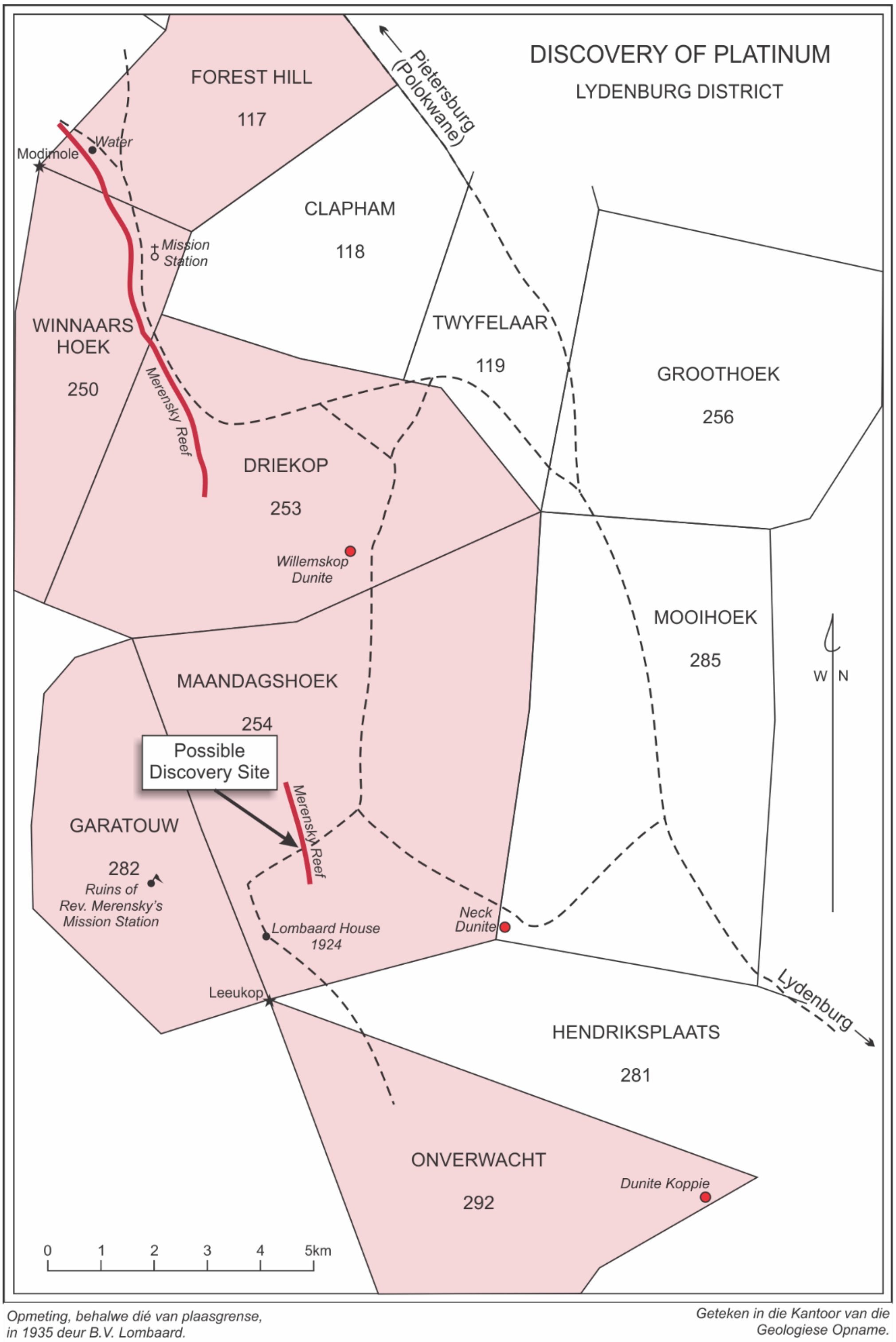
Discovery of the Merensky Reef

Hans Merensky was aware that the dunite pipes were discordant bodies of limited size, and was convinced that the layered rocks, specifically the pyroxenitic layers, which may contain secondary Cu, were a far more important target. Accordingly, A. F. Lombaard, on behalf of the LPS, made the "far more important finding" of a layered reef in the southern part of **Maandagshoek** (Wagner, 1924; Lombaard, 1945; Lehmann, 1955). Most reports intimate the reef was discovered in September 1924, but Lombaard (1945) has suggested the discovery was made in August.

Historical assays obtained by the LPS reported grades of 3.1-6.2 g/t combined platinum-group elements and gold in the Merensky Reef. A copy of the original map from the Hans Merensky archives, Westphalia, depicts details of the region (map presented here and on the cover of the South African Journal of Geology, volume 102). The exact location of the discovery site has not been determined. Despite Lombaard having undertaken the rock chip sampling, the LPS insisted the provisional name be changed from the Lombaard Reef to the "Merensky Reef" (Lehmann, 1955).



Sketch Map of Maandagshoek by Hans Merensky (1925). Features of interest are as follows: (i) Ephemeral nature of the streams and rivers in the Moopetsi Valley; (ii) Location of the alluvial and elluvial panning; (iii) The platiniferous dunite pipes at Mooihoek and Driekop shown as red circles; (iv) Unmineralized pipes at Maandagshoek; (v) Chromite is the UG2 (see map of Gain, 1985); (f) Merensky Reef depicted as the "Norite Reef"; (vi) Exact location of the Merensky Reef discovery site not shown



Copy of map prepared by B. V. Lombaard in 1935 (Lombaard, 1945). The discovery of an economic platinum deposit in the dunite pipe at Mooihoek, by Hans Merensky and his Lydenburg Platinum Syndicate on 15 August 1924, is one of the most significant geological events in South Africa. This was followed by discovery of the dunite pipe at Driekop ("Willemskop") with identification of the Merensky Reef, at Maandagshoek, accredited to A. F. Lombaard. The Onverwacht pipe was discovered by F. W. Blaine (Rand Mines). Note use of new farm numbers. Translations from the original map (in Afrikaans) by Bennie Cilliers

Wagner (1929) referred to the Merensky Reef as the "Mother Lode". The LPS delineated the reef northward which was found to outcrop extensively on Driekop and Winnaarshoek. The continuity of the orebody to the south of the Steelpoort River, including at Dwarsriver, occurred in the first days of October 1924. Several months later, the LPS located the Merensky Reef in the Western Limb, as well as the lateral equivalent, i.e., the "Platreef," in the Northern Limb.

Platinum Rush

By early 1925, news of the platinum discoveries circulated, and a claims rush ensued. Large sections of the Bushveld Complex were prospected. This included the remaining extent of the farm Mooihoek, which was made available by the government (Anonymous, 1925b). Prospecting activities included core drilling of the dunite pipes and opening up of numerous trenches and declines on the Merensky Reef (Wagner, 1925c-e; 1926a-b: 1927; 1929).

No additional mineralized pipes have been discovered in the Bushveld Complex, despite the subsequent recognition of numerous discordant bodies.

A historical building known as "Merensky's Office" at Driekop is constructed of dressed blocks of anorthosite

Historical Mining

The mid-to late 1920s was a short-lived boom when the Pt price was five times that of gold. Mining commenced at the Onverwacht pipe in 1926. This was the first of the platinum deposits in the Bushveld Complex to be exploited (Scoon and Mitchell, 2010). The mine was established by Rand Mines. The orebody at Onverwacht was accessed by a vertical shaft. A processing plant was built on site. With the exception of small-scale workings in the Urals, Russia (Kovaloff, 1925), Onverwacht may constitute the worlds' oldest underground platinum mine.

Evaluation of the Mooihoek and Driekop pipes, and of the Merensky Reef, the latter having been pegged over several tens of km of strike by the LPS, required a refinancing and registration of "Lydenburg Platinum Ltd" (Merensky, 1925c; Lehmann, 1955). In 1925, the company was purchased by the Gold Fields mining group and floated on the Johannesburg and London stock exchanges. Lydenburg Platinum established mines on the dunite pipes at Mooihoek and Driekop in 1927, the ore being processed at a central concentrating plant located at Maandagshoek. Part of the slimes dam at Maandagshoek can be observed, as can the shaft foundations at Mooihoek. The adit and glory hole depicted by Wagner (1929) are accessible at Driekop.

Trial mining of the Merensky Reef was achieved on the back of profits from the two dunite pipes, although this proved problematic due to lower grades, higher mining costs, and metallurgical issues (Wagner 1929). Trenches and underground workings from this period can be examined at several localities, including at Winnaarshoek where an extensive network of on-reef declines and drives have been refurbished (Mitchell and Scoon, 2007).

The collapse of metal prices in 1929 due to the worldwide depression resulted in closure of all of the platinum mines in the Eastern Limb. The Driekop pipe was reopened for a brief period in the 1950s. Mining of the Merensky Reef in the Eastern Limb was delayed until the 1970s. Most current mining operations in the Eastern Limb exploit the UG2 Reef.

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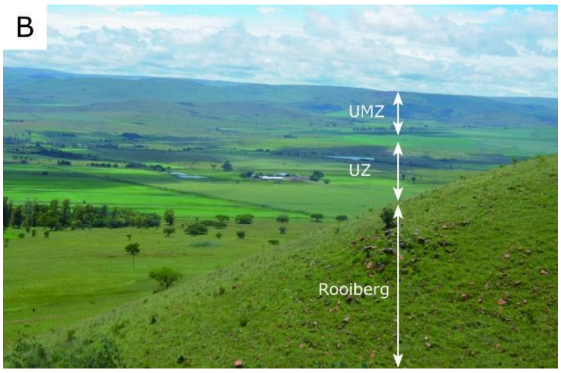
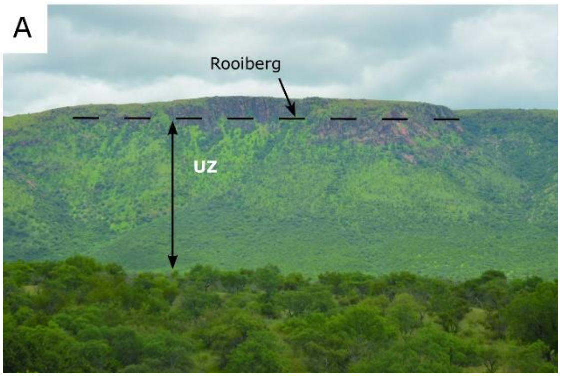
EL-1 Views of the Eastern Limb

The main road from Middleburg to Steelpoort traverses the regional plateau prior to descending into the Eastern Limb near Stofberg. The Rooiberg felsites can be observed on the west side of the road with boulders of granophyres (roof rocks) visible near the base of the pass. The UZ occupies a broad, fertile valley.

To the north of Stofberg, the road cuts across the UZ. Outcrops of Ti-magnetite can be observed. The distinctive red soils are emphasized. In the vicinity of Roossenekal (note cultural heritage), the strip mining of the Main Magnetite Layer is visible. The mine site was formerly operated by Highveld Steel and Vanadium.

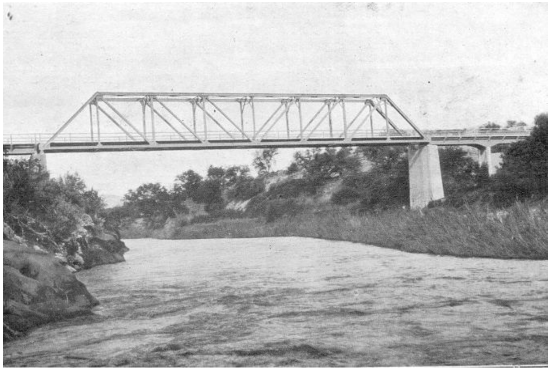


Gentle landforms in the Southern Sector have resulted in the UZ occupying a broad, fertile valley.



The planar nature of the roof contact with the Rooiberg Group (felsites) and the UZ is clearly visible in the Bushveld Escarpment at Tygershoek

As the road descends into the Steelpoort Valley, views of the Bushveld Escarpment open out to the west. The planar nature of the roof contact, i.e., between the UZ and the Rooiberg felsites is apparent.

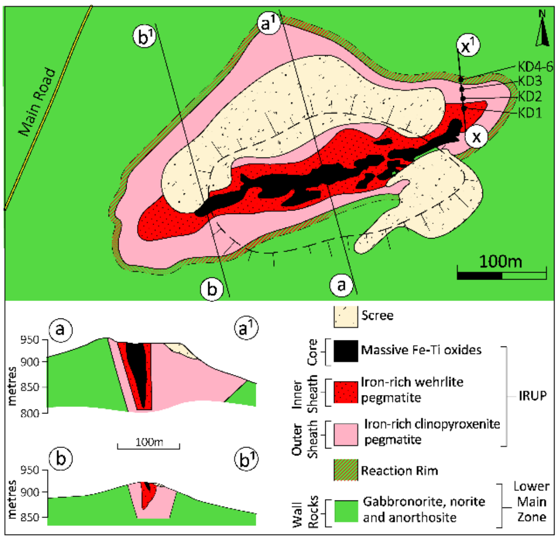


The "Steel Bridge" which gave rise to the name of the Steelpoort River was constructed in the late 1920s. Historical photograph from Wagner (1929)

View looking east from the main road south at Annex Grootboom showing part of the disjointed range of koppies on the eastern side of the Steelpoort Valley. The hills are comprised of the LCZ and UCZ; the MPS may be observed in some localities. The chromite mine exploits the MG layers from both an open pit and underground workings

EL-2 IRUPs at Kennedy's Vale and Spitskop

To the east of the main road, next to a large ferrochrome smelter, is the site of the disused **Kennedy's Vale mine**. The orebody occurred as part of a steeply-inclined, dyke-like body, rather than a pipe, which has been almost entirely mined out. The dyke is zoned. The massive vanadium-rich Ti-magnetite and ilmenite occurred in a core-zone enclosed by an outer sheath of IRUPs with disseminated Fe-Ti oxides (Van Rensburg, 1965; Scoon et al., 2017). The orebody was mined from an open pit. The mine operated intermittently between the 1950's and final closure in 2004 at which time the resource had been almost entirely depleted (the dyke peters out with depth). The mine originally produced both pig iron and vanadium, although in recent years the only product was vanadium, extracted by means of chemical leaching



Map and sections of the Kennedy's Vale dyke redrawn from an original by the African Exploration Company

The discordant body at **Spitskop** is situated in the Steelpoort Valley, to the west of the main road between Kennedy's Vale and Steelpoort. The resistant nature of the IRUPs has resulted in a prominent koppie. This exposure includes large aggregates of Ti-magnetite and ilmenite. The shape of the koppie is consistent with the IRUP forming a pipelike body although the depth extent is liable to be limited.

Mining at Kennedys' Vale has resulted in the almost complete removal of the koppie

The characteristic dark coloration of the IRUPs, Spitskop

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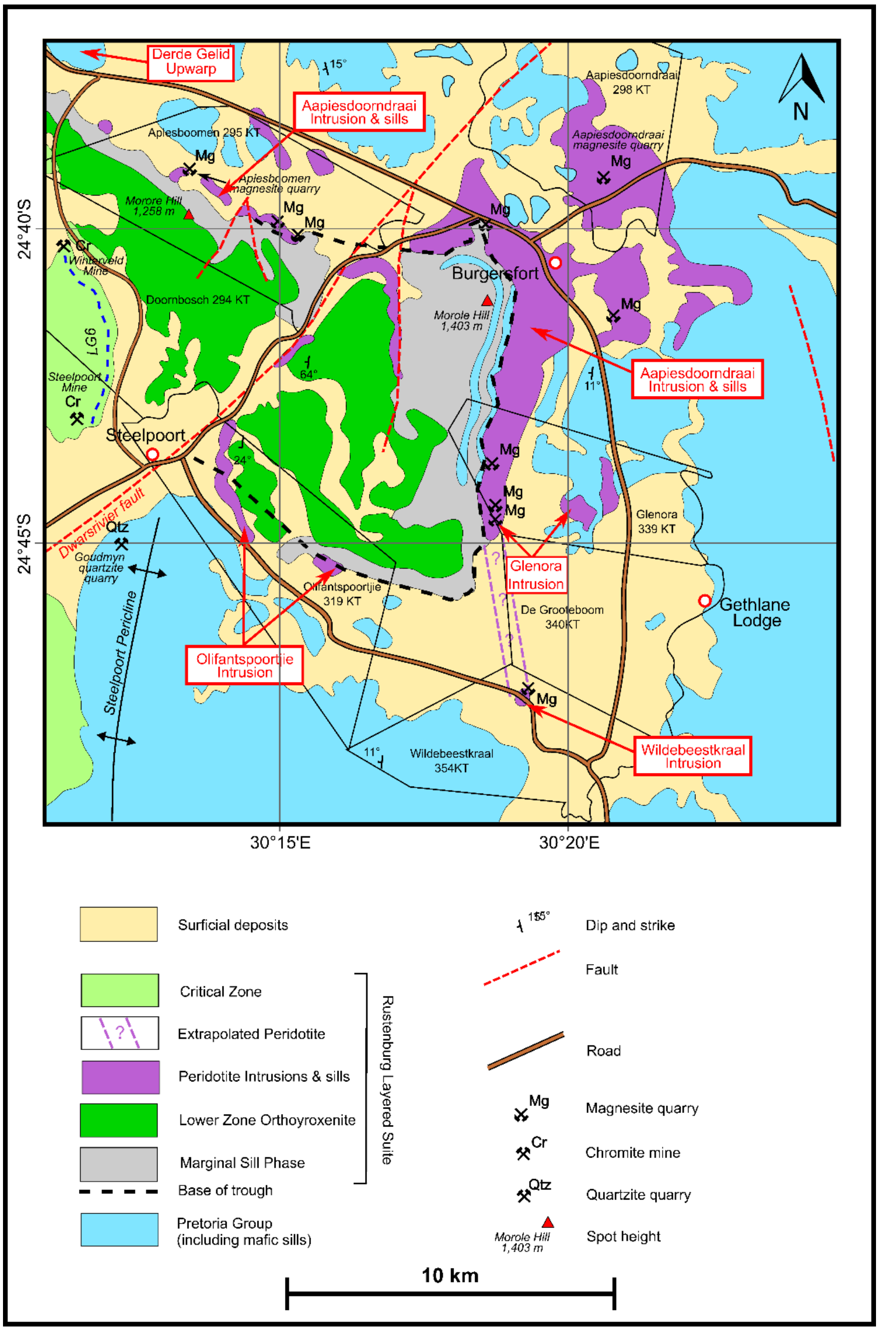
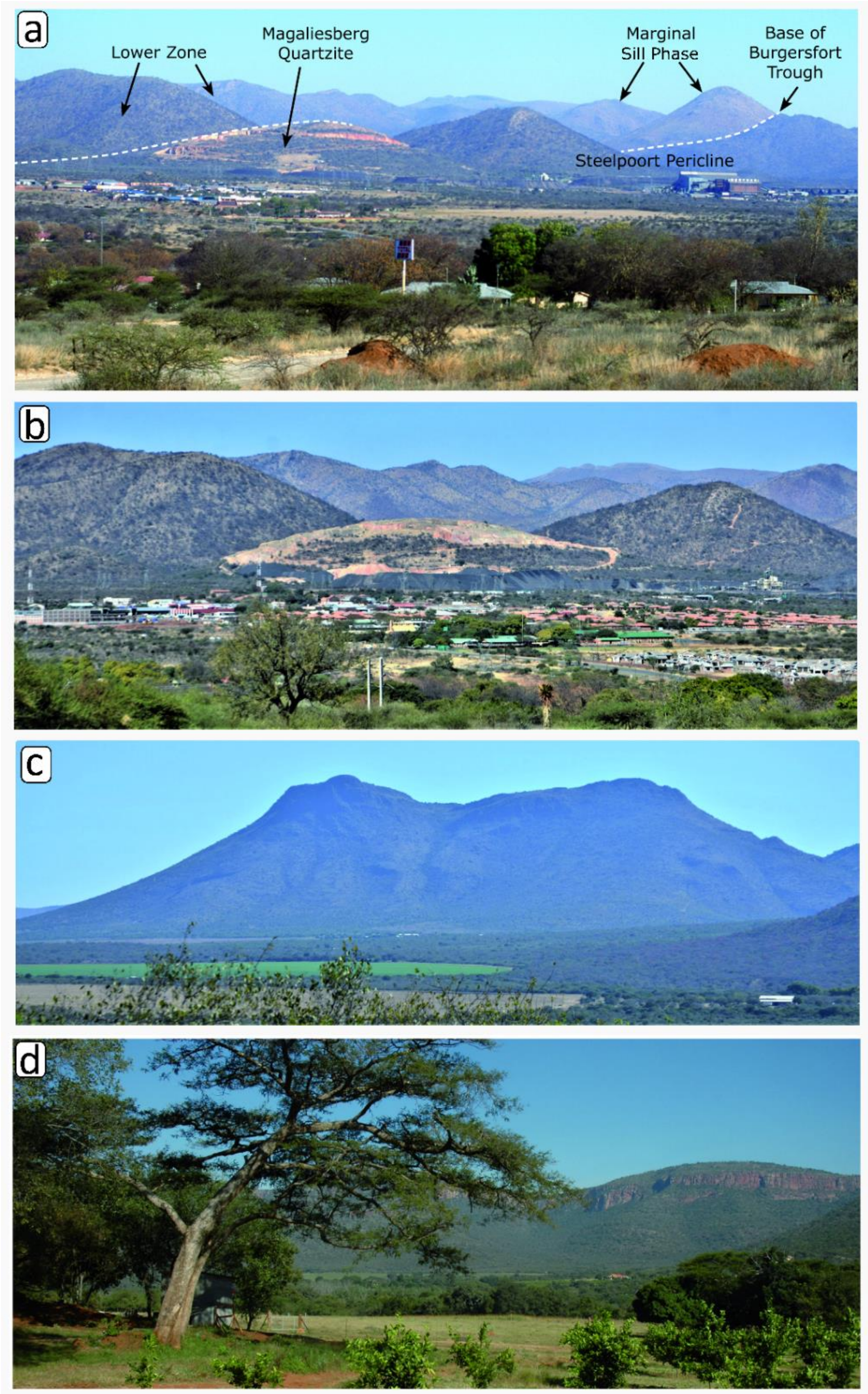
EL-3 Burgersfort Trough



Geological map (in part schematic) of the Burgersfort trough with localities described in the text and selected mines and quarries. The extent of the peridotite intrusions/sills is in part schematic. Simplified from the 1:250,000 scale geological map produced by the Council for Geoscience, as well as the maps of Sharpe and Harmer (1985), Molyneux (2008) and Clarke et al. (2009a)



Views (a) and (b) looking east at Doornbosch towards the Marone Mountains and the southern limit of the Burgersfort trough. Offices of the Eastern Chrome mine (foreground), Tubatse ferrochrome smelter, and the quartzite quarry at Goudmyn visible; (c) View of the MSP at Morole Hill looking west; (d) View looking east from Glenora of the prominent scarps of the Magaliesberg quartzite. The valley in the foreground correlates with sills of peridotite and micropyroxenite.

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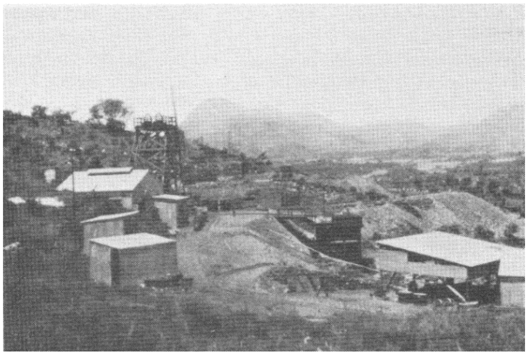
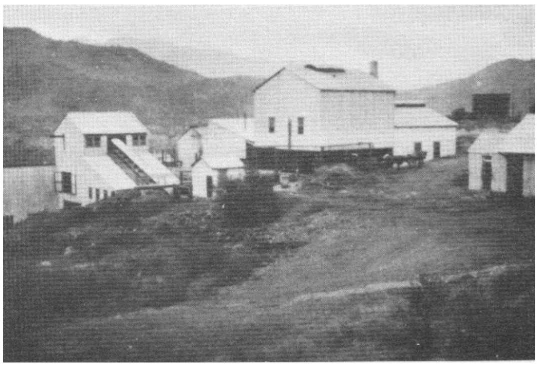
EL-4 Onverwacht Pipe

The Onverwacht pipe is situated on the mine leaseholds of Winterveld Chromite mine (Eastern Chrome mines) and Modikwe Platinum mine. The site warrants preservation as a national monument, as it is the oldest platinum mine in South Africa. The locality is particularly famous as the orebody contained some of the highest grades ever reported (1886 g/t in a hand sample of chromitite-rich ore). In addition, the unusual mineralogy enabled identification of iron-rich olivine and anomalous spinels with compositions part-way between chromite and Ti-magnetite (Wagner, 1929; Frankel, 1942; Lombaard, 1956).

Moreover, the early magmatic hypothesis of Wagner for the dunite component of the pipe provided evidence for the existence of ultramafic melts, prior to discovery of komatiites in the Onverwacht Formation of the Barberton Mountain Land by Viljoen and Viljoen (1969).





Historical photographs of the Onverwacht Platinum mine site and processing plant (probably in 1927) (from Wagner, 1929)

The Onverwacht pipe is emplaced in the LCZ. The layered sequence is dominated by feldspathic orthopyroxenite with outcrops of the LG6, LG7 and MG1 chromitites having been mapped on surface. The dunite pipe is orientated at 78^0 NE, i.e., approximately perpendicular the primary layering. The pipe has disrupted the igneous stratigraphy and dips have been steepened. Structural disruptions have sterilized the LG6 chromitite layer, the principal orebody at Eastern Chrome mines, over a strike length >500 m.

The most comprehensive descriptions of the Onverwacht pipe are by Wagner and Mellor (1925) and Wagner (1929). We are reliant on these early contributions as all that now remains of the orebody is minor offshoots and veins on the edge the glory hole. The dunite on surface is severely serpentinized. Wagner established the depth of alteration to correspond to the water table.

Scoon and Mitchell (2009) presented the results of new surface mapping. Drill-hole logs provided from the archives of Eastern Chrome mines show the pipe to be semi-concentrically zoned. The unusual nature of the mineralogical-chemical zonation and is emphasized. The three-dimensional shape of the main body of magnesian dunite, which has a diameter of approximately 100 m, has proved difficult to constrain. The central part of the pipe, or stock, is surrounded by gently-dipping sheets, fingers, and lenses that splay outward for several hundreds of meters. The duniet is enclosed by an outer envelope composed of harzburgite. This feature is highly irregular and ultimately merges imperceptibly into the pyroxenitic wall rocks. The small, richly mineralized core-zone forms a downward tapering “carrot-shaped” body. The surface part has been mined out from a glory-hole. The core-zone is zoned: an inner unit of exceptionally coarse-grained iron-rich dunite pegmatite enclosed an outer unit of iron-rich wehrlite pegmatite. Accessory phases include coarse crystals of hornblende and phlogopite, small grains of apatite, and meter-sized lumps of Ti-magnetite-ilmenite.

The existence of two or more assemblages in the pipe, i.e., magnesian dunite and harzburgite (main stock; outer envelope) and iron-rich ultramafic pegmatites (core-zone) has been confirmed by whole-rock data and mineral compositions (Scoon and Mitchell, 2010). The composition of the former is tightly constrained (olivine Fo83-80), whereas the latter exhibit a much broader range (olivine Fo64–44). The presence of irregular slabs of chromitite contained within the central parts of the pipe provide key field evidence. Wagner (1929) interpreted the chromitite slabs as xenoliths of the LG6.

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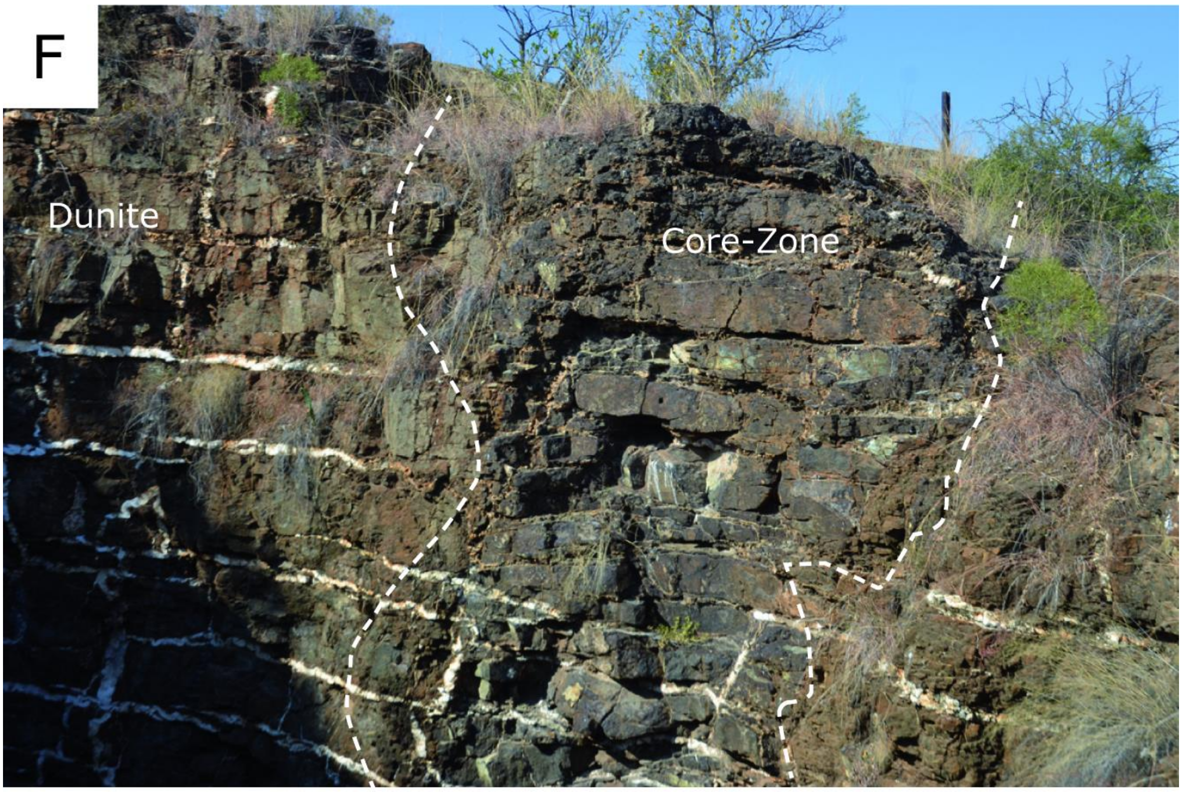
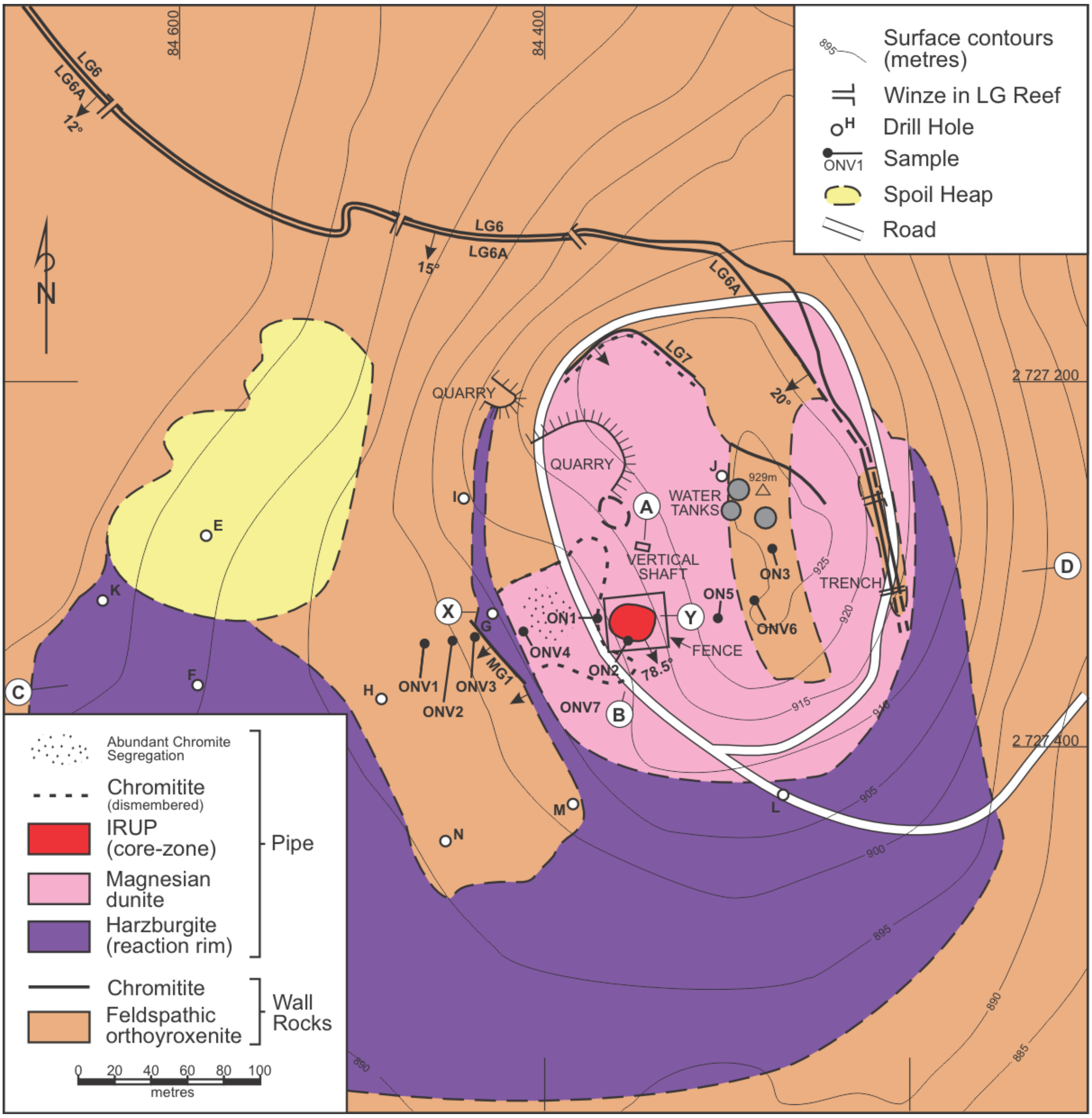
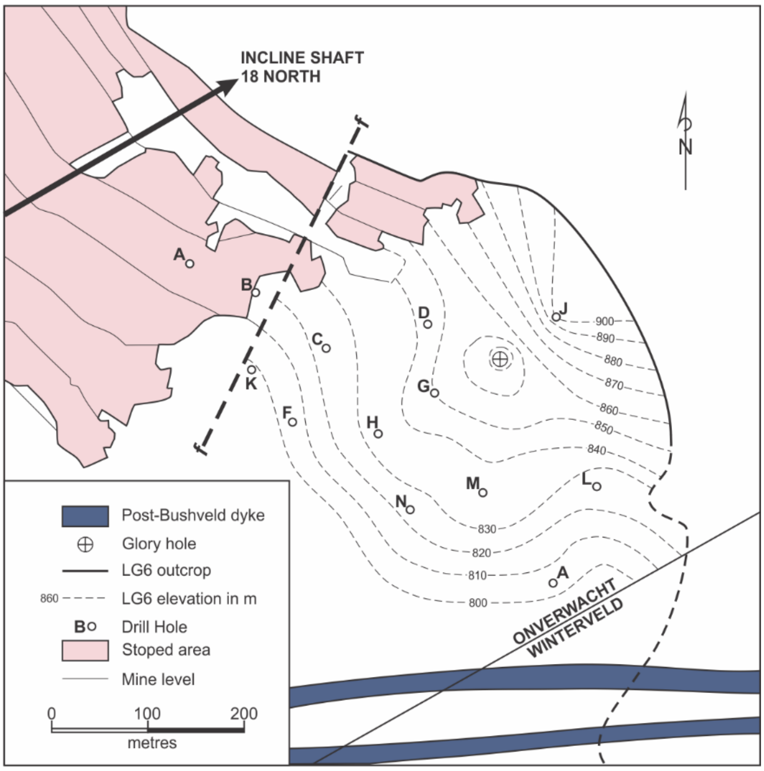


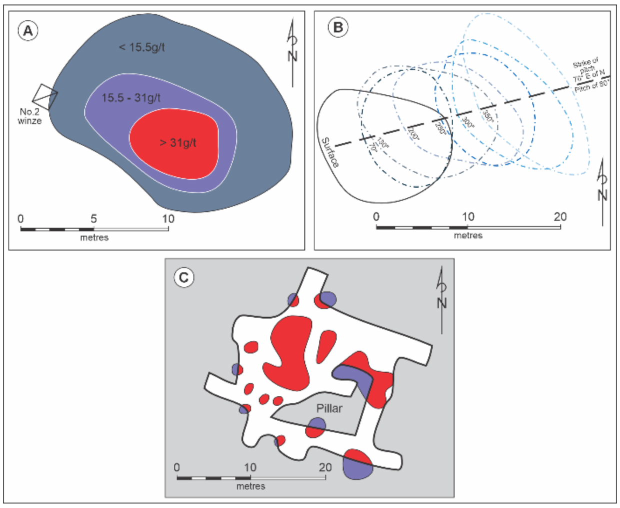
The rim of the glory hole at the Onverwacht pipe is dominated by barren dunite (with reticulate veining of secondary magnesite) but includes a protuberance of the Pt-rich core-zone (dark). This view remains almost unchanged since illustrated by Wagner (1929)



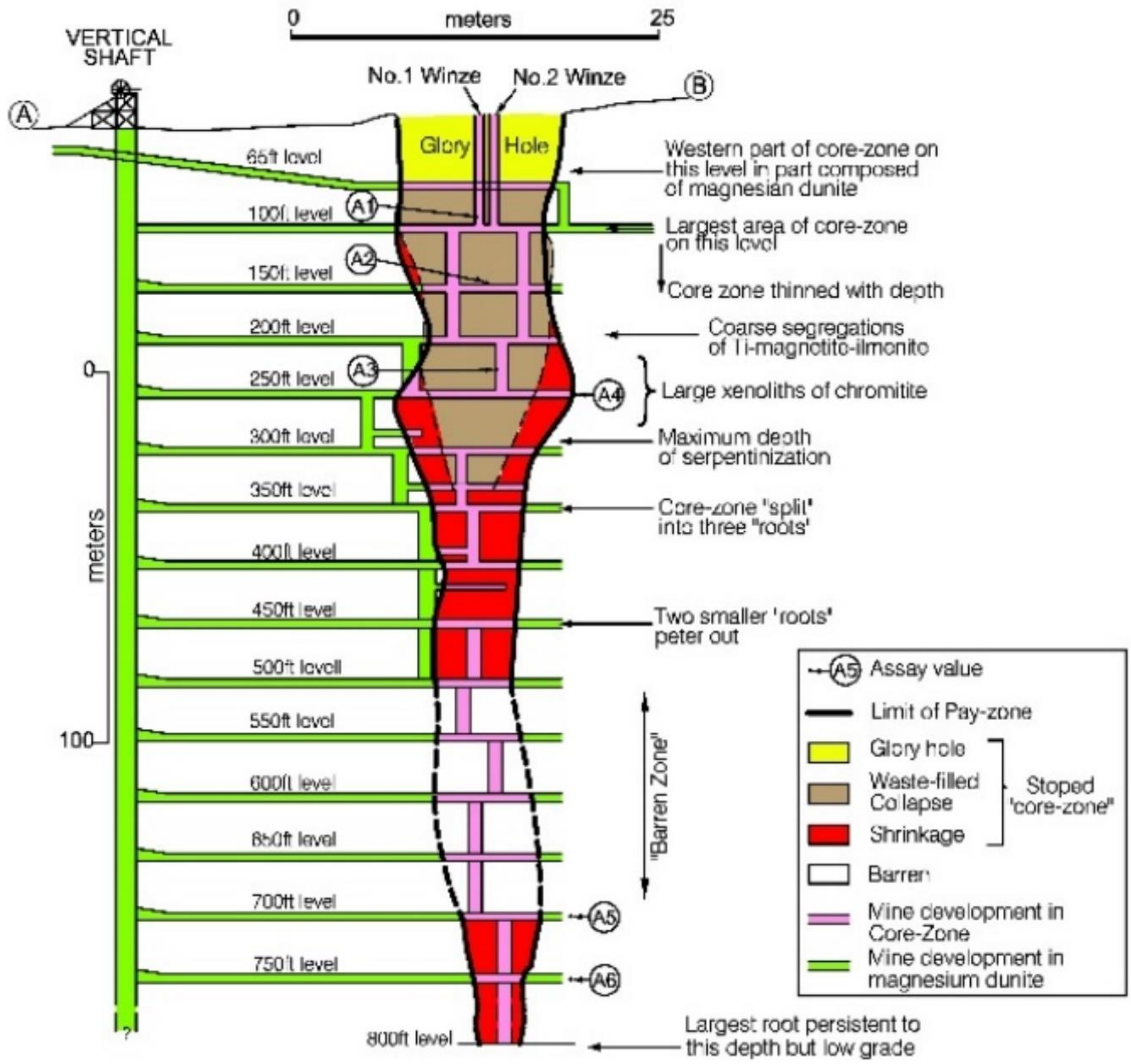
Geological map of the Onverwacht pipe based on surface mapping at a scale of 1:500. Geological features and infrastructure located from the glory hole and roads by means of tape and compass. Base plan and contours from 1:10,000 scale orthophotographs. Drill-hole collars and position of vertical shaft provided by Eastern Chrome mines. Inclination of mineralized core-zone (78.5° at 118°) after Wagner (1929). Perimeter of the pipe estimated from surface outcrops and soil type. AB and CD=section lines presented here; XY=estimated position of section line of Cameron and Desborough (1964). From Scoon and Mitchell (2010)



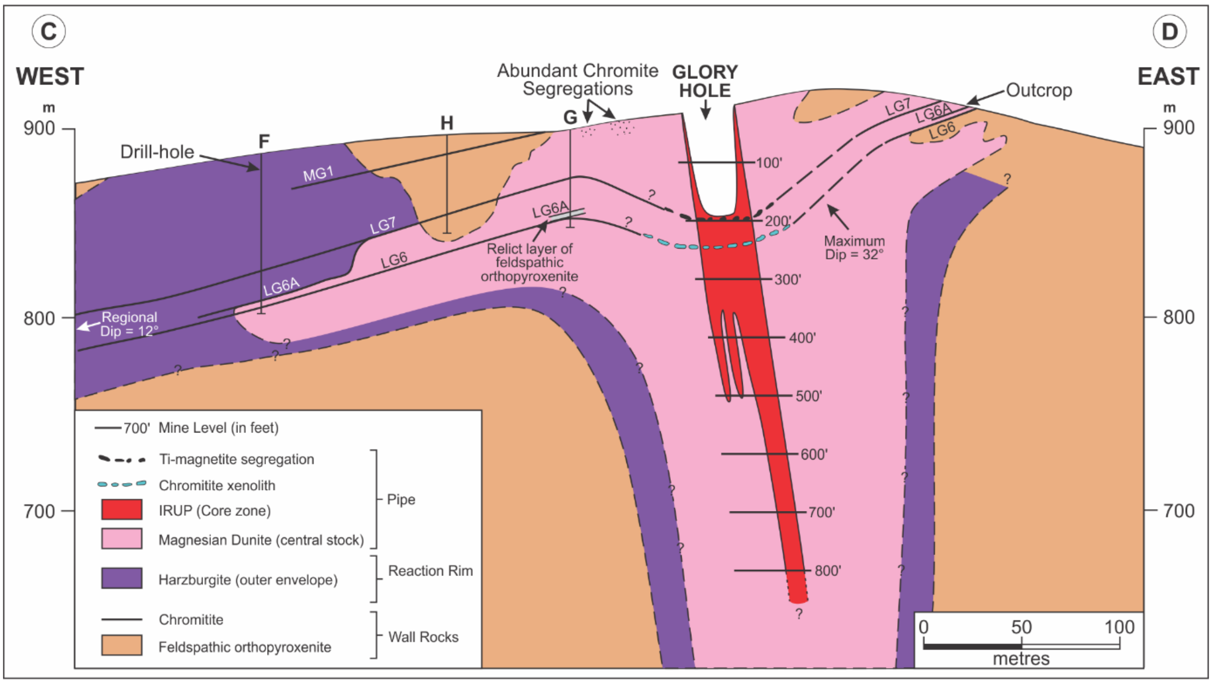
Contour plan showing the location of drill-holes and downwarping of the LG6 chromitite layer in the vicinity of the Onverwacht pipe (in part based on plans provided by Eastern Chrome mines)



(A) Assay plan of the 65-foot level (20 m) showing the concentric distribution of PGE grades and perimeter of the mineable resource in the core-zone at Onverwacht. The highest grades of PGE were associated with the coarsest hortonolite dunite pegmatite in the centre of the core-zone; lower grades occurred partly within an annular ring of slightly less coarse hortonolite wehrlite pegmatite and on the western side partly within the magnesian dunite; (B) Composite plan showing perimeter of the mineable resource (cut-off grade approximately 3g/t PGE) in the core-zone at Mooihoek from surface to the 350-foot level (107m). Wagner recorded that in the upper levels of the mine the mineralization was almost entirely constrained within the hortonolite dunite pegmatite, whereas below the 150-foot level (46m) the core-zone included large bodies of magnesian dunite. Below the 220-foot level (67m) the core-zone was dominated by magnesian dunite with the hortonolite dunite pegmatite restricted to small, irregular bodies. Grades increased uniformly toward the centre of the core-zone, *e.g.* the average grade on the 350-foot level was 10.7g/t but a centre winze contained 65g/t PGE; (C) Plan of the 160-foot level (49m) showing mineable areas (cut-off grade approximately 3g/t PGE) in the core-zone at Driekop. The grade of individual "pay-bodies" varied from 2.3g/t to 84g/t PGE with the higher grades found in association with the segregations of iron-rich dunite-wehrlite; the magnesian dunite was typically barren except within the limits of the "pay-bodies". All orientated north up. After Wagner (1929)



Mine section AB aligned at 012 degrees and looking approximately east based on original document of Onverwacht Platinum Limited with four times horizontal exaggeration. Position of the vertical shaft relative to the glory hole does not conform to the location of the shaft collar on more recent mine plans. The shaft was eventually developed to a depth of 320 m. Geological features from Wagner (1929). Assay values of note (total PGE): A1=214 g/t (sample of iron-rich dunite pegmatite with coarse segregation of phlogopite); A2=31 g/t (average of central part of orebody in upper part of mine); A3=1186 g/t (sample of contact between iron-rich dunite pegmatite and chromitite slab); A4=29 g/t (average of 211 m2 area of core-zone); A5=17 g/t (average of 39 m2 area of core-zone); A6=9.5 g/t (average of 39 m2 area of core zone)



Geological section CD of the Onverwacht pipe aligned at 084° and looking approximately north. Corresponds to the alignment of Wagner's (1929) section. The MG1 and LG6 layers are correlated with Wagner's Upper and Lower Chromitites, respectively. The LG7 was not shown on Wagner's section. The three-dimensional shape of the magnesian dunite and harzburgite is in part schematic, as the contact with the feldspathic orthopyroxenite wall rocks is diffuse. The occurrence of sheets and fingers of magnesian dunite and harzburgite are based on the drill-hole logs. Similar sheets and fingers probably occur at depth but have been omitted due to lack of data. The steepening in the dip of the chromitite layers is based on mapping and drill-hole logs. Interpretation of the chromitite slabs (main stock and core-zone) as xenoliths of the LG6 layer, and of the Ti-magnetite segregations (core-zone) as altered xenoliths of the LG7 layer suggests that these features have been transported downwards. From Scoon and Mitchell (2010)

The outcrop of the LG7 chromitite on the western extremity of the Onverwacht pipe. The chromitite is intercalated with harzburgite (part of the pipe) and is structurally disrupted

EL-5 Mooihoek Pipe

The Mooihoek pipe is the site of the discovery of economic platinum in South Africa. The orebody is the type locality of the “hortonolite dunite pegmatite” (Wagner, 1929). The iron-rich dunite pegmatites, or IRUPs, were the first locality where the Cu-Fe sulphides mooihoekite and haycockite were identified (Cabri and Hall, 1972).

Cabri

The mining site has been modified by development of new houses. Field relationships are rather poorly known. The sections of Wagner (1929) incorporated information from the mine workings (no longer accessible). The core-zone has been almost entirely mined out. The Mooihoek pipe is located in the UCZ. The pipe is concentrically zoned, as shown on the map below, in which four primary units have been identified:

1. Leuconorite, anorthosite, pyroxenite (UCZ wall rocks).
2. Clinopyroxenite and wehrlite pegmatites (outer envelope of pipe).
3. Magnesian dunite (stock-like body).
4. IRUP (core-zone)

References

Cabri, L. J. and Hall, S. R. (1972). Mooihoekite and haycockite, two new copper-iron sulphides and their relationship to chalcopyrite and talnakite. American Mineralogist, 57, 689–708.

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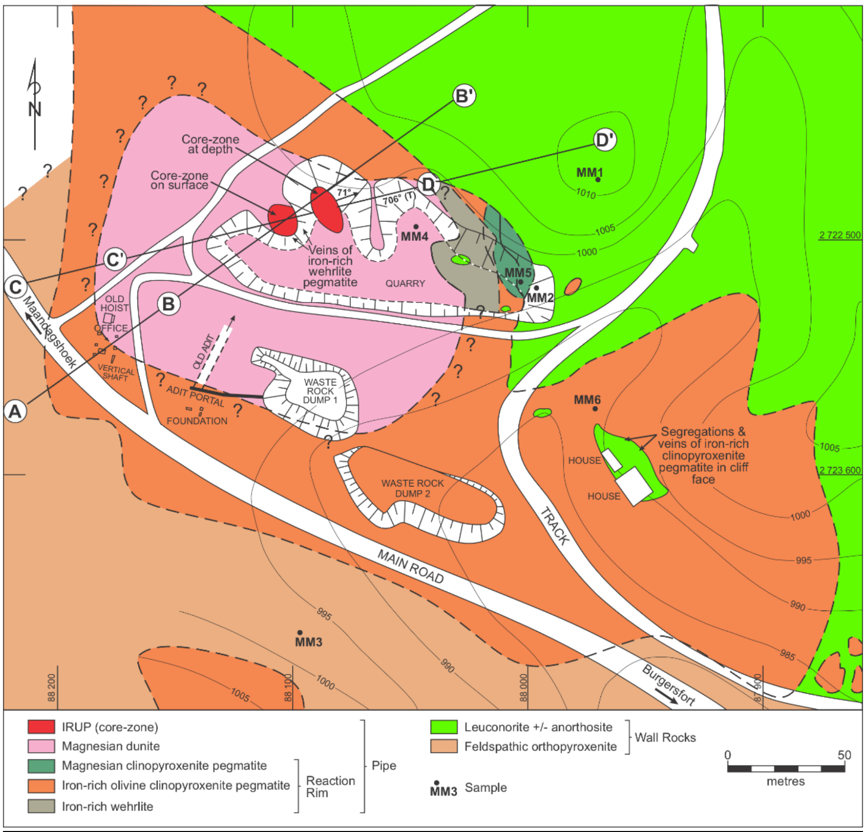
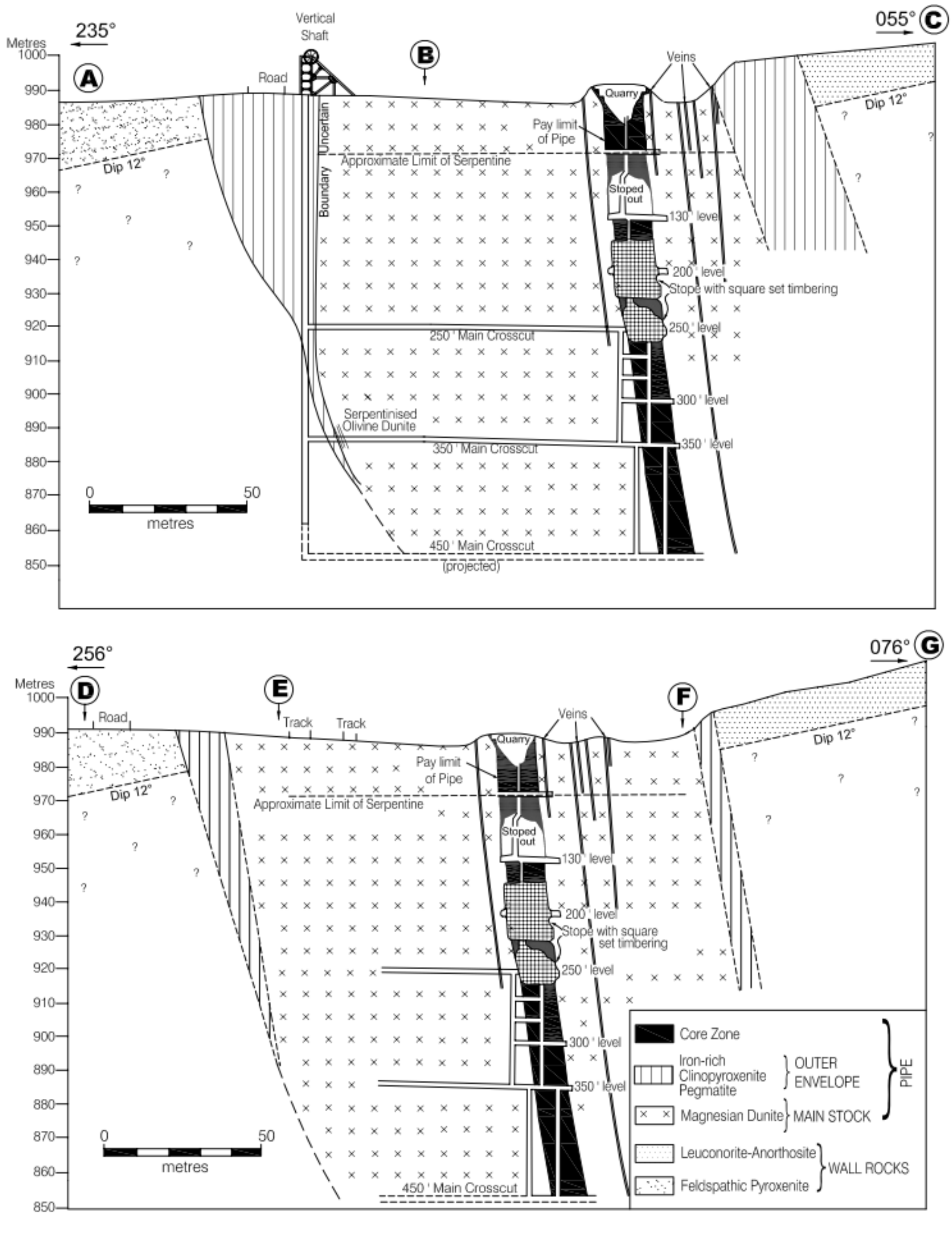
Wagner, P. A. (1929). The platinum deposits and mines of southern Africa: Edinburgh, Oliver and Boyd, 326 p.



Geology of the Mooihoek pipe based on new surface mapping at a scale of 1:500. Geological features and infrastructure positioned by theodolite from a base station surveyed into the South African Local Origin (LO) system using central meridian 31° east. Surface contours in part from new survey and in part from 1:10,000 orthophotographs. Inclination of mineralized core-zone (80° at 076°) after Wagner (1929). Section lines ABC and DEFG. From Scoon and Mitchell (2011)

View of the Mooihoek pipe looking northward. The core-zone was formerly located in part of the quarry, at the foot of the koppie which was partly removed by mining. The Lebalelo Mountains (background) are composed primarily of outcrops of leuconorite and anorthosite, UCZ

Downward protuberances of iron-rich clinopyroxenite pegmatite, part of the outer envelope of the Mooihoek pipe. Wall rocks are composed of leuconorite and anorthosite



Geological sections of the Mooihoek pipe. (a) Section ABC looking approximately northwest. The part labelled AB is from Wagner (1929) and has been re-orientated by reference to position of shaft collar. (b) Section DEFG looking approximately north. The part labelled EF is from Wagner (1929) and has been re-orientated by reference to position of core-zone. Boundary of the core-zone (orebody) defined by pay-limits, as emphasized by Wagner (1929), not by lithology. The cylindrical body of iron-rich dunite and wehrlite pegmatites that define the orebody near-surface thins and degrades with depth ("carrot-shaped")

EL-6 Driekop Pipe

The Driekop pipe was discovered by Hans Merensky and his Lydenburg Platinum Syndicate (Merensky, 1925a; Scoon and Mitchell, 2004b). Mining was initially undertaken by Lydenburg Platinum Ltd. (1927-1930) in conjunction with mining of the Mooihoek pipe. The ore from both localities was processed at the Maandagshoek plant. The Driekop mine was run more recently as stand-alone operation by Otavi Mining (1956-1958). The resource at Driekop, particularly in comparison to the reef deposits, was small. Near-surface ore was extracted from an open quarry, with deeper ore accessed by drives from a vertical shaft. Ore was selectively mined, with waste being hand sorted or retained as pillars (Wagner, 1929). The glory hole that is visible today (open from surface to a depth of 91 m) may have formed by removal of pillars. The in-situ grade was highly variable (2.3 to 84 g/t PGE). The mill feed grade over the life of mine was 4.6-6.2 g/t PGE (Wagner, 1929). The orebody can be observed on the sides of a gallery accessed by the main adit (preserved by Anglo Platinum as an historical monument). Some of the old workings, including the vertical shaft, were reopened by Anglo Platinum (1977–1983) for trial mining of the UG2 layer (Mossom,1977).

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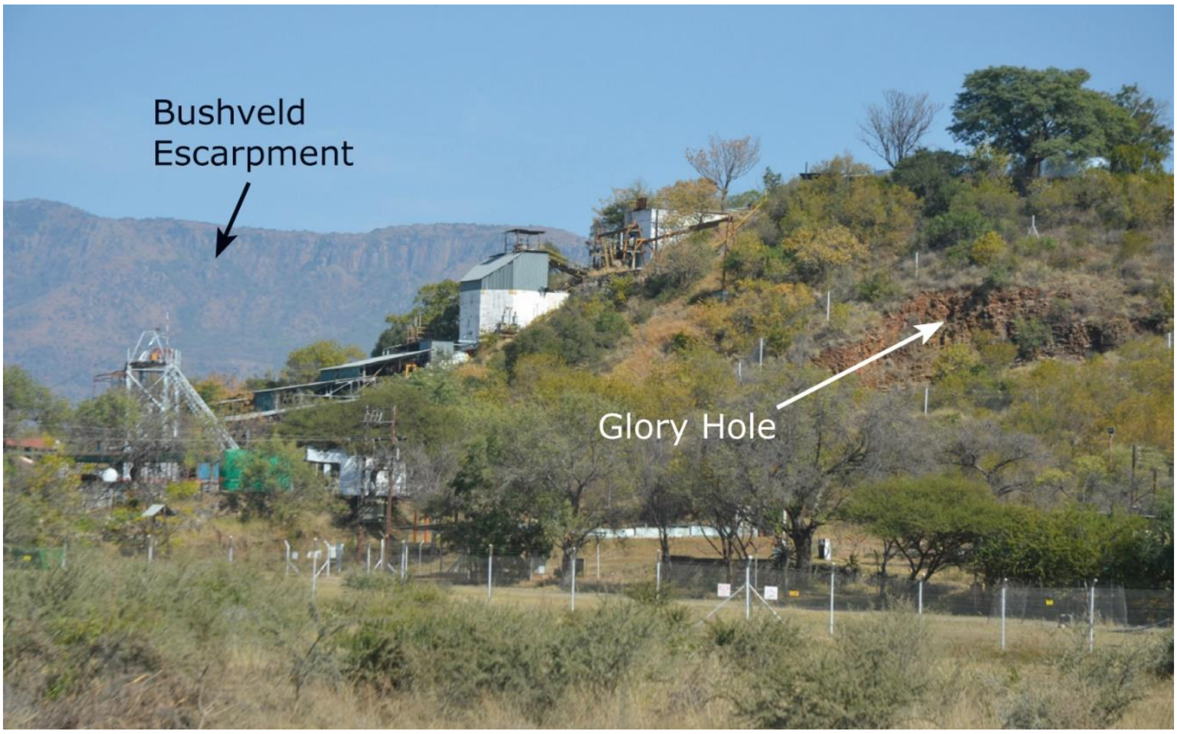
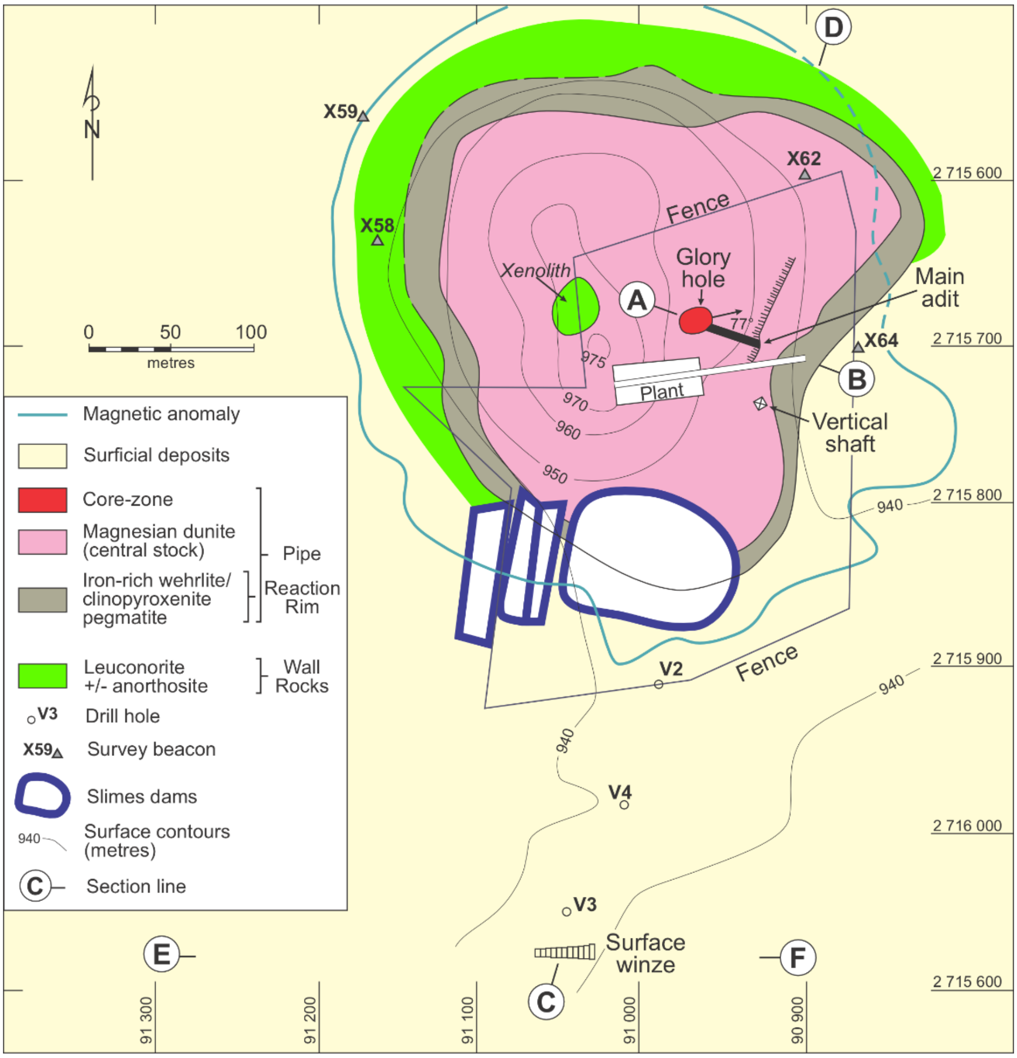
Scoon, R. N. and Mitchell, A. A., 2009, A multi-stage orthomagmatic and partial melting hypothesis for the Driekop platiniferous dunite pipe, eastern limb of the Bushveld Complex, South Africa: South African Journal of Geology v. 112, p. 187–196.

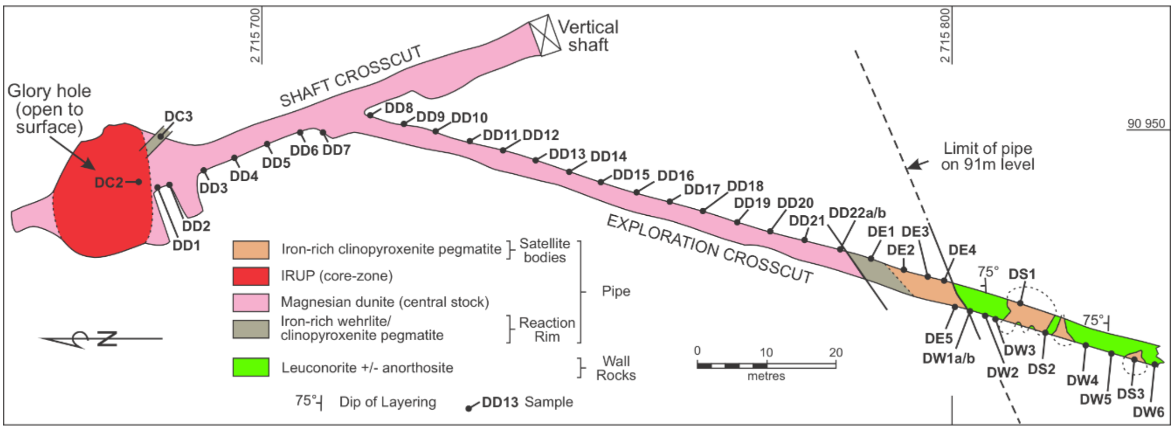
Wagner, P. A. (1929). The Platinum Deposits and Mines of South Africa. Edinburgh: Oliver and Boyd, 326 pp.



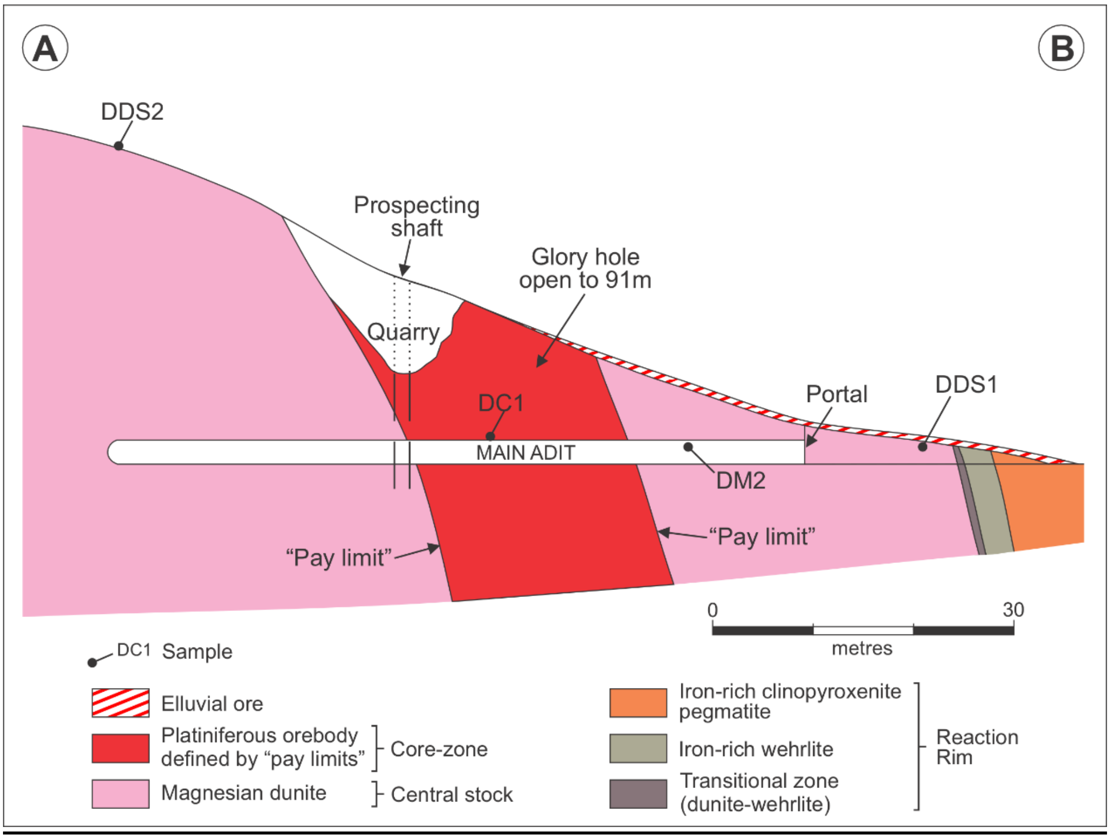
View of the eastern flanks of the Driekop pipe. The resistant nature of the dunite stock has resulted in a koppie, "Khubetswane" (or Willemskop), in the centre of the Moopetsi Valley. The glory hole in the pipe is located asymmetrically. Also visible as is the old shaft headgear and adit portal and some of the plant constructed for trial mining of the UG2. From Scoon and Mitchell (2009)

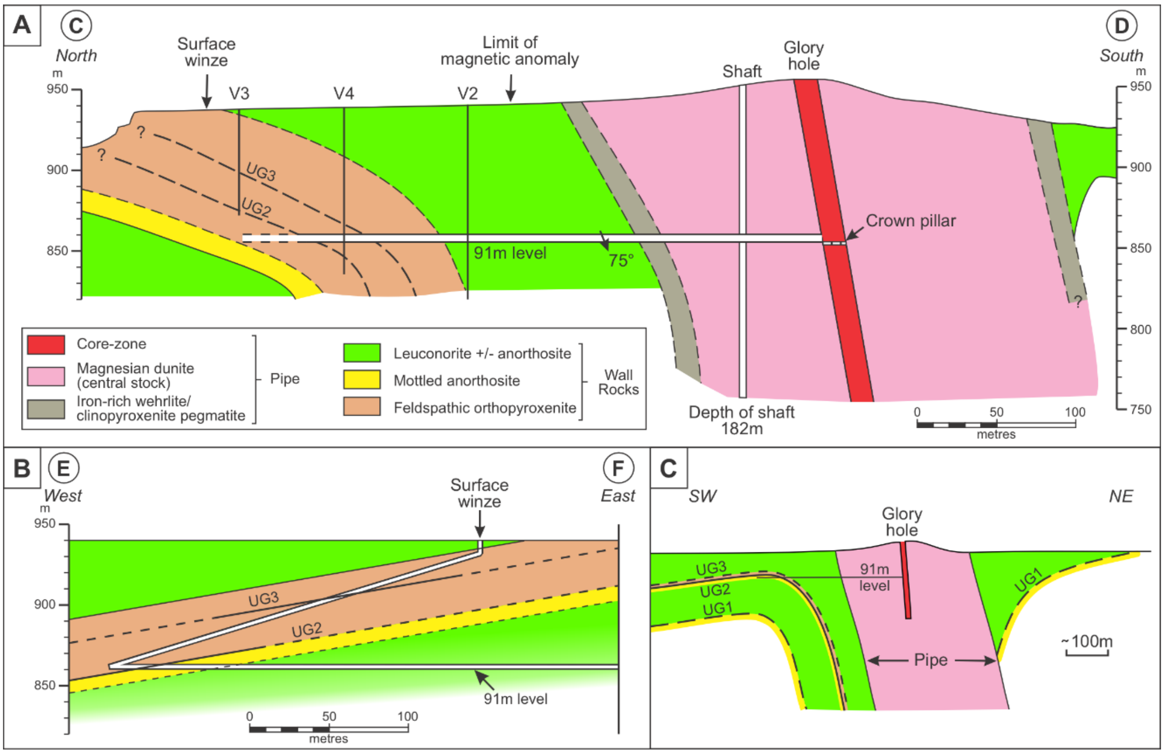


Surface geological map of the Driekop pipe based on original mapping at a scale of 1:1000. The inclination of the mineralised core-zone is after Wagner (1929). Coordinates based on South African Local Origin (LO) system using central meridian 31° east. Surface contours from 1:10,000 scale orthophotographs. Location of drill-holes (V2-V4) and magnetic anomaly after Mossom (1977). AB, CD and EF refer to section lines. From Scoon and Mitchell (2009)

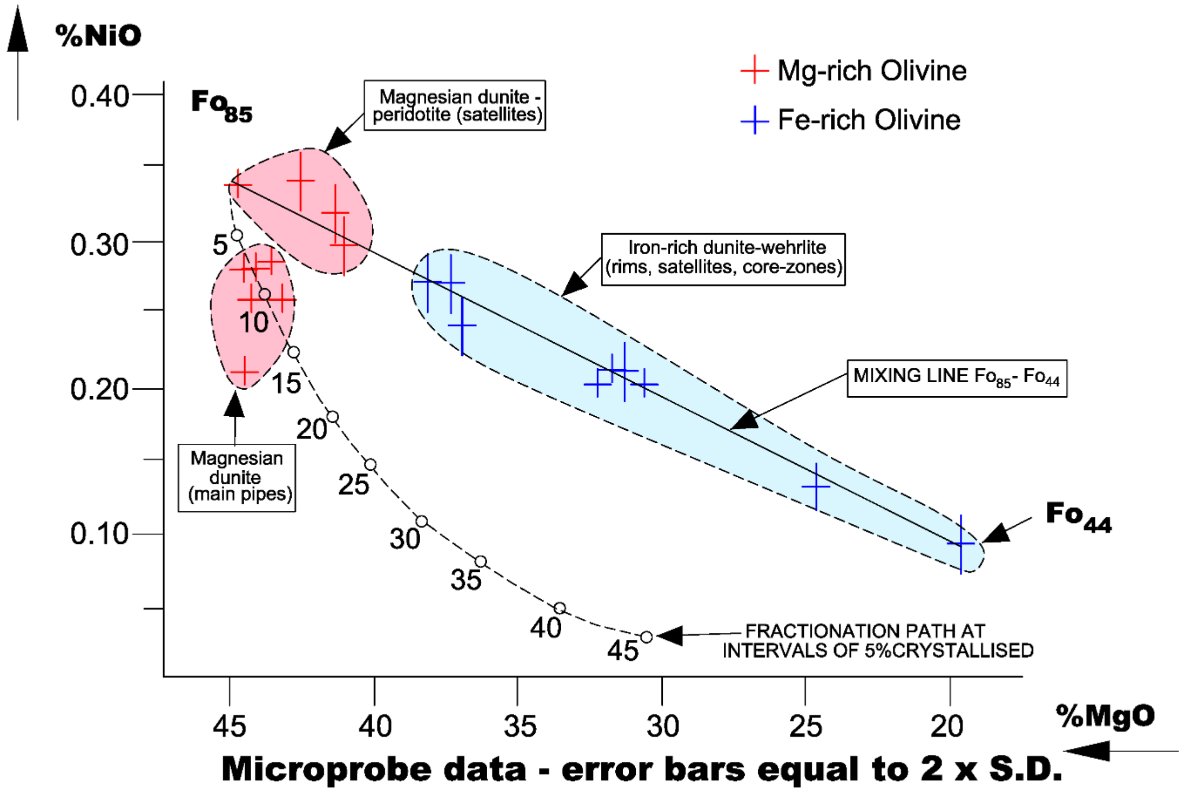


Geological plan of part of the 91 m level workings based on original mapping at scale of 1:200 of sidewalls and roof





(A) Geological section looking approximately west (based on new mapping and drill-holes V2-V4); (B) Geological section looking north (based on mapping of surface winze); (C) Schematic section looking approximately northwest



Plot of weight % NiO versus MgO: in olivine based on electron microprobe analyses with error bars equal to two standard deviations. The olivine from the magnesian dunite stocks in the Driekop (DR), Mooihoek (MO), Onverwacht (ON), and Twyfelaar (TW) pipes, as well as the barren Winnaarshoek pipe (WH), approximates to a theoretical fractionation path. The olivine from the core-parts of the mineralized pipes, Driekop (samples DR2 and DR3), Twyfelaar (sample TW8), Onverwacht (sample ON2), and Mooihoek (sample MO4), plot on a linear trend. This is interpreted as a mixing line defined by the most primitive (sample DS4) and fractionated (sample MO4) olivine within the pipes. The latter composition is within analytical error of the average composition for IRUPs from the Upper Critical Zone (IRUP) and for Replaced Merensky Reef (Replaced MR). Also plotted for comparative purposes are averages for olivine from the Merensky Reef (normal MR), the Lower Zone (LZ) and the Lower Critical Zone (LCZ). From Scoon and Mitchell (2011)

EL-8 Merensky Reef, Maandagshoek

The Merensky Reef was discovered in the southern part of Maandagshoek but as noted earlier, the exact location has not been ascertained. There are two likely sites. The site next to the road that leads to the hospital is accessible. The other possibility, an outcrop in a spruit located south of the outcrops shown in Lombaard's map, is rather remote. The site next to the road includes a small quarry. The prospecting shaft that was sunk here is no longer accessible.

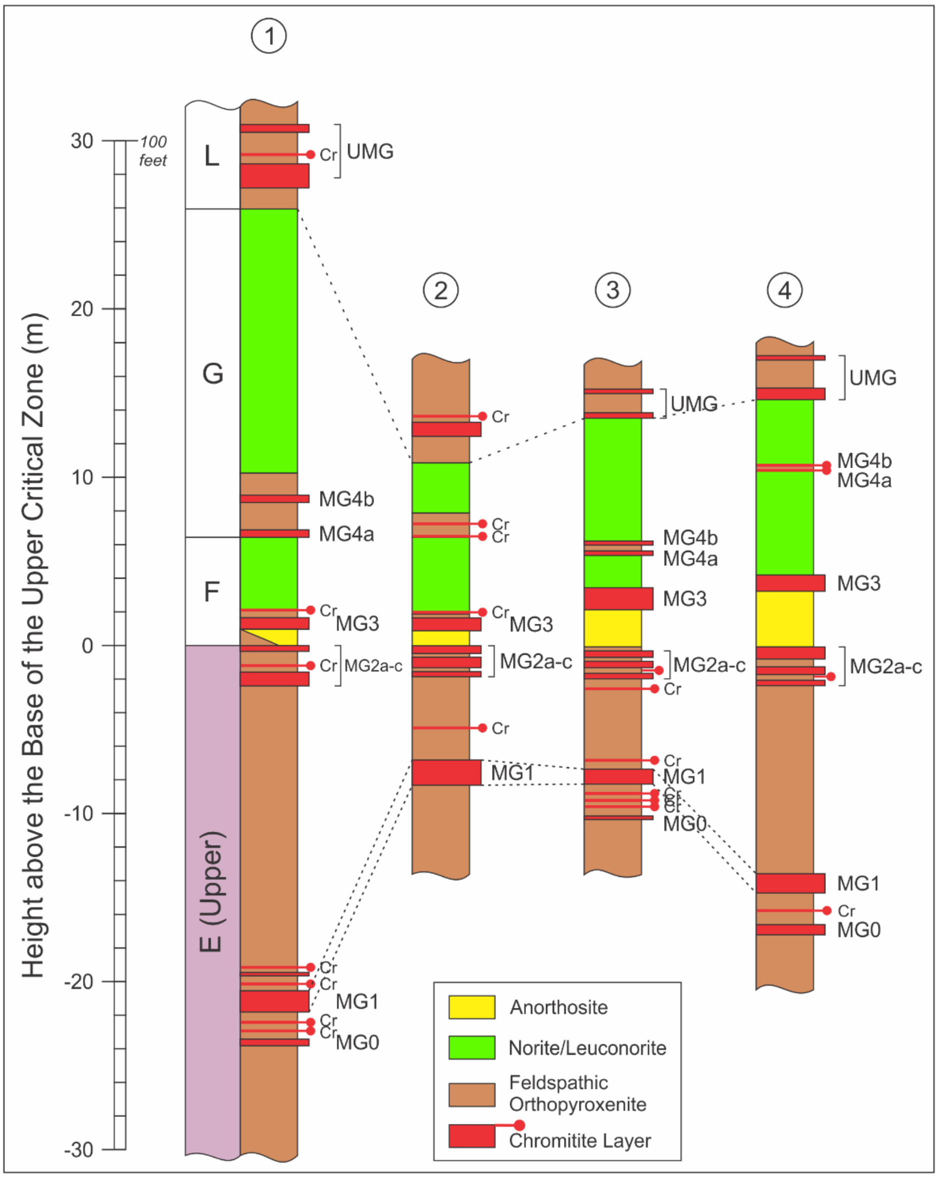
The outcrop of the Merensky Reef in the quarry has been exposed to extensive surface oxidation. The feldspathic orthopyroxenite contains two thin chromite stringers. The presence of secondary copper sulphides is a diagnostic feature.

The Merensky Reef at Driekop outcrops in the lower part of a low ridge aligned parallel to strike. The ridge is capped by the resistant Merensky Anorthosite, a prominent marker layer in the UCZ. The outcrop peters out southward (left of photograph). The discovery site at Maandagshoek is situated in the centre of the broad Moopetsi Valley. The ridge is more or less contiguous in a northerly direction. View looking west towards the Bushveld Escarpment (LMZ)

EL-9 De Grooteboom Chromite mine

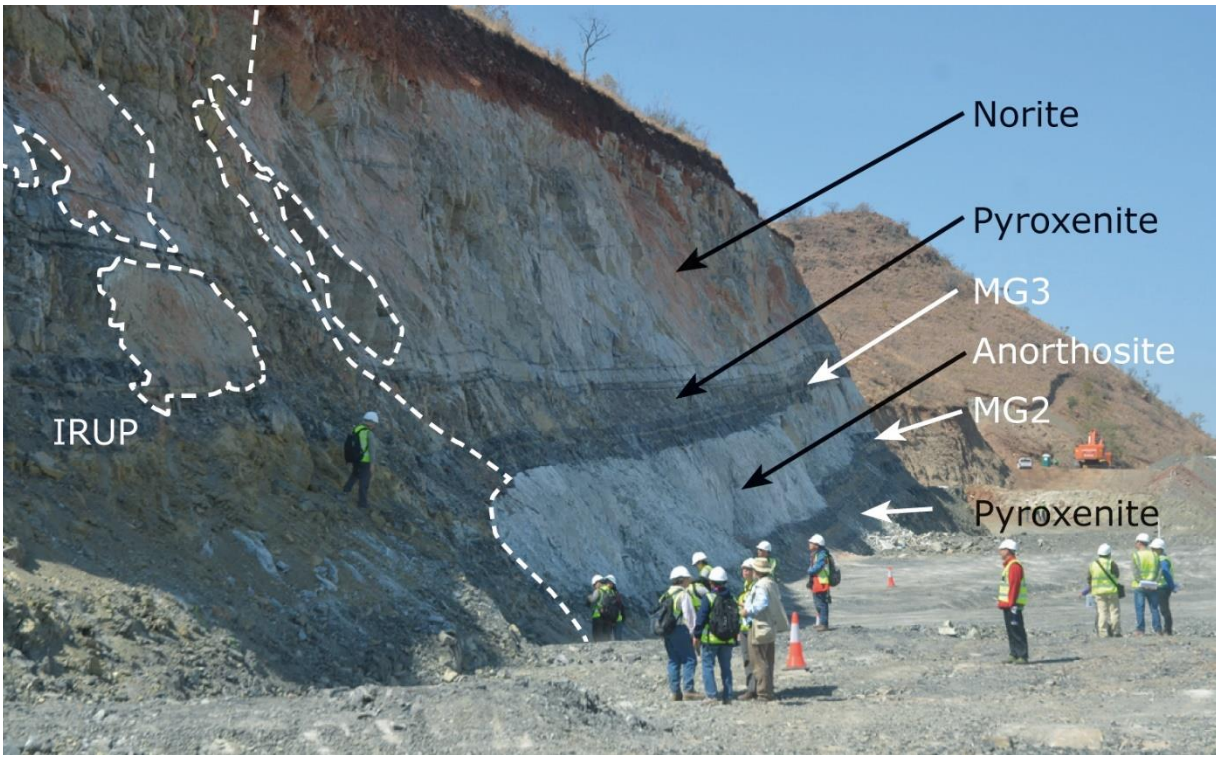
The De Grooteboom chromite mine includes an open pit in which discordant bodies of IRUPs can be examined. The mine is extracting the MG1-MG4 chromitites. The MG3 Anorthosite forms a prominent marker. The anorthosite is underlain by the MG2 seams (as many as 4 individual layers may be recognized) and overlain by the MG3.

View of the De Grooteboom open pit, looking north



Columns showing the occurrence of the MG chromitites in the Southern Sector, Eastern Limb. The sequence at De Grooteboom is similar to that at Tweefontein South (column 1)

The multiple nature of the MG2 and MG3 chromitites as seen in the De Grooteboom open pit. The MG2-ad seams occur below the MG3 Anorthosite; the MG3a-c seams are located either above the anorthosite or, as in this case, in the upper part of the anorthosite

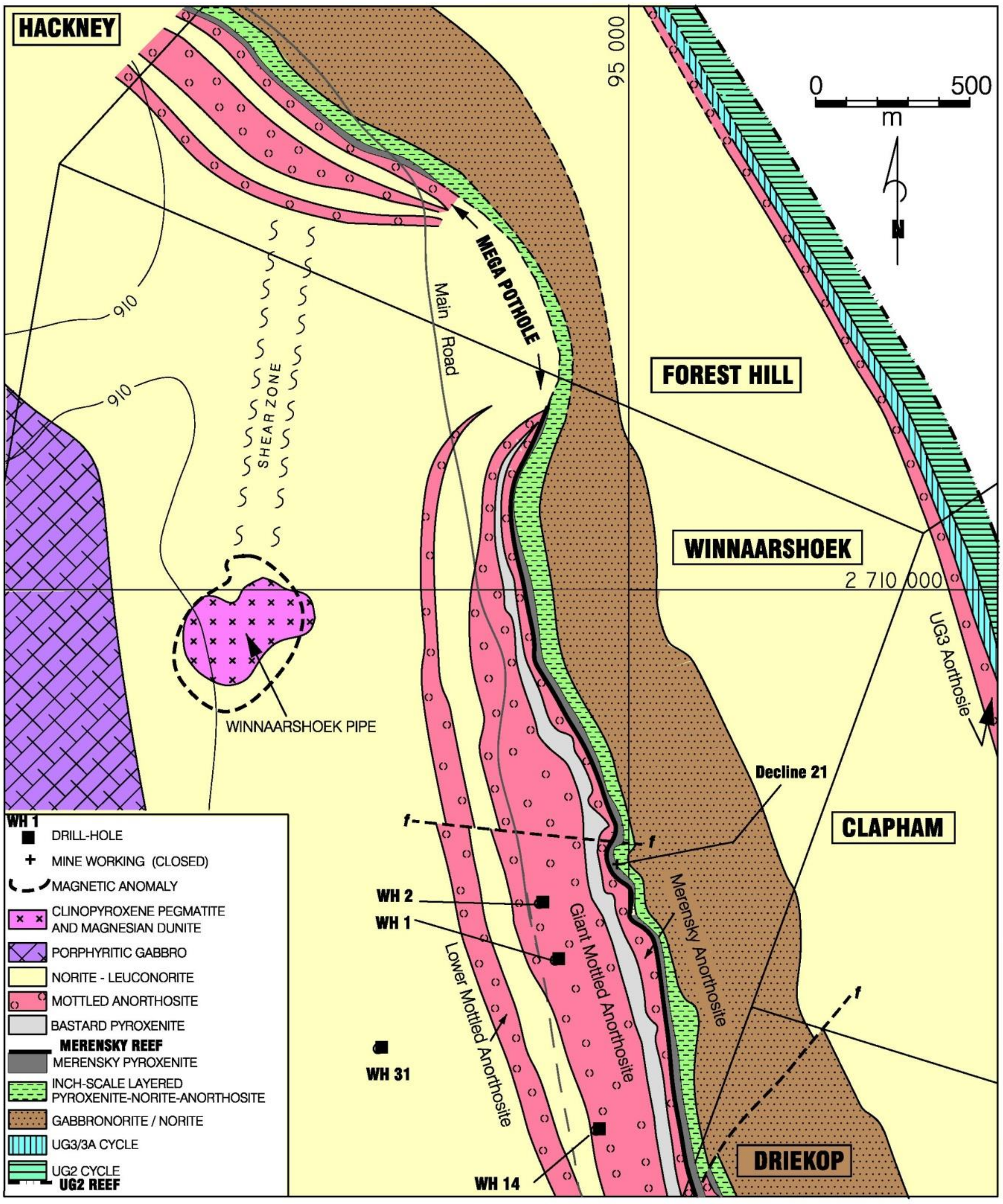


An irregular body of IRUP (dark) penetrates downward and partially replaces a layered sequence of norite, feldspathic orthopyroxenite and chromitite, open pit at the De Grooteboom mine

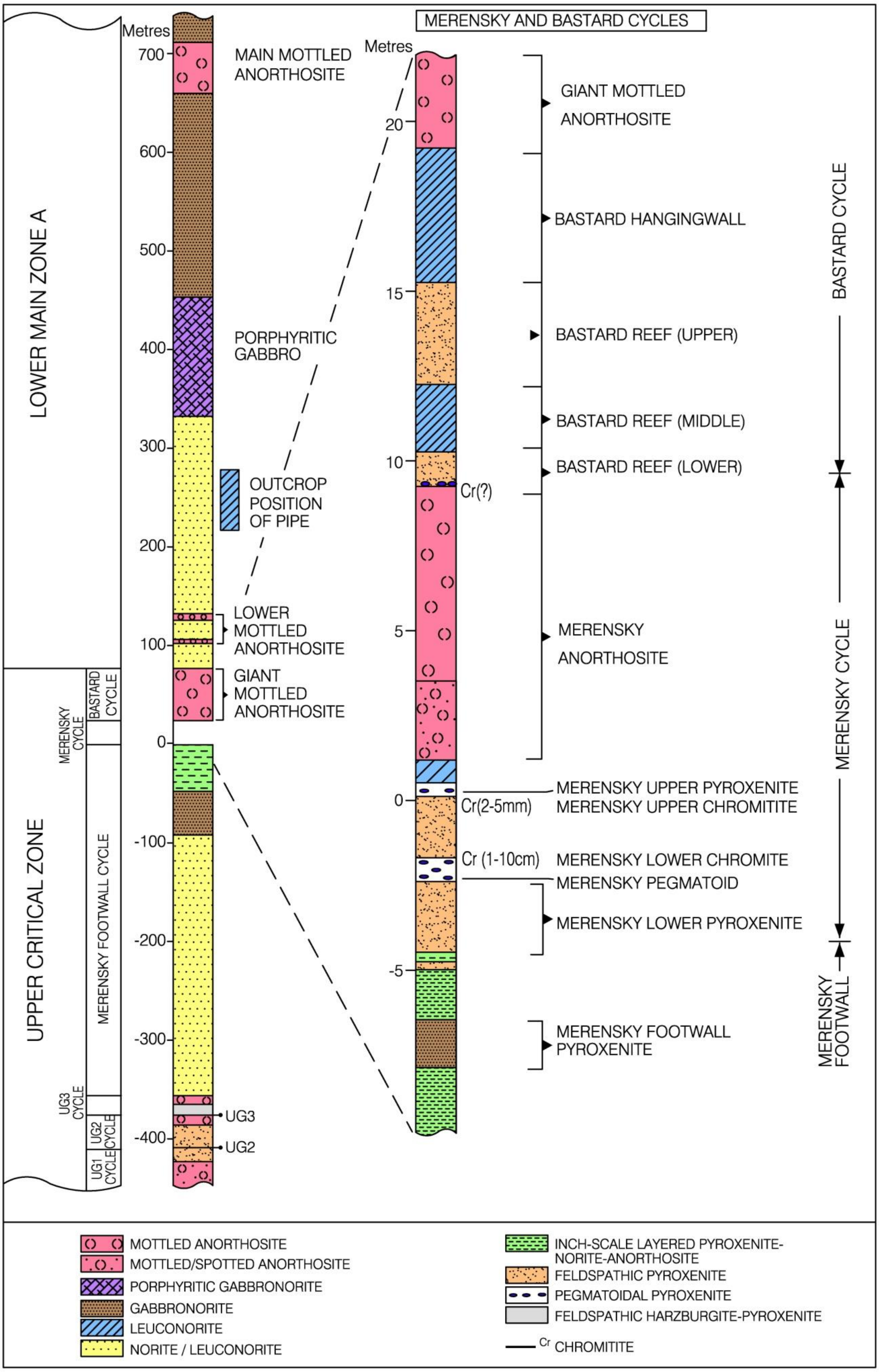
EL-10 Merensky Reef, Winnaarshoek

A regional geological map of Winnaarshoek illustrates the continuity of marker layers in the UCZ, including the Merensky Reef. The principal marker layers are shown on the stratigraphic column. The Merensky and Bastard Reefs are associated with the resistant Merensky anorthosite and Giant Mottled anorthosite.

The anorthosites outcrop as part of a low, linear, ridge that can be traced over several km. The Merensky Reef crops out on the eastern slopes (e.g., as seen on Driekop). A central hollow is associated with the Bastard Reef. The Giant Mottled anorthosite is one of the most laterally persistent layers in the RLS (Vermaak, 1976).



Surface map of Winnaarshoek showing details of the RLS and the dunite pipe. From Mitchell and Scoon (2007)



Stratigraphic column for part of the Lower Main and Upper Critical Zones, Winnaarshoek

Aerial view of the historical workings on the Merensky Reef, Winnaarshoek. View looking approximately west with the line of trenches on the east facing slopes marking the outcrop of the reef

History

Despite the Merensky Reef being discovered at Maandagshoek, the most extensive underground workings are at Winnaarshoek. This is one of only a handful of localities where the Merensky Reef crops out: the reef can be traced along strike for several km. This area is part of the Marula platinum mine. The main resource is the UG2 Reef.

Overview

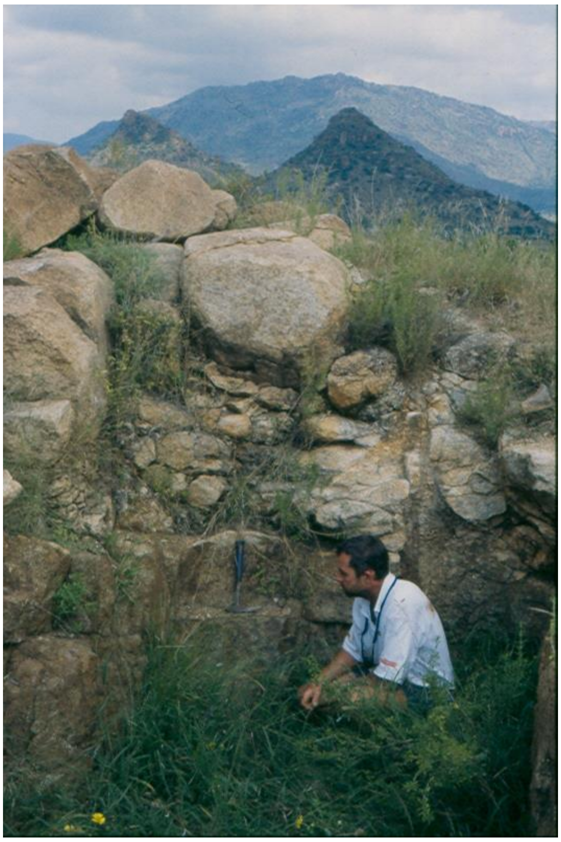
The Merensky Reef is an extraordinarily complex and variable orebody that is difficult to model, whether genetically or for the purposes of ore reserve estimates. This is partly due to the vertical changes in the distribution of the PGE and also due to potholes. Throughout the Bushveld Complex, potentially economic PGE mineralization is generally found within a "reef zone, rather than a specific layer. Three or more discrete layers can be identified, including thin layers or stringers of chromite. The mineralization may be developed over several layers with a combined thickness of up to 5 m in width, yet the highest grades are restricted to much narrower parts of this reef zone. Where a so-called thin reef facies is developed (typically <25 cm), as in the Brakspruit section of the Rustenburg platinum mine, the entire reef is condensed into a single relatively thick chromitite layer (typically <5 cm). The wider reef zones tend to yield lower mineable grades.

Merensky Unit

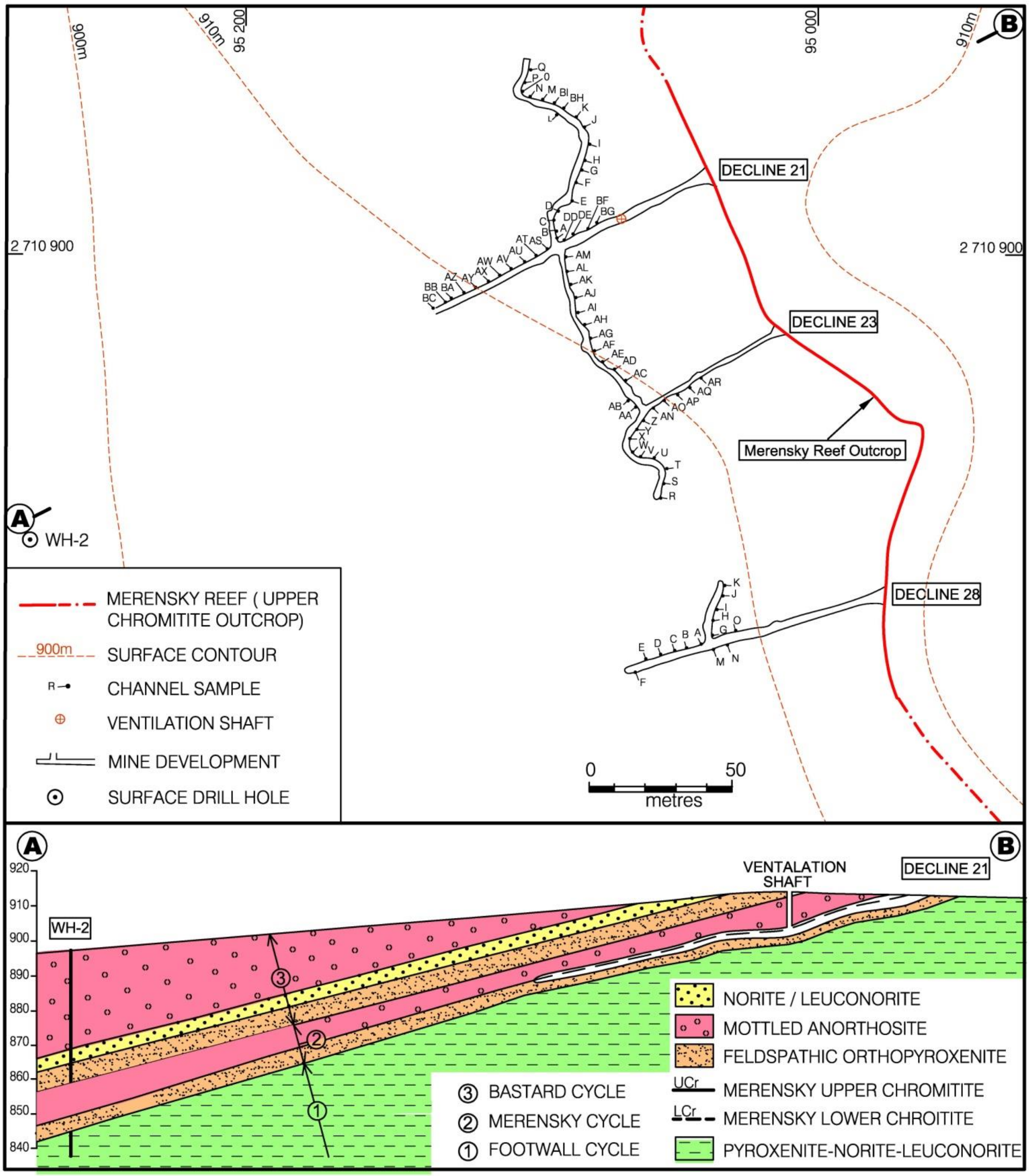
The Merensky Reef is contained within the Merensky unit. A basal layer of medium-grained feldspathic orthopyroxenite (2–5 m thick) containing two thin chromite stringers is overlain by a sequence of norite-leuconorite (0.1–1 m), spotted-mottled anorthosite (3–5 m), and mottled anorthosite (5–8 m). The two principal components of the unit, i.e., the basal pyroxenite and the upper anorthosite are separated by a contact that is sharp yet irregular and nonplanar.

The footwall to the Merensky unit is composed of a cm-scale, chaotically layered norite with thin layers of feldspathic orthopyroxenite (invariably unmineralized) and anorthosite. The Merensky unit is overlain by the Bastard unit. At Winnaarshoek, this consists of the Bastard Reef (a double layer of feldspathic orthopyroxenite with a norite middling) succeeded by a leuconorite layer, and then the distinctive Giant Mottled Anorthosite. A thin, irregular stringer of chromite occurs at the base of the Bastard unit. The basal part of the Bastard Reef includes minor amounts of base metal sulphides and low-grade PGE mineralization.

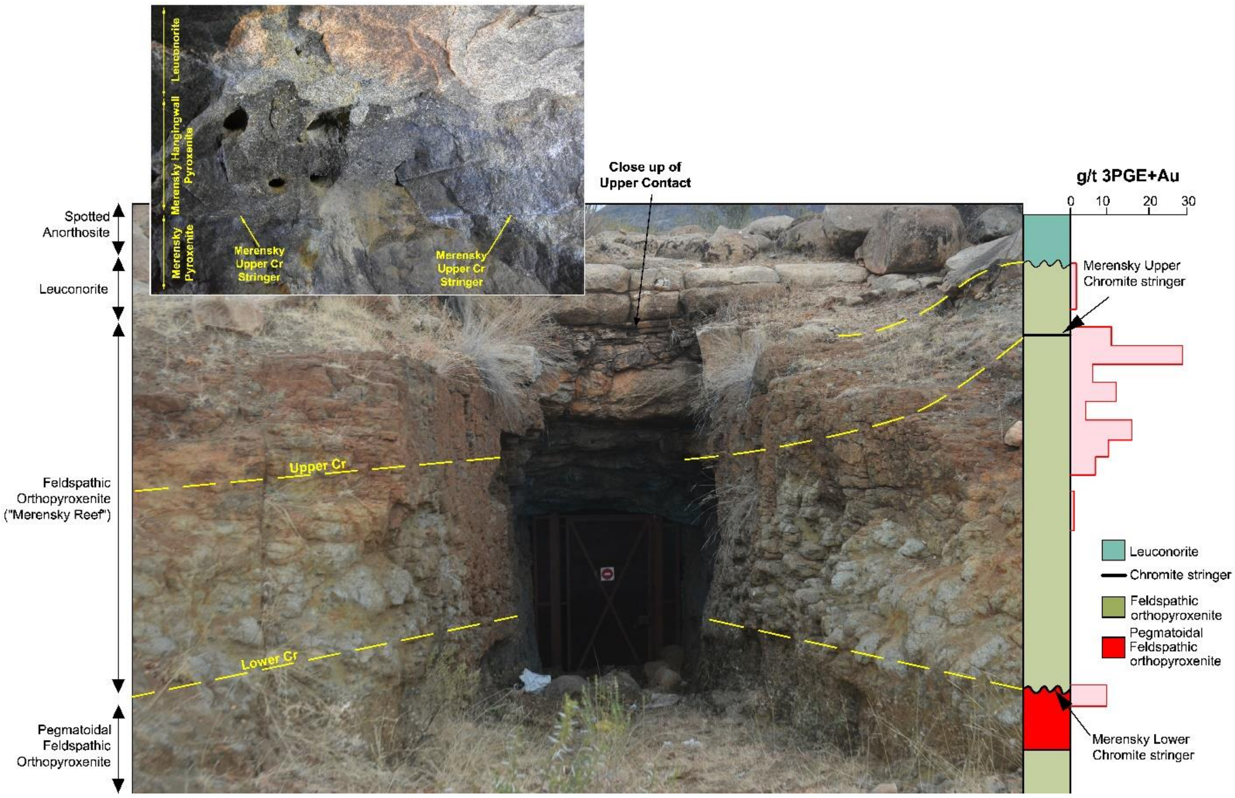
The “Merensky pyroxenite” is constrained to a part of the basal pyroxenites averaging 1.8 m thick. The zone is bounded by two chromite stringers. Both the underlying “footwall” pyroxenite (1–2 m thick) and overlying “hangingwall” pyroxenite (average 40 cm thick) are typically either barren or poorly mineralized with respect to PGE, although the latter includes prominent base metal sulphides. No mineralization has been recorded in the overlying norite-anorthosite component. The uppermost of the two chromite stringers is generally 3-8 mm thick and forms a regular, laterally persistent layer. The lower chromite forms a far more irregular stringer, 1-15 mm thick, and may be locally absent. Feldspathic orthopyroxenite pegmatite (or pegmatoid) forms a well-defined, laterally persistent layer, typically 25 to 50 cm thick directly, beneath the lower chromite. Pegmatitic segregations are sporadically developed in the hanging-wall pyroxenite, a few tens of cm above the upper chromite. Relatively small, irregular patches may also be encountered within the Merensky pyroxenite itself. In the pegmatite below the basal chromitite, individual grains of chromite are moulded around the coarse crystals of orthopyroxene and plagioclase.



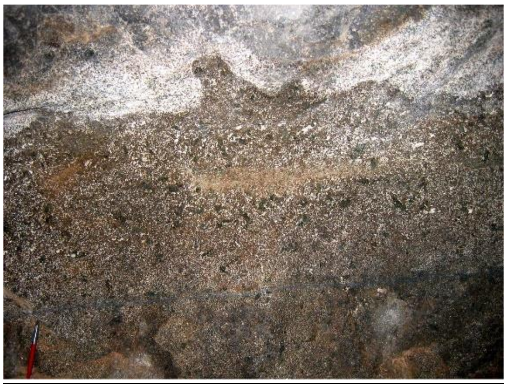
Trench dating from the 1920s on the Merensky Reef, Winnaarshoek. The reef zone is capped by anorthosite (large boulders). View looking west of the twin koppies and Bushveld Escarpment (LMZ)



Map and section of some of the historical declines on the Merensky Reef at Winnaarshoek (from Mitchell and Scoon, 2007). Access to decline 21 and the connecting drive south includes vertical channel samples at 5 m intervals

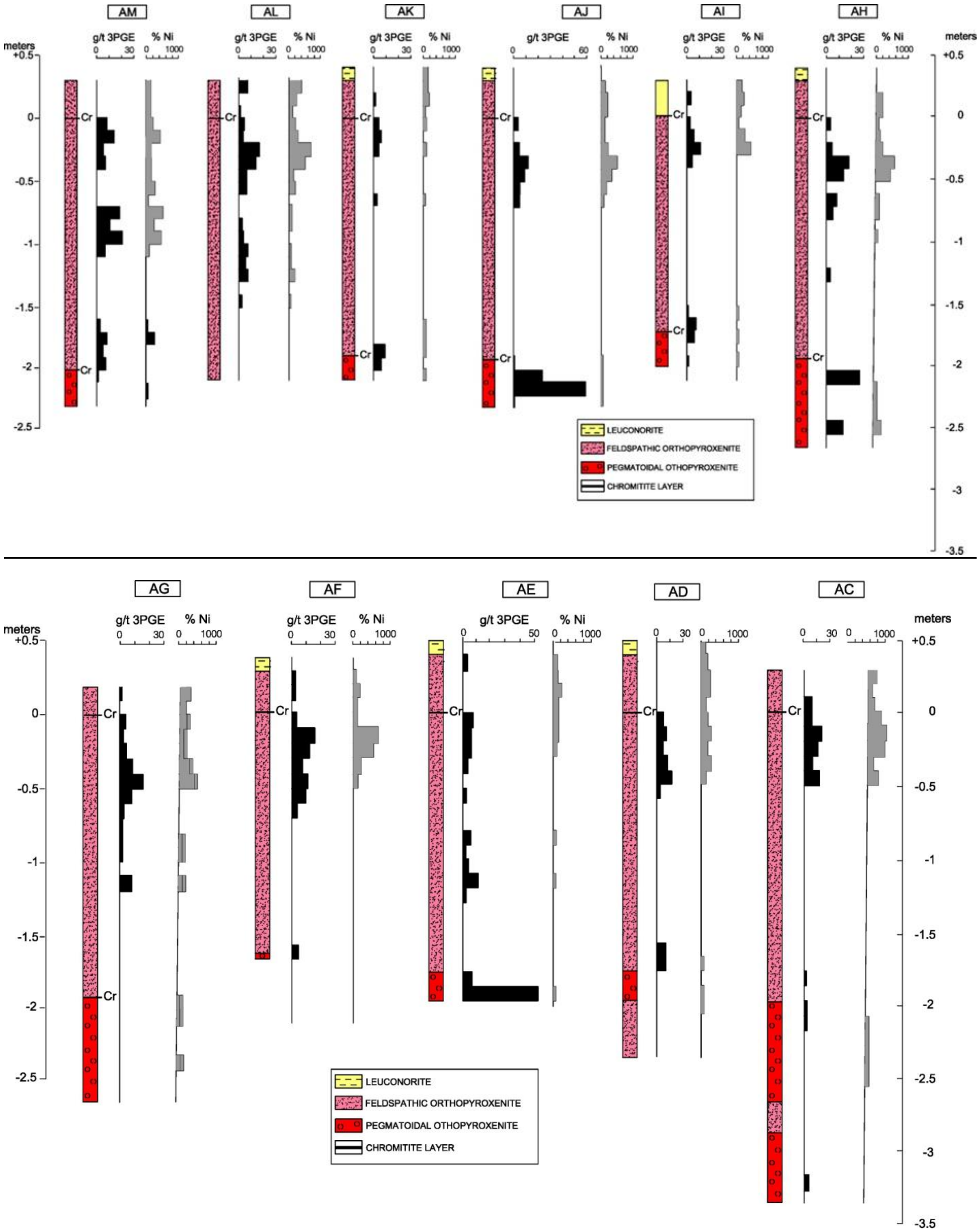


Entrance to Decline 21, Winnaarshoek showing the layered nature of the Merensky Reef and the PGE grade profile

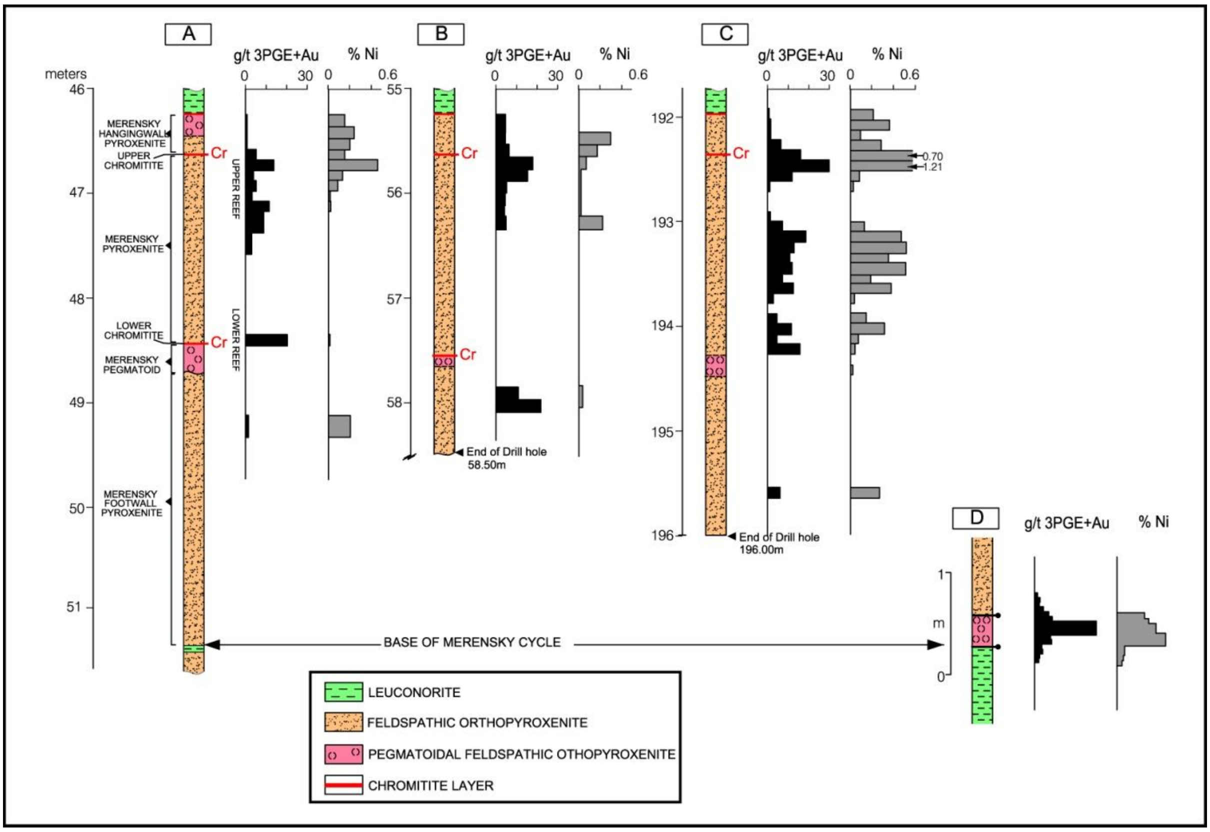


The irregular, scalloped contact of the Merensky hangingwall pyroxenite, Winnaarshoek

The contact may have a blocky nature indicative of the disruption of the layering prior to intrusion of the pyroxenitic "sill"



Channel samples AM through AA, Decline 21



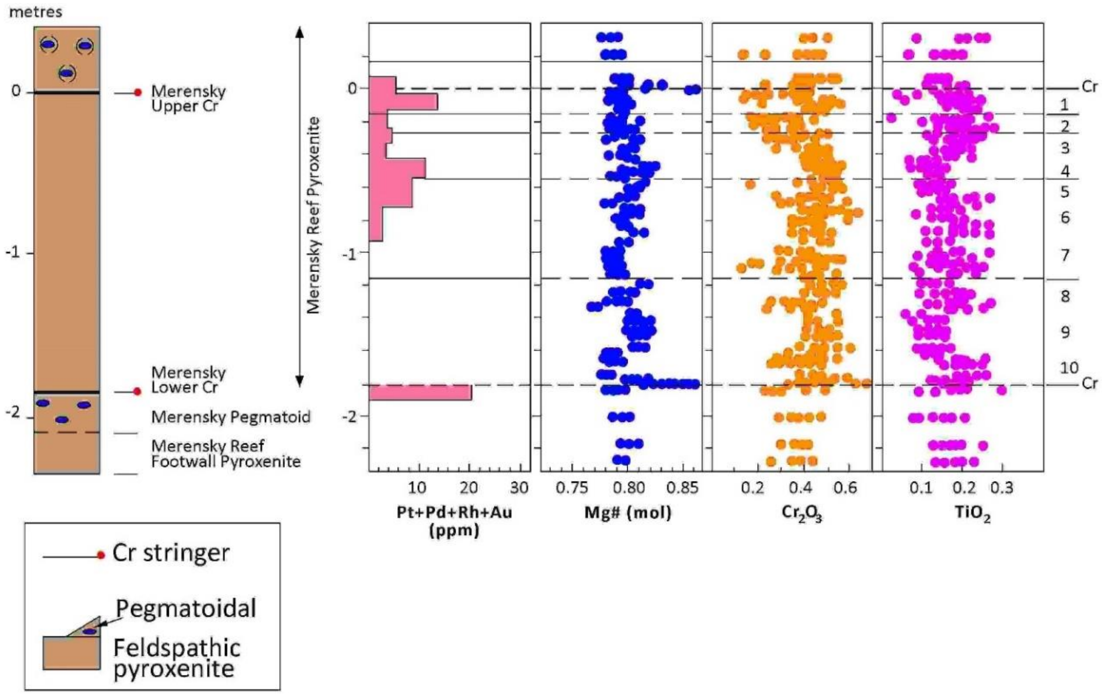
The three Merensky Reef variants identified by Mitchell and Scoon (2007) at Winnaarshoek. A=typical Upper Reef; B=poorly mineralized Upper Reef with substantial PGE in Lower Reef; C=richly mineralized Lower and Upper Reefs; D= Section from Kroondal, Rustenburg for comparison

Mitchell and Scoon (2007) identified three styles of reef at Winnaarshoek. The typical reef is a well mineralized Upper Reef (50-100 cm thick) capped by the upper chromite stringer. This feature, colloquially referred to as "top loading", is characteristic of the reef throughout the intrusion (Viljoen, 1999). A poorly mineralized Upper Reef occurs in which the Lower Reef may be considerably richer than average. A thick reef contains mineralized Lower and Upper Reefs.

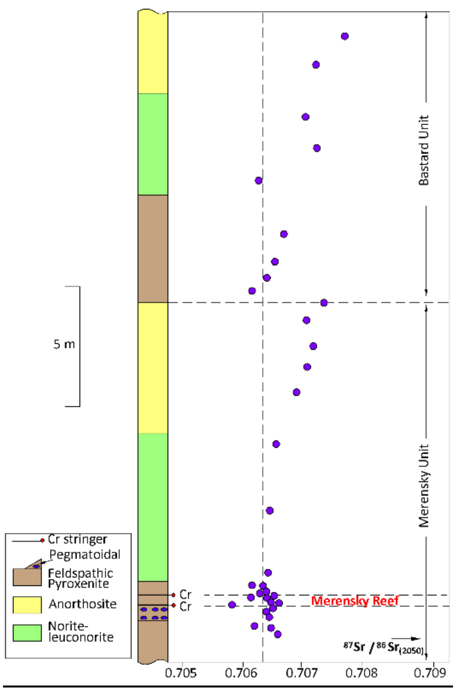
Despite the gross relative uniformity of the Merensky Reef on a property-wide scale at Winnaarshoek, underground channel samples display remarkable variations in grade distribution. Peaks in PGE concentrations are coincident with the most primitive compositions of orthopyroxene, plagioclase, and chromite, the dominant rock-forming minerals. The lower PGE concentrations are associated with the most evolved mineral compositions and elevated whole-rock incompatible element concentrations. In addition, the lowest-grade Merensky Reef described by Mitchell and Scoon has the most chemically evolved footwall. The richest intersection has a relatively primitive footwall. Moreover, the lowest grade intersection contains anomalously low concentrations of disseminated chromite and the richest reveals anomalously extreme amounts.

Data based on both whole-rock and electron microprobe analyses on cm vertical scales indicate that the absolute concentrations of PGE are related to the primary mineralogy of individual layers.

The Sr isotopic systematics of the Merensky and Bastard units has been widely debated. Of considerable importance is that the isotopic in-homogeneity in the Northern Sector of the Eastern Limb is restricted to the anorthositic components (Lee and Butcher, (1990) and does not occur within the pyroxenitic sections (as it does in the Western Limb). The likelihood of the pyroxenitic and anorthositic components of the Merensky unit at Winnaarshoek being products of discrete magma lineages is supported by new, unpublished Sm-Nd isotopic data of Steve Prevec, Mark Raines and RNS.



Detailed, mm-spaced electron microprobe analyses of the orthopyroxene in the Merensky Reef pyroxenite at Winnaarshoek by Mitchell and Scoon (2007) reveal numerous small-scale variations. These data are supported by electron microprobe analyses of the plagioclase and Cr-spinel, as well as by whole-rock data. Each of the ten subdivisions identified here may represent a discrete magma pulse within the "pyroxenitic sill." The composite nature of the layer is further enhanced by the two chromite stringers (separate magma pulses) as well as by the layers of pyroxenite below the pegmatoid and above the uppermost stringer



Sr isotopic systematics of the Merensky and Bastard units at the Atok (or Bokoni) platinum mine, Eastern Limb. Data of Lee and Butcher (1990)

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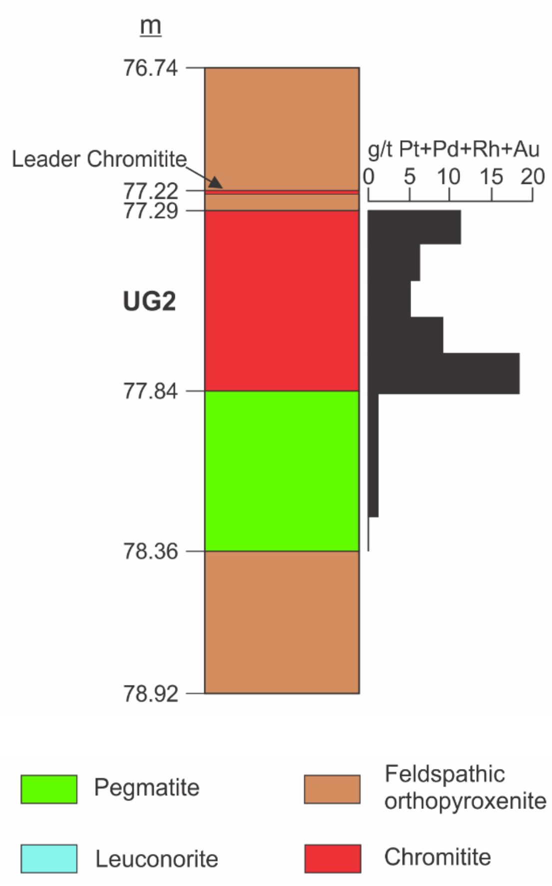
EL-11 UG2 and Winnaarshoek Pipe, Marula Platinum mine

UG2 Overview

The PGE-rich nature of the **UG2 Reef** was possibly first reported by Hall and Humprey (1908), based on samples obtained by Hans Merensky from the Eastern Limb. This did not constitute an orebody at the time as the fineness of the PGE inhibited metallurgical recoveries (Wagner, 1929). The identification of the mineralized chromitites may have drawn impetus from knowledge of the relationship between chromitites and PGE in the Urals (Kovaloff, 1925; Lipovsky, 1926; Razin, 1976), as discussed by Scoon and Mitchell (2004a). The successful recovery of the PGE from the UG2 Reef was delayed until the late-1970s (Vermaak, 1985).

The average thickness (60-120 cm) and PGE grade (5-8 g/t) of the UG2 is remarkably consistent, despite the PGE interelement ratios reporting significant differences between the Eastern and Western Limbs (Gain, 1985; Vermaak, 1985; Hiemstra, 1986; Farquhar, 1986; Leeb-du Toit, 1986; Viljoen and Hieber, 1986; Viljoen *et al*., 1986a; 1986b; Lee, 1996; Maier and Barnes, 2008; Junge *et al*., 2014; Viljoen, 2016; Mitchell *et al*., 2019a). The presence of lower and upper peaks in the "typical" mineralization profile has been widely commented on and can be seen at Winnaarshoek and Rustenburg.

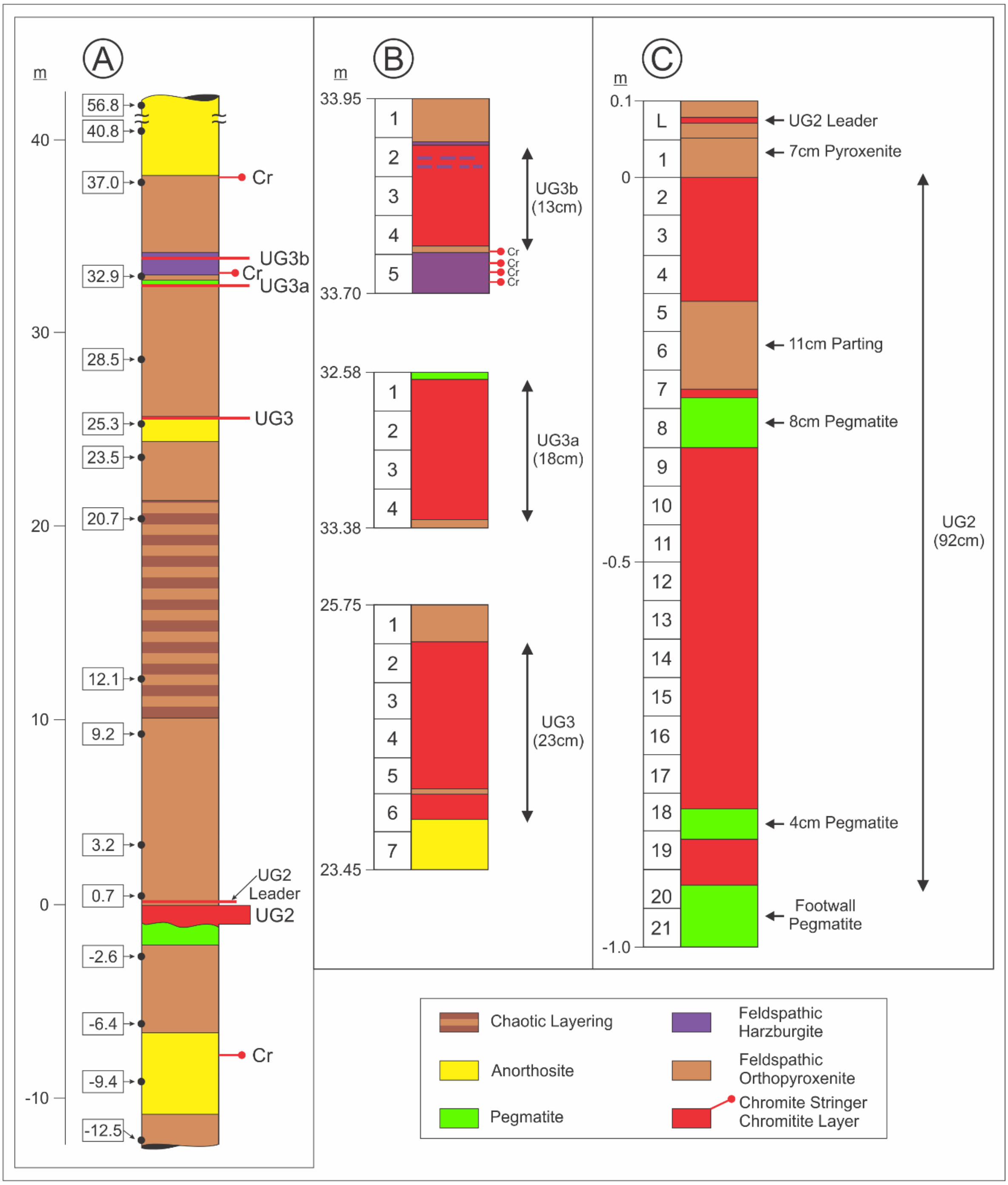
The close affinity between the PGE and distribution of Cr-spinel in the UG2 profile is well known, as is the paucity of base-metal sulphides. Mineralogical studies have shown the PGE primarily occur as platinum-group minerals (PGM), disassociated from the base-metal sulphides (Hiemstra, 1979; 1986; McLaren and De Villiers, 1982; Kinloch, 1982). The Ru, Ir and Os are generally contained in grains of laurite enclosed within the Cr-spinel. The Pt, Pd, and Rh occur as a complex suite of minerals attached to the exterior of the grains of Cr-spinel.



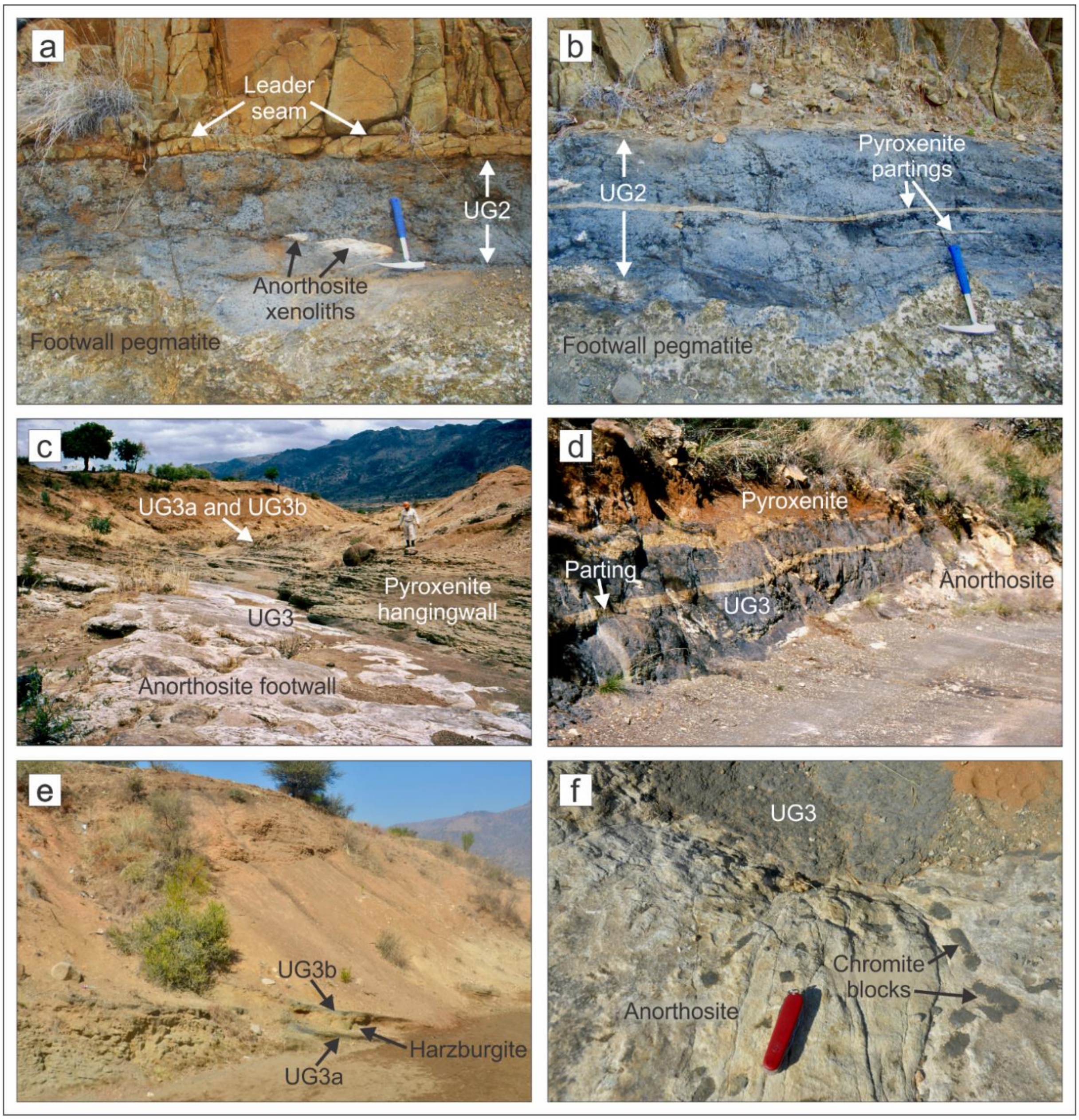
Vertical distribution of the PGE in the UG2 Reef at Winnaarshoek

Stratigraphy

The stratigraphy of the UCZ at Winnaarshoek, part of the Marula Platinum mine, has been described by Mitchell and Scoon (2007) and may be considered to be representative of this part of the Eastern Limb (South African Committee for Stratigraphy, 1980; Cameron, 1982). The UCZ is unusually thick in this region (±1,000 m) and the vertical separation of the UG2 chromitite and the Merensky Reef (±400 m) is correspondingly greater than other parts of the intrusion. A 300 m-thick unit of gabbronorite (±subordinate leuconorite-anorthosite), which has not been reported from other regions, is a significant component. The interval between -10.5 m below the UG2 to approximately 15 m above the UG3b is shown here. The three anorthosite layers, i.e., the UG2 and UG3 Footwall anorthosites and the anorthosite situated above the UG3b each constitute regional markers. A thin "reaction" chromite stringer occurs on the base of the uppermost



Stratigraphic column for drill-hole WH-1, Winnaarshoek, showing lithologies, marker layers, and position of the whole-rock samples. The igneous layering in the study section can be explained in terms of two syn-magmatic pyroxenitic sills. The lower sill hosts the UG2 and UG2 Leader, and the upper sill contains the UG3, UG3, and UG3b. The sills are sandwiched between well-defined layers of anorthosite; (b) UG3, UG3a, and UG3b; (c) UG2 and UG2 Leader



(a-b) The UG2 Reef in the outcrop at Hackney (north of Winnaarshoek). The chromitite is underlain by pegmatite and overlain by medium-grained feldspathic orthopyroxenite, the latter containing a thin Leader seam. The irregular nature of the footwall contact is emphasized, as is the knife-sharp and planar nature of the hangingwall. The internal parting consists of pyroxenite. The xenoliths are anorthositic. The nodular appearance of the UG2 reflects the occurrence of coarse-grained mosaics of Cr-spinel; (c-f) The UG3 and UG3a-b chromitites at Maandagshoek. The UG3 is underlain by anorthosite and overlain by pyroxenite. The pyroxenite parting in the UG3 is a distinctive feature. The UG3a-b are separated by layers of pyroxenite and harzburgite. The chromitite blocks in the UG3 footwall anorthosite are derived from downward protuberances of the UG3.

anorthosite (analysed by Scoon and Costin, 2018). The stratigraphically highest chromitite layers, i.e., the UG3a and the UG3b (thicknesses of 0.18 m and 0.13 m, respectively), are separated by a sequence of finely layered pyroxenite and feldspathic harzburgite ("harzburgite"). The UG3 (thickness of 0.23 m) is underlain by the UG3 Footwall anorthosite which has a spotted texture in the lower part and a mottled texture in the upper part. The mottling is ascribed to the presence of irregular or ovoid-shaped oikocrysts of pyroxene. The UG2 (thickness of 0.92 m) is underlain by a footwall pegmatite (thickness of 1.05 m) and contains internal bodies of pegmatite and a pyroxenite parting. The latter have resulted in the UG2 being approximately 0.25 m thicker than the mine average). The upper contact of the UG2 is sharp and planar and is aligned parallel with the UG2 Leader seam (thickness of 10 mm).

Outcrops

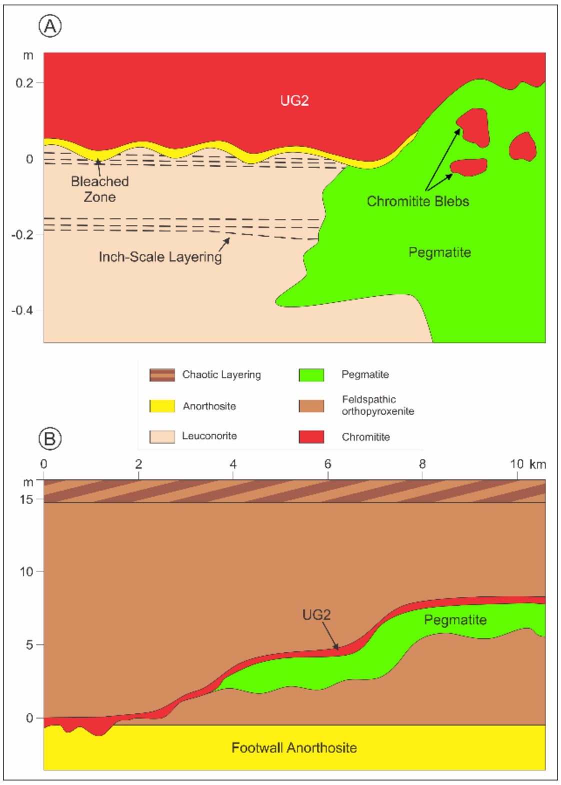
The UG2 and UG3 chromitites do not outcrop at Winnaarshoek. The outcrop of the UG2 at Hackney, on the adjacent farm, illustrates the broad field setting, including the footwall pegmatite and hangingwall pyroxenite. The UG3 and UG3-b seams outcrop at Maandagshoek, a locality where Gain (1985) has described the regional geology. The uppermost part of the UG3 Footwall anorthosite contains disseminations and blocks of chromite.

The high PGE content of the UG2 Reef, as well as of the UG2 Leader seam at Winnaarshoek was noted earlier. The PGE profile of the UG2 at Maandagshoek (Gain, 1985), part of the Modikwe Platinum mine, is similar to Winnaarshoek (Wimpie Britz, pers. Communication, 2016). The UG3 chromitites each contain moderate PGE grades (3-4 g/t PGE+Au), as reported at Maandagshoek (Gain, 1985), and confirmed at the Marula mine by commercial assays, but are too thin to justify mining in the current economic climate.

Footwall and Hangingwall Lithologies

An appreciation of the footwall and hangingwall lithologies is critical in attempts at unravelling the petrogenesis of the UG2. The UG2 is underlain in many areas of the Bushveld Complex by a thin, irregular body of feldspathic orthopyroxenite (±olivine) or melanorite with a characteristic coarse-grained, or pegmatitic texture. The concept of the footwall "pegmatite" (or "pegmatoid") as being a primary layer, or the normal footwall, as intimated by Mathez and Mey (2005), needs to be corrected. The pegmatite is a younger feature which has a discordant relationship with the primary igneous layers. The contact between of pegmatite and chromitite is irregular, in part as the pegmatite contains cm-sized lumps or blebs of chromite which have been derived from the UG2 (Viljoen *et al*., 1986a-b). The chromite blebs may be richly mineralized. The pegmatite may have been emplaced laterally, between the chromitite and the primary footwall (Scoon *et al*., 2024a). The latter includes medium-grained feldspathic orthopyroxenite ("pyroxenite"), leuconorite, or anorthosite. The "UG2 Footwall anorthosite" is a regional marker (Mitchell *et al*., 2019a). In localities where the leuconorite or anorthosite is encountered, the basal contact of the UG2 is dimpled (rather than markedly irregular). The contact is demarcated by a 1-2 cm-thick layer of plagioclase. A similar "bleached" zone occurs at the contact between anorthosite and the Merensky Reef (Eales *et al*., 1988). The dimpling is locally displaced by cusp-like protuberances of chromitite which cut downwards over 1-15 cm and crosscut the cm-scale modal layering.

The erosive nature of the UG2 chromitite in respect of the footwall stratigraphy provides important constraints to the formation of the chromitite. The dimpling and protuberances are liable to be a continuum with the saucer-shaped or subvertical-walled "potholes" which transgress downwards over several metres (Eales *et al*., 1988). The catastrophic nature of the UG2 potholes in the Western Limb has been documented in detail (Leeb-du Toit, 1986; Viljoen and Heiber, 1986; Viljoen *et* *al*., 1986a; 1986b; Hahn and Ovendale, 1994; Lomberg et al., 1999; Viring and Cowell, 1999; Van der Merwe and Cawthorn, 2005). At Crocodile River, we have observed steeply inclined potholes which peter out into subvertical chromite veins. Steep-sided potholes are relatively infrequent at Winnaarshoek, although rolls that expose the footwall anorthosite are significant.



Panel diagram showings the relationship between the UG2 and the footwall at (a) Crocodile River, Western Limb and (b) Winnaarshoek. The dimpled contact with the leuconorite includes protuberances of chromitite that crosscut the primary, cm-scale layering, as well as a bleached zone of anorthosite. The footwall pegmatite is a younger, discordant feature which contains blebs of chromite dismembered from the UG2. The height of the UG2 in (b) varies relative to the ostensibly single layer of pyroxenite. After Scoon et al. (in prep.)

The UG2 is invariably overlain by a 3-12 m thick layer of pyroxenite which contains 1-2 cm-sized oikocrysts of chromian augite. This lithology is similar to the thick sequences of pyroxenite that dominate the LCZ. The pyroxenite hosts the UG2 Leader seams. The contact between the chromitites and the pyroxenite is knife-sharp and planar. Mine geologists use the upper contact of the UG2 to obtain the regional dip, noting the irregular nature of the basal contact. The Leader seams at Winnaarshoek include one mappable layer (thickness of 1-2 cm) and several chromite stringers (defined by one or two grains of Cr-spinel). In the Southern Sector (Eastern Limb), including at Dwars Rivier, the UG2 is associated with two relatively thick Leader seams which may be the lateral equivalent of the UG3 chromitites (Hornsey, 2006). Each of the Leader seams, irrespective of thickness, reveals knife-sharp contacts. The Leader seams contain moderate PGE mineralization and yet have a negative impact on mining as they cause significant hangingwall instability.

Many of the chromitite layers in the Bushveld Complex contain internal "partings," a mining term for sheet-like bodies (or strata) aligned parallel with the primary igneous layering. Partings have parallel contacts, thicknesses of a few cm or tens of cm, and may extend along strike for several hundred metres. The partings in the LG6 chromitite, which consist of pyroxenite indiscernible from the host stratigraphy are particularly well known (Cameron and Desborough, 1969; Worst, 1986; Scoon *et al*., 2024a). The UG2 contains pyroxenitic partings similar to those in the LG6. The chromitites also contain lens-shaped bodies which reveal angular margins, and which peter out laterally over a few cm or tens of cm. Chromitites in the LCZ contain lenses of pyroxenite; chromitites in the UCZ contain lenses of pyroxenite, norite, and anorthosite (Cameron, 1982). The lenses are adjudged to be xenoliths which have been rotated and transported over large distances. In addition to the partings and xenoliths, chromitites contain internal (discordant) bodies of pegmatite, as described from the LG6 (Cameron and Desborough, 1969; Scoon *et al*., 2024a).

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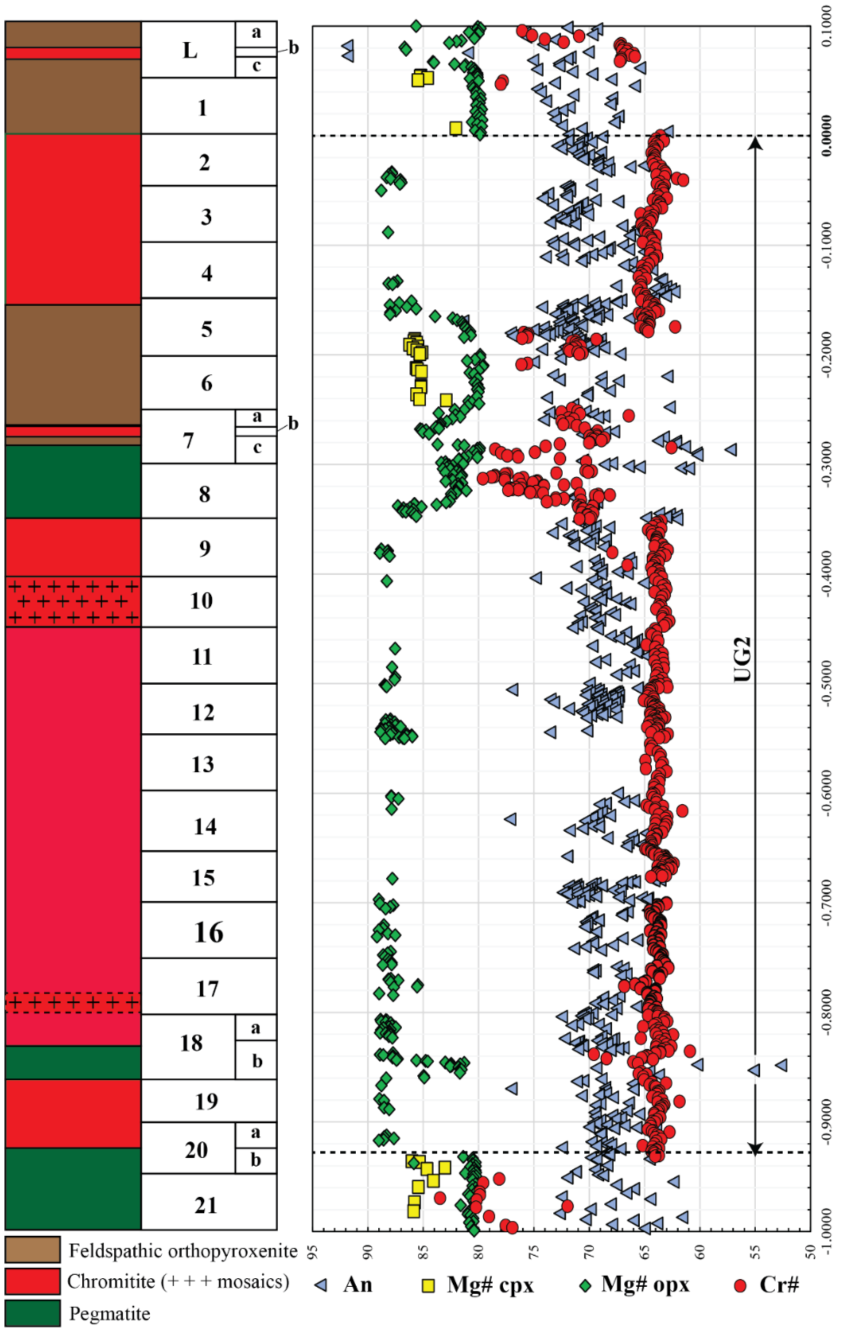

Vertical profile of the UG2 and UG2 Leader at Winnaarshoek (samples UG2/1-21 and UG2/L). The composition of the Cr-spinel (mol. % Cr), plagioclase (An), orthopyroxene (En) and clinopyroxene (cpx) is based on electron microprobe analyses at an average vertical spacing of 1 mm. After Scoon et al. (in prep.) with analytical data by Gabi Costin

Winnaarshoek Pipe

The Winnaarshoek pipe crops out in a broad valley close to the edge of the Bushveld Escarpment. The pipe crosscuts a sequence of norite and leuconorite located between the Lower Mottled anorthosite and Porphyritic gabbro, two laterally contiguous marker layers in the LMZ some 100 to 300 m above the Merensky Reef. The surface expression is a subcircular feature with a diameter of 300-450 m. A shear zone with minor discordant ultramafic bodies transects the pipe. The pipe comprises two cores of magnesian dunite and an extensive rim of moderately iron-rich clinopyroxenite pegmatite. The contact between the dunite and clinopyroxenite is irregular and may be demarcated by wehrlite pegmatite.

In outcrop, the magnesian dunite is partially serpentinized and forms resistant knolls overlain by a thin, red soil with abundant birbirite float (a mixture of serpentine, opaline silica, limonite, secondary magnetite, and magnesite). The clinopyroxenite pegmatite crops out as low-lying pavements with clusters of boulders. Veins and segregations of clinopyroxenite, typically less than 1 m in width, crosscut the magnesian dunite. A trench has been excavated in the southern part of the pipe, but there is no documentation that this locality was prospected for platinum.

A drill hole (6118) collared in the pipe intersected clinopyroxenite pegmatite near surface and a monotonous sequence of magnesian dunite from 73.7-700 m. Thin veins of wehrlite and clinopyroxenite pegmatites crosscut the dunite. The dunite is otherwise massive and homogeneous, with no evidence of layering or wall rock contamination. The clinopyroxenite pegmatite is weathered to a depth of 28 m, but below this depth the rocks are relatively unaltered, with the exception of localized serpentinization next to fractures and joints. The pipe is strongly magnetic in comparison with the layered sequence, owing to secondary (low-Ti) magnetite in the partially serpentinized magnesian dunite. The magnetic signature exaggerates the size of the body, as it does for the iron-rich ultramafic pegmatite pipes (Viljoen and Scoon, 1985), although as the latter contain primary Ti magnetite they yield much more intense anomalies. Magnetic data indicate that the Winnaarshoek body is a deep-rooted pipe, inclined steeply toward the northeast, an interpretation supported by drill hole 6118 but in part deduced from similarities with the platiniferous Driekop pipe.

The wall rocks proximal to the Winnaarshoek pipe are severely disrupted. Marker layers are thinner than normal and gradually disappear toward the pipe. The dip increases from the regional average of 12° to more than 30°. This progressive change from a normal sequence to an entirely anomalous succession is apparent from drill holes WH-23, WH-34, WH-52, and WH-56, which were intended to locate Merensky Reef in this area. Drill hole WH-52 intersected a partially anomalous succession in which the Giant Mottled anorthosite appears typical, yet the Bastard Reef and Merensky anorthosite are entirely absent, and the Merensky Reef is unusually thin. Drill hole WH-23 also intersected a partially anomalous succession, but here the Giant Mottled anorthosite is pinching out (the Bastard Reef and Merensky anorthosite are again absent) and the Merensky Reef is restricted to low-grade segregations. In drill holes WH-34 and WH-56 the entire succession is dominated by homogeneous leuconorite, and no marker layers were identified.

References

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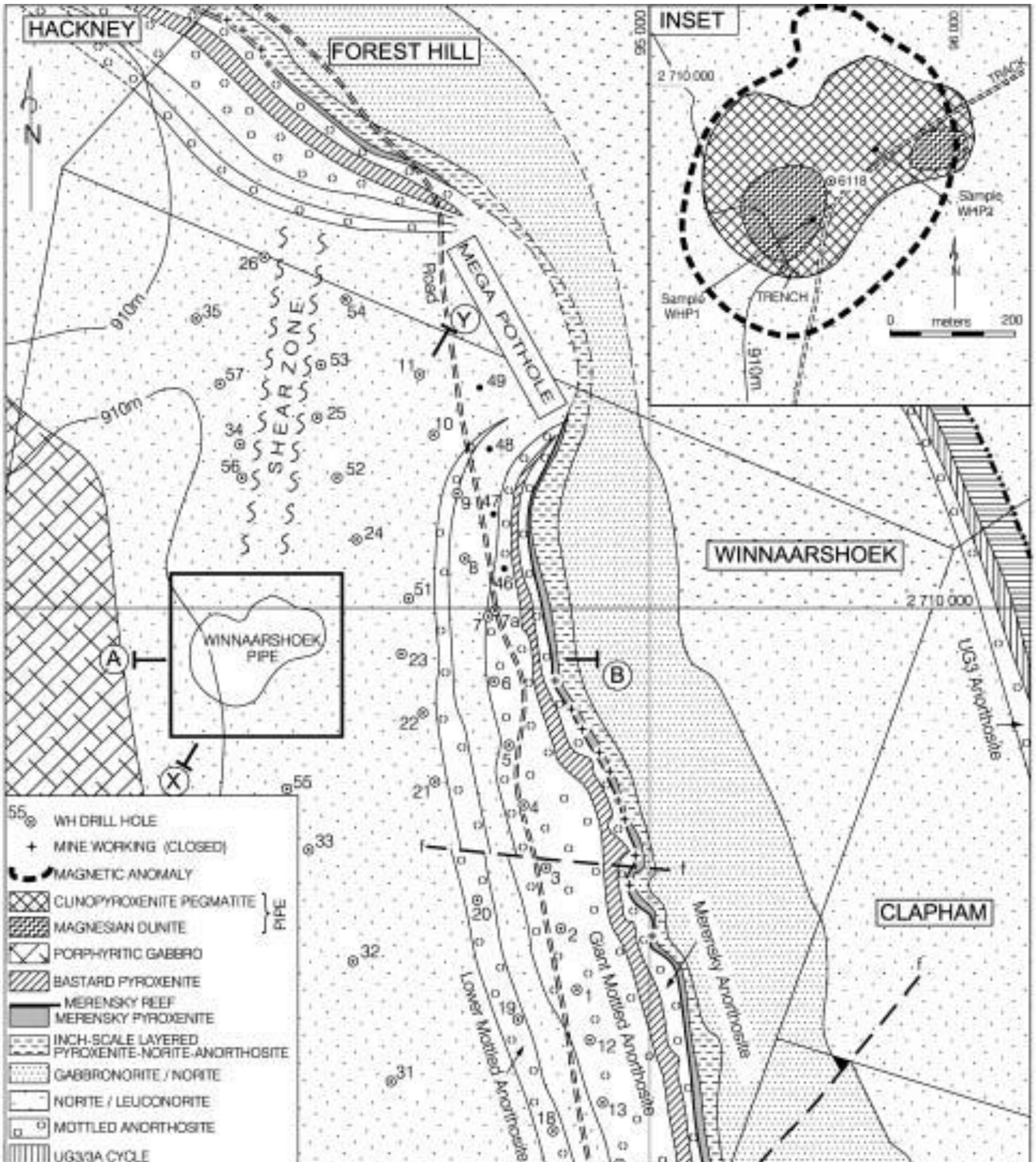
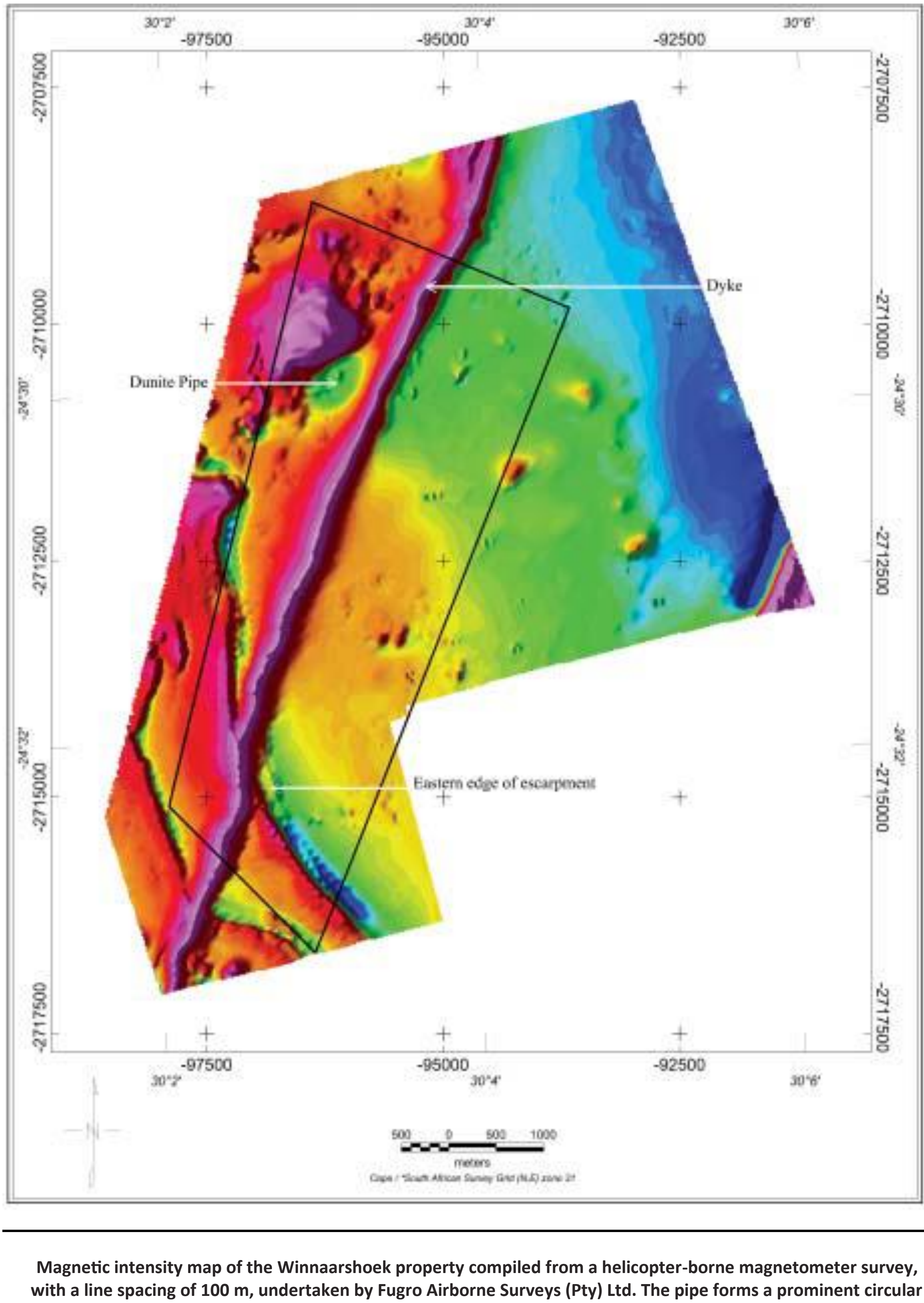
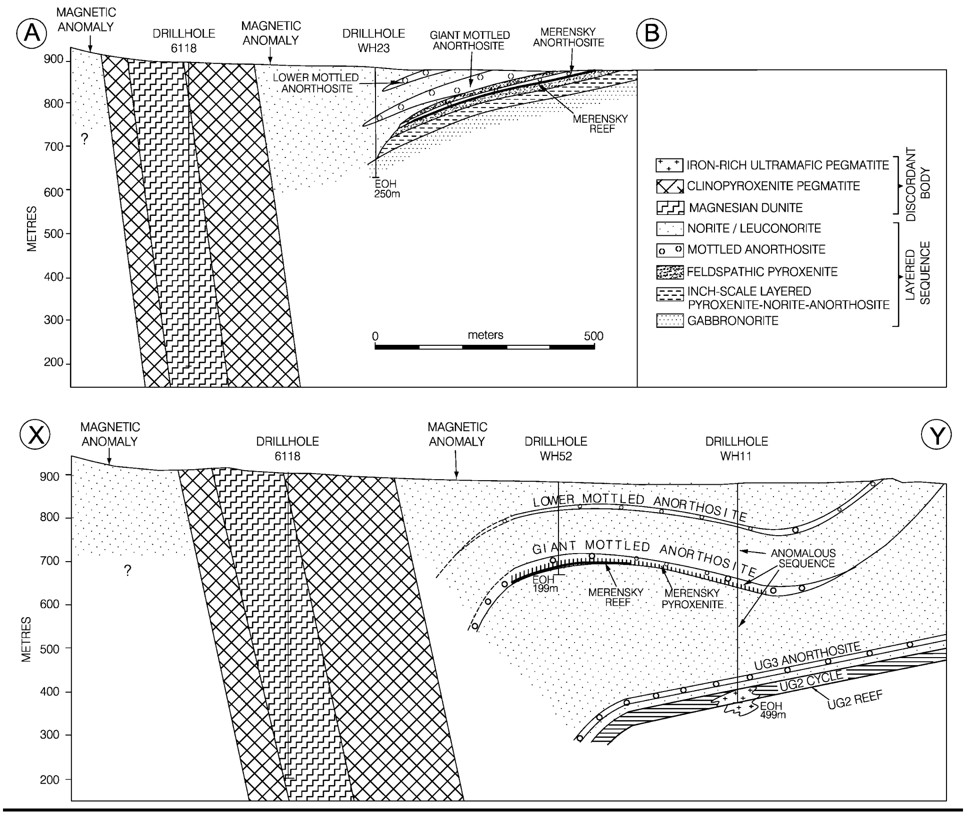


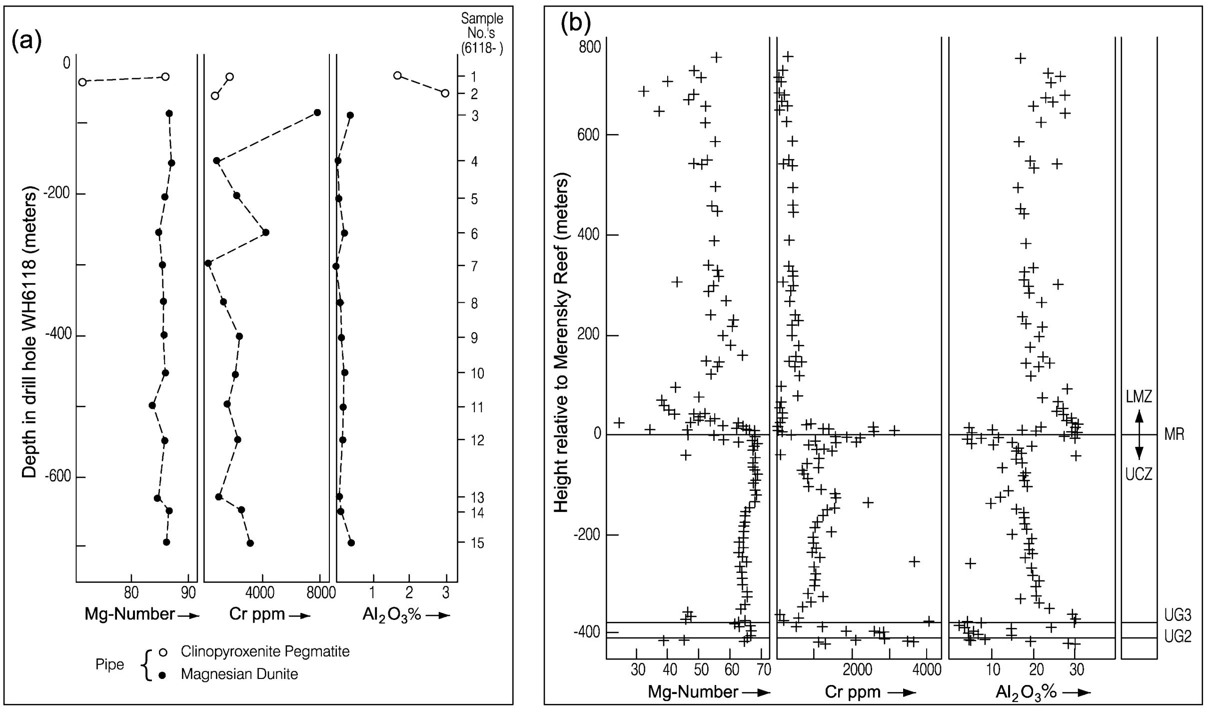
Geologic map of the northern part of the Winnaarshoek property depicting marker layers within the Upper Critical and Lower Main zones, the mega-pothole, and position of the "WH" series of drill holes. Note that drill hole WH-45 is located in the southwestern part of the property. Inset shows details of the Winnaarshoek pipe, location of drill hole 6118 and the two surface samples. Coordinates based on South African Local Origin (LO) system using central meridian 31° east. Mapping was undertaken at a scale of 1:5,000 using DTM-corrected aerial photographs. Three-dimensional modelling of drill core and mapping data provided information in areas of poor outcrop. AB and XY = sections lines (presented in Fig. 7); f = fault; — = UG2 reef. From Scoon and Mitchell (2004b)



Magnetic intensity map of the Winnaarshoek property compiled from a helicopter-borne magnetometer survey, with a line spacing of 100 m, undertaken by Fugro Airborne Surveys (Pty) Ltd. The pipe forms a prominent circular anomaly. Other features of note include a prominent linear anomaly associated with a post-Bushveld dike < 20 m thick in outcrop, the eastern edge of the escarpment of the Leolo Mountains, and subtle linear anomalies associated with anorthosite layers in the UCZ and LMZ



Cross sections A–B and X–Y of the Winnaarshoek pipe with drill hole locations. Steepening of the wall rocks and pinching out of marker layers proximal to the pipe is evident in both section lines. From Scoon and Mitchell (2004b)

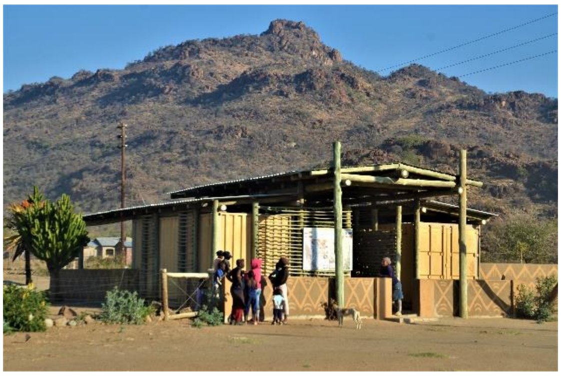


Plot of whole-rock Mg number, Cr and Al2O3 against height for (a) the Winnaarshoek pipe (drill core samples 6118/1-15) and (b) for cumulates from the UCZ-LMZ at Winnaarshoek (samples from drill holes WH-45 and WH-1)

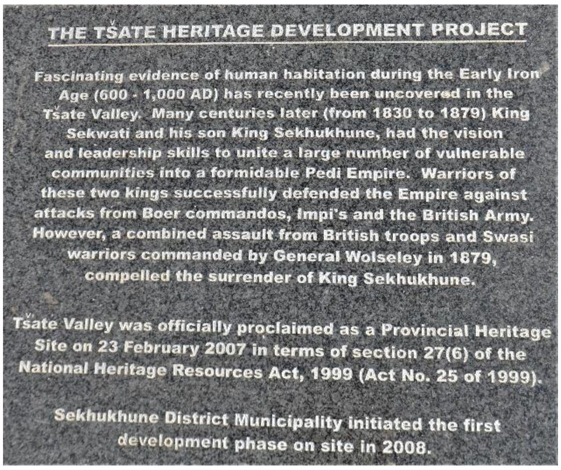
EL-12 Views of the LMZ and the Tsate Cultural Centre

The Bushveld Escarpment at Tsate and Winnaarshoek is dominated by gabbronorite of the LMZ

Large boulders of gabbronorite ate the entrance to the Tsate Cultural Centre



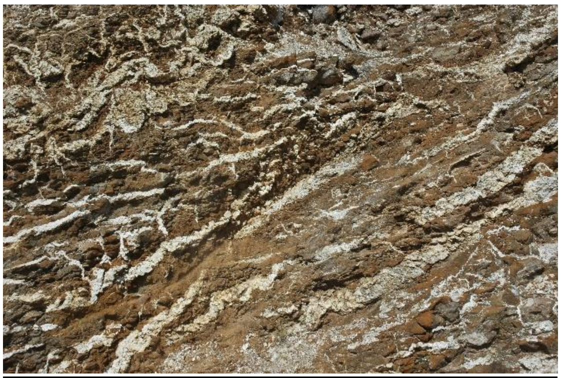
Tsate Cultural centre



Memorial to the Battle of Sekhukhune (1879), Tsate Valley

EL-13 Magnesite quarry and Twyfelaar Pipe

The Twyfelaar locality is situated in the Clapham trough, a broad, synclinal feature situated between the Groothoek chromite mine and village of Mecklenburg (Scoon and Mitchell, 2023). The trough contains a thick succession of the MSP and LZ and is underlain by the Magaliesberg Formation, the latter rocks being exposed in the Madikabje Hills. The MSP and LZ outcrop in rugged, angular hills with prominent scarps, as well as in a linear ridge that extends for approximately 15 km along strike. The cuesta topography is due to differential erosion of the gently dipping igneous layering. In the LZ, this is enhanced by the differential erosion of layers or sheets of peridotite. Magnesite has formerly been quarried from the serpentinized outcrops at Forest Hill and Twyfelaar. The quarry at Twyfelaar is located on the west side of the main road at the eastern slopes of Semea.



Magnesite in the quarry at the foot of Semea Hill, Twyfelaar, is developed on layers of peridotite in the LZ

Ptygmatic folding of magnesite veins can be ascribed to volume changes during serpentinization, Twyfelaar.

Based on three drill-cores, Wilson (2015) described the igneous layering in the Clapham trough in considerable detail.

Reconnaissance mapping indicates that the **Twyfelaar pipe** crosscuts the Lower zone. The pipe crops out on the northeastern flanks of the prominent Semea hill and is elongated in a northeasterly direction with a maximum dimension of 180 m. The main component of the pipe is a magnesian dunite that exhibits relatively little serpentinization, possibly owing to its elevated position above the valley floor. Wagner (1929) documented that serpentinization in the platiniferous pipes is dictated by height of the water table, and he emphasized that it cannot, therefore, be ascribed to deuteric fluids.

View of Twyfelaar pipe, Semea Hill. The dunite is covered by a thin, red soil

The contact between the pipe and the orthopyroxenite wall rocks at Twyfelaar is irregular and diffuse over a few tens of cm. Minor amounts of pipe-derived olivine occur within the orthopyroxenite for several meters from the contact. The PGE mineralization is restricted to minor segregations and veins of iron-rich dunite and iron-rich wehrlite pegmatite located wholly within the magnesian dunite, the latter being largely barren (Wagner, 1929). Individual segregations attain dimensions of 0.5 m but rapidly become smaller with depth. The pipe was never mined commercially although several trial shafts, adits, and trenches were developed (Merensky, 1925). Segregations of iron-rich wehrlite pegmatite in trenches demarcated by pits and a relatively large parsnip-shaped body was observed in the walls of the shaft designated “a.” Wagner (1929) reported that low-grade Pt mineralization also occurs in small schlieren of chromitite (1–2 cm), which we have found are associated with the iron-rich wehrlite pegmatite. Large lumps (1–25 cm) of chromitite float were also located, but these are restricted to the magnesian dunite. Whether this chromitite is an integral part of the pipe or is xenolithic (derived from downwarping of the LG1-LG4 chromitite layers?) is not known.

References

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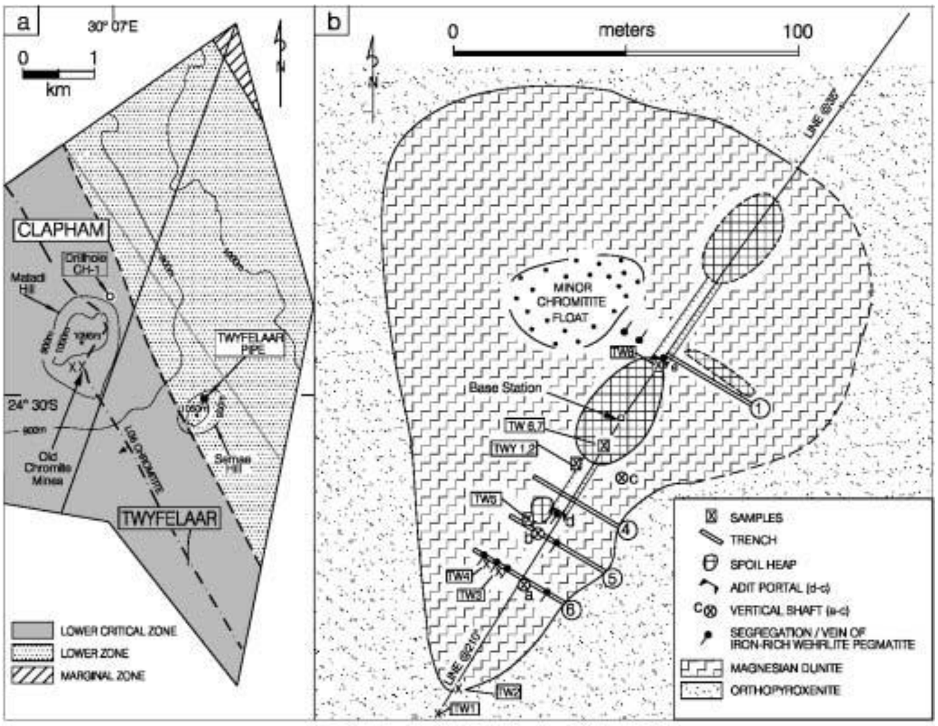


Schematic geologic map of the Clapham and Twyfelaar properties showing the position of abandoned chromite mines, location of drill hole CH-1 and Twyfelaar pipe, and approximate outlines of the Matadi and Semea hills. (b) Tape and compass map of the Twyfelaar pipe (mapped at a scale of 1:1,000). Trench numbers estimated from Merensky (1925); trenches 2, 3, and 7 not located, but the trial shafts and adits were probably sunk in the latter half of the 1920s. All three vertical shafts (a, b, and c) and both adit portals (d and e) are developed in areas where segregations and veins of iron-rich wehrlite pegmatite are notably abundant. From Scoon and Mitchell (2004b)

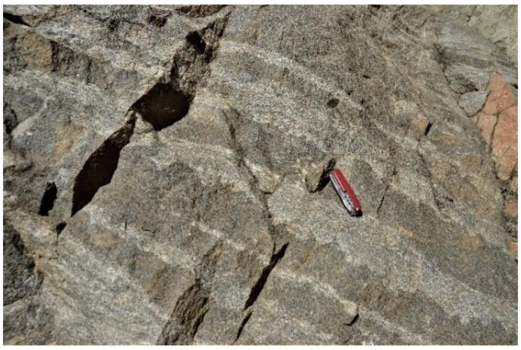
EL-14 MSP, De Grooteboom

The outcrops of the MSP at De Grooteboom are situated in the Steelpoort structure. This feature extends over approximately 200 km2 in the boundary area between the Southern and Northern Sectors and incorporates the Steelpoort pericline, the Eerste Geluk dome, the Dwarsrivier fragment and the Steelpoort and Dwarsriver faults (Hiemstra and Van Biljon, 1959; Willemse, 1969; Sharpe and Chadwick, 1982; Scoon and Teigler, 1995; Uken and Watkeys, 1997; Uken, 1999; Clarke et al., 2005). The Transvaal Supergoup is strongly deformed in this region, notably so on the flanks of the Steelpoort pericline. The latter is capped by the Steenkampsberg Formation; the Magaliesberg and Silverton Formations occur in the core.

The MSP is present on the western and eastern flanks of the pericline, but the LZ is restricted to the eastern flanks (part of the Burgersfort trough). On the western flanks, the MSP is discordantly overlain by the LCZ. Near Steelpoort, the MSP is relatively thin and displays a steep, angular discordancy with the floor rocks. The sill-like nature of the MSP is apparent from descriptions by Harmer and Sharpe (1985) who reported the presence of "pyroxenitic sills folded around closures of the Steelpoort pericline, along with tectonically thinned quartzites and interbedded hornfels".

The MSP at De Grooteboom is composed of migmatite (dark, banded) together with calc-silicate xenoliths

Farther south, including at De Grooteboom, Frischgewaagd, Rietfontein and Zwakwater, the MSP is relatively thick (1 to 2 km) and is part of an extensive magmatic shear zone. Irregular sheets of feldspathic pyroxenite, norite-gabbronorite, and quartz norite are intercalated with rafts of quartzite (Harmer and Sharpe, 1985; Clarke et al., 2005). The distinction between MSP and syn-Bushveld sills in the Pretoria Group is obscure. Calc-silicate xenoliths (derived from the Vermont Formation) are a significant component of the MSP at De Grooteboom. The migmatite exposed next to the xenoliths reveals a fine-grained norite-gabbronorite host containing thin bands of micropyroxenite (Figure 4b and c). Metre-sized sheath or disharmonic folds are indicative of early-stage deformation, i.e., when the MSP was partially crystalline (Sharpe, 1986; Clarke et al., 2005).



Fine-grained norite-gabbronorite and micropyroxenite in the migmatite show evidence of disharmonic folding. Flame textures on the upper contacts of the bands of micropyroxenite suggest injection of pyroxenitic magma into the norite-gabbronorite

References

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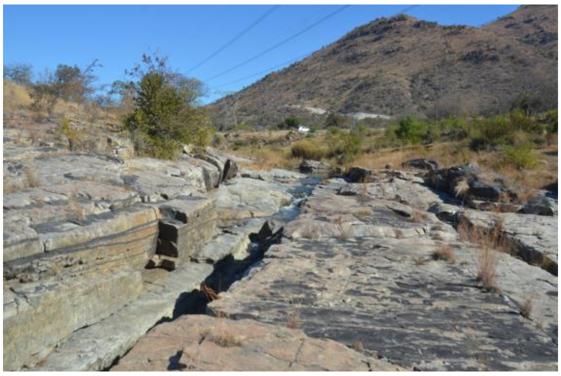
EL-15 UG1, Dwars Rivier

The national monument at Dwarsrivier is one of the most famous geological localities in South Africa. Access is from a track leading off the Lydenburg-Kennedy's Vale road. The intricate layering of chromitite and anorthosite is a feature of the UG1 chromitite throughout the intrusion. The main layer of chromitite is between 0.5 and 1.3 m thick but is both low grade (Cr/Fe ratio approximately 1.3) and only weakly mineralized (total PGE < 2 g/t on average). The interstitial material within the chromitite is plagioclase.



View of the narrow slot of the Dwars River looking south at the National Monument. The UG1 chromitite layer (dark) is seen to the centre right. The gently westward-dipping layers of chromitite intercalated with anorthosite in the footwall to the UG1 include a dip slope covered by a thin skin of chromitite. The hill slopes include mine workings associated with the UG2

The main UG1 chromitite layer is sandwiched between layers of anorthosite (footwall) and feldspathic orthopyroxenite (hangingwall)

The most intriguing feature is the presence of thin, bifurcating layers of chromitite within the anorthosite footwall. The thickness of chromitite i.e. main layer plus footwall layers remains more-or-less constant. The main layer is thickest in the southern part of the exposure (west of the river) and can be seen to initiate the bifurcation by the presence of a thin wedge of anorthosite that creates two layers of approximately equal thickness. The upper layer remains intact, but the lower layer divides, initially into two relatively thick layers. The lowermost of the latter two layers then cuts down into the anorthosite and repeatedly bifurcates into increasingly, and thinner and thinner, layers and stringers. Most of the bifurcation is seen to occur in a northward direction although some layers and stringers also rejoin the same layers.

The thin chromitite stringers reveal evidence of both brittle and ductile deformation, the latter suggesting evidence of migration of interstitial melt. Other features of note are partially resorbed xenoliths of anorthosite within the chromitite and occurrence of dendritic mottles of pyroxene in the footwall anorthosite.

Bifurcating layers and stringers of chromitite within anorthosite in the footwall to the UG1 include evidence of ductile deformation

The unusual occurrence of bifurcating chromitite layers within an anorthosite interpreted in context of the U and A lineage of magmas may be indicative of magma mixing processes (Sharpe and Irvine, 1983).

The possible existence of mobile chromite-rich crystal mush within an injection of ultramafic magma (Eales, 2002; Eales and Costin, 2012), however, is compatible with field evidence i.e. chromitite slurries have disengaged from the main layer and slumped into, and intruded, a partially crystalline anorthositic substrate. The dominant southward bifurcation is indicative of magma flowage and the presence of areas of intense footwall activity related to localized feeders.

The UG1 chromitite includes xenoliths of partially resorbed anorthosite

Injection of chromite-charged magma was accompanied by a major seismic event: syn-deformational features are found within the UG1 footwall throughout the RLS.

The dendritic mottles are interpreted as evidence of partial (disequilibrium) melting of the anorthosite (Mitchell and Manthree, 1998) and localized downward draining of melt. This hypothesis is suggested on the premise that disequilibrium partial melting of noritic rocks may produce a pyroxenitic melt as the plagioclase remains largely inert (Naslund, 1986; Philpotts et al, 1999).

Deformation of chromitite stringers in the footwall anorthosite includes formation of chromite schlieren and ptygmatic folding

Dendritic mottle (oikocrysts) of pyroxene within a thin layer of anorthosite intercalated between two chromitite layers

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