Geology 314
Accretion of the Bushveld complex

Foreword:

This document is not a stand-alone document; it's written as an example showing how the documents of the prac 9 (Geol 314, Stellenbosch, 2007) can be used to discuss the construction of the Bushveld complex. It is written in a form as similar as possible to a scientific paper, and does obviously go much beyond what was expected in this prac!

1. Introduction

The Bushveld complex is, by far, the largest layered mafic intrusion in the world. From bottom to top, the Complex features rocks evolving from peridotites and pyroxenites, to gabbros and finally to diorites and rare granites. The overall trend towards more differentiated rocks upwards is evocative of closed-system magma differentiation, by fractional crystallization, leaving a succession of cumulates at the bottom of the magma chamber. On the other hand, the sheer size of the complex, together with other chemical evidence discussed below, suggest that the Bushveld probably evolved by the accretion of successive batches of magma. Here, I will discuss some salient petrological and geochemical features of the complex, and integrate them in a global model for the accretion and evolution of the complex.

2. Geological setting

2.1. Regional geology

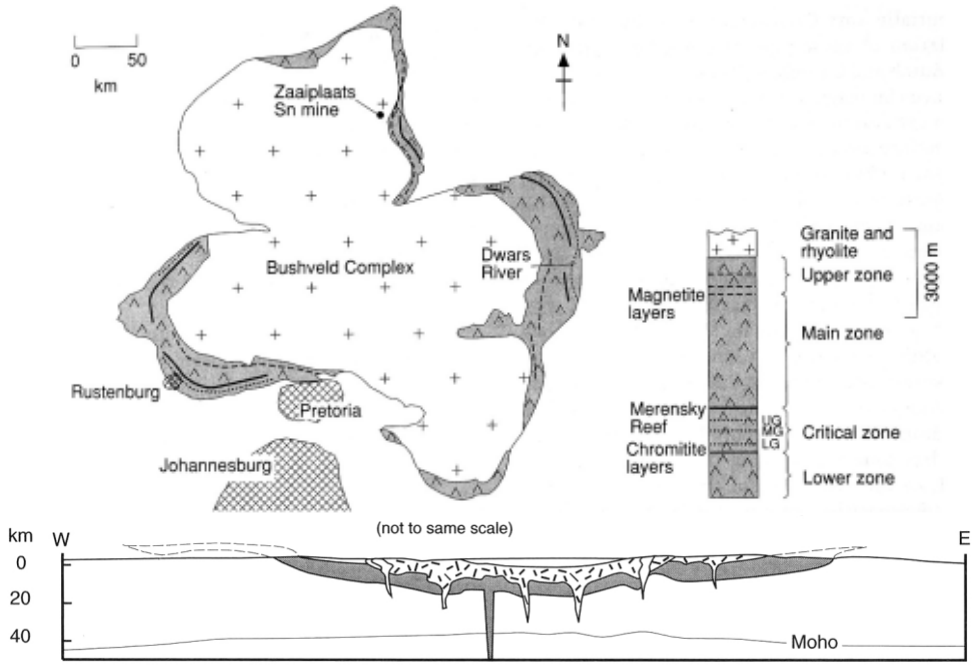

Figure 1: Map and cross-section in the Bushveld Complex (Winter 2002).

The Bushveld complex crops out in the Northern part of South Africa, in the provinces of North-West, Limpopo and Mpumalanga. It is about 300-400 km wide and 5-10 km thick; its total surface is close to 55,000 km^2. However, a large part of the complex is actually covered by younger deposits, and the actual outcrop of mafic rocks has a complex ring shape, allowing to identify three main "lobes" (fig.1):

- A western lobe, forming an arc from Pretoria to Rustenburg to Warmbaths (Bela-Bela);
- An eastern lobe, from North of Belfast to Burgersfort;
- A northern lobe, from Potgietersrus (Mokopane) to Villa Nora.

The complex is mostly flat; it forms a sill intrusive into older rocks. The footwall is mostly Transvaal group sediments, occasionally the Archaean basement of the Kaapvaal craton; the hanging-wall is often made of rhyolites from the Rooiberg group, emplaced shortly before the complex itself.

The Complex emplaced at ca. 2.05 Ga (Harmer and Armstrong 2000), probably in a very short time period (< 1 Ma), in an essentially intraplate situation. However, subduction and collision zones were active in southern Africa at the time, resulting in the development of faults that probably guided the emplacement of the Complex.

2.2. Stratigraphy

Four main units, or groups, are recognized in the complex, allowing to define a regional stratigraphy (Fig. 1):

- The **lower zone** (discontinuous, up to 1 km thick) is mostly made of ultramafic cumulates (peridotites and pyroxenites), with subordinates norites and gabbros;
- The **critical zone** (ca. 1 km) is strongly layered, and shows numerous "magmatic cycles", rangind from pyroxenites to norite to anorthosite, with occasional chromitite layers. The top most portion of the critical zone (or lowermost of the main zone) is PGE-rich, and is called the "Merensky reef".
- The **main zone** (ca. 4 km) is made of a thick, monotonous sequence of gabbro-norite;
- The **upper zone** (1.5 km) is layered and evolves upwards from norites to gabbros, diorites and minor felsic intrusives.

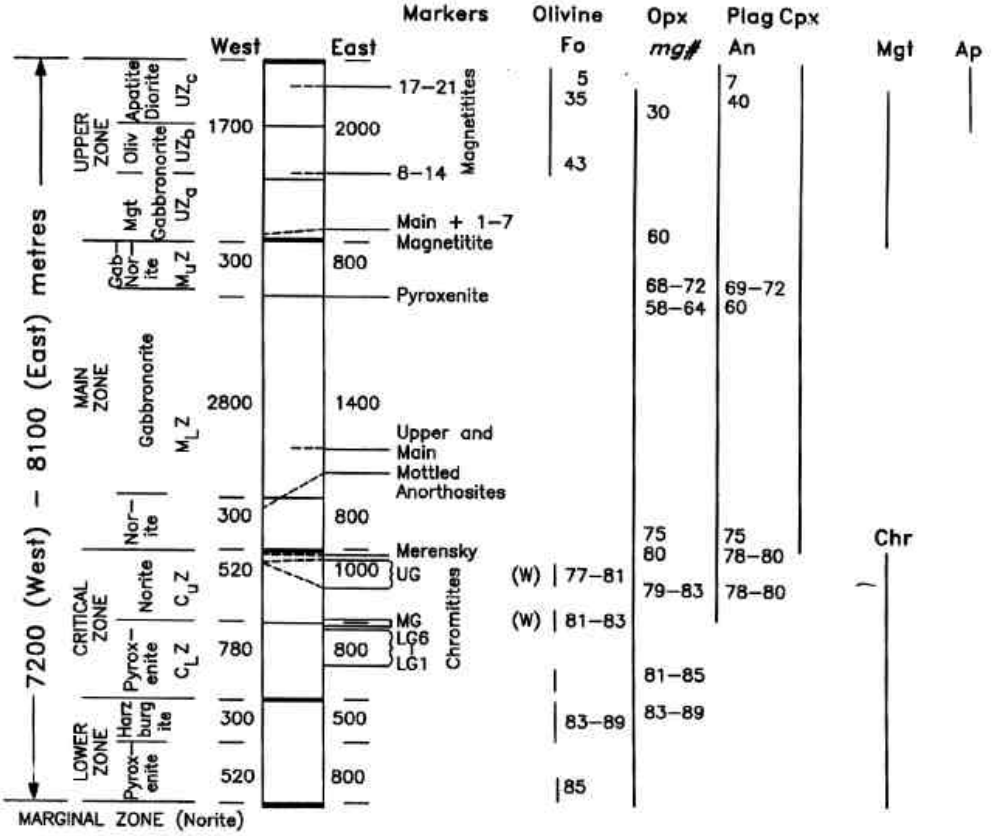

Figure 2: Synthetic "log" in the Bushveld complex, showing the evolution of mineral compositions (Eales and Cawthorn, 1996)

3. Petrography

3.1. Lower and critical zones

Samples from the lower and critical zones are periodites, pyroxenites, norites and some anorthosites; chromitite layers are also found. Although all minerals are not present in all samples, the generalized sequence of crystallization is olivine ? orthopyroxene ? plagioclase (anorthite-rich) (Figure 3); this is the succession that is predicted by a Fo(rsterite)-An(orthite)-SiO2 ternary phase diagram, for a composition starting in the Fo field, left of the En-An joint but probably close to it.

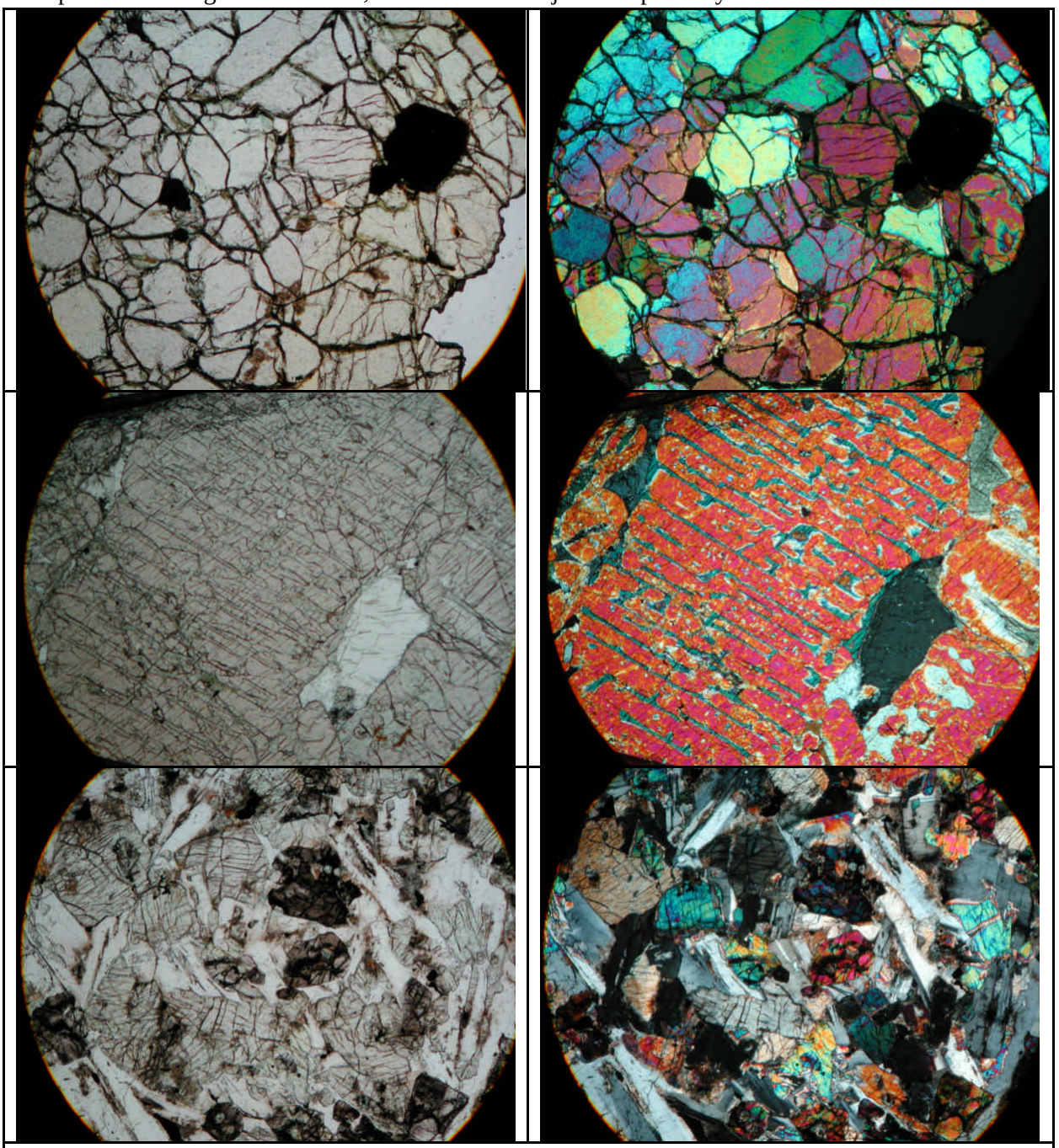

Figure 3: Microphotographies of samples from the lower and critical zones. For each sample, a PPL photo is on the left and XPL on the right. From top to bottom: dunites, pyroxenites (note the exsolution lamellas in the orthopyroxene, and the intersticial plagioclase), olivine-norite.

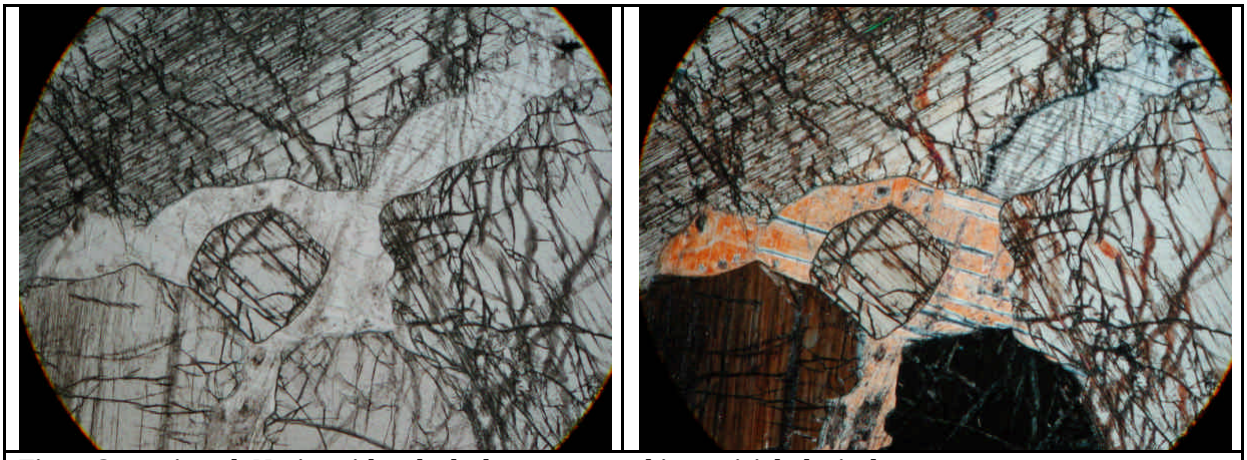

Figure 3, continued. Norite with euhedral pyroxene and intersticial plagioclase.

As the magma cools down to the liquidus (A on figure), it arrives on the liquidus surface in the "forsterite" field. It therefore forms forsterite, and the composition of the remaining liquid evolves directly away from the olivine (forsterite) corner. When the liquid composition reaches the peritectic joint En-Fo (B) (which is peritectic and not cotectic, as the mineral En does not plot in the En field – see phase diagram prac, or Winter chap. 6 p. 98 & chap 7 p.109), liquid and olivine react together to form enstatite; the liquid follows the peritectic joint. Since it started in the Fo-En-An triangle, the olivine is not entirely consumed; the liquid eventually reaches point (C), where it crystallizes. Olivine is largely resorbed by the peritectic reaction, explaining its relatively low abundance in most norites.

However, while the mineralogy and textures do match a pure fractional crystallization model, it must be kept in mind that the critical zone is made of a succession of magmatic cycles, starting with ultramafic cumulates (peridotites/pyroxenites) and evolving upwards into norites and anorthosites. Whereas the evolution within each cycle is compatible with pure, in-situ differentiation, the very existence of successive cycles calls for another explanation.

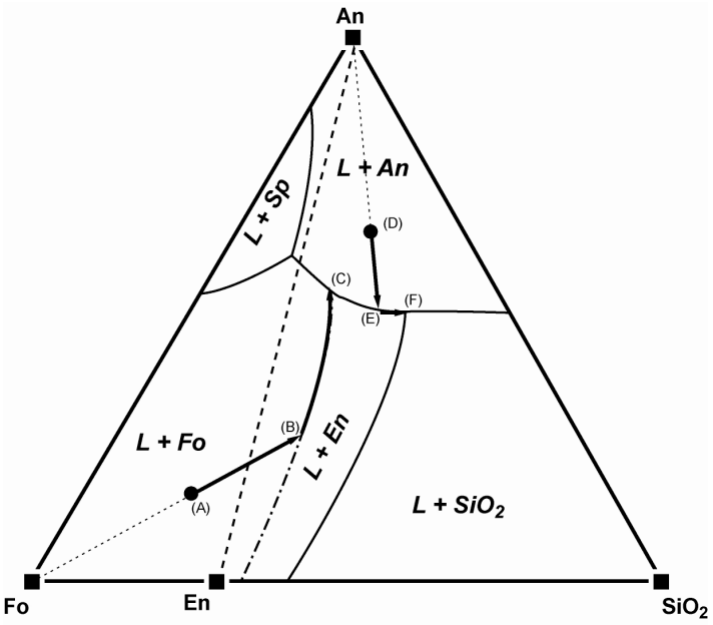

Figure 4: Evolution of the critical (A-B-C) and main (D-E-F) zone magmas in a Forsterite-Anorthite-Silica diagram. Modified after Winter (2002)

3.2. Main zone

Norites from the main zone show different features. Here, the first mineral to crystallize is more commonly plagioclase, followed by orthopyroxene. This "reversed" sequence (compared to the critical zone) can also be explained by fractional crystallization – assuming an initial magma with a

composition within the An field of the Fo-An-SiO2 diagram, figure 4 (e.g. D). Such a magma will first form anorthite, until it reaches the cotectic An-En (at E) and follows it to the eutectic (F).

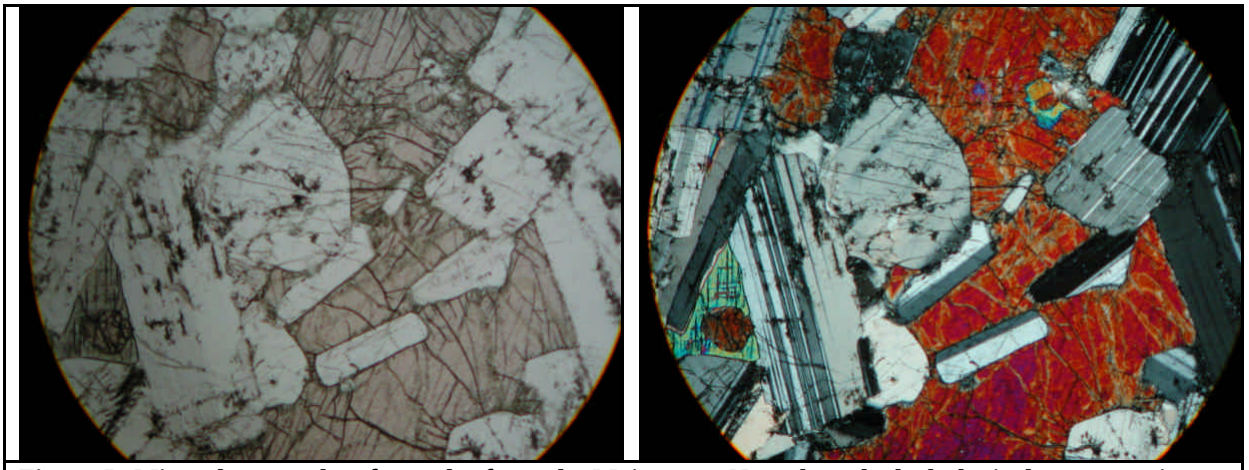

Figure 5: Microphotographs of samples from the Main zone. Note the euhedral plagioclase, occurring as inclusions in orthopyroxene.

This shows that the parent magma for the main zone was different from the parent magma of the critical zone. Whereas the former had a composition in the An field, the latter was in the Fo field. Petrography therefore shows that at least two contrasting types of magmas existed within the Bushveld intrusion, suggesting at least one event of magma addition into the magma chamber.

Finally, the main zone is not, or weakly, layered; in particular the cyclicity that is typical from the critical zone is essentially missing here. The main zone is almost exclusively made of gabbronorite, suggesting that the batch of main zone magma essentially cooled in-situ as one unit, with minor crystal settling (to form cumulate layers).

3.3. Upper zone

No samples were supplied for the Upper Zone. Examination of the "stratigraphic" column reveals that (1) the upper zone shows an upwards evolution consistent with differenciation, from pyroxenite to gabbro-norite to diorite; (2) The upper zone shows little or no cyclicity, although several magnetite layers are present, similar to the chromitite layers in the critical zone.

Mineralogical data show that olivine (more precisely, Fayalite-rich olivine, close to the iron-reach end-member) is present at the top of the upper zone. This is unexpected and difficult to account for when simply considering the Fo-An-SiO2 system; however, in Fo-An-SiO2 iron is not considered (or implicitely associated with MgO, assuming both behave in the same way and substitute perfectly for each other). Examination of systems that separate FeO from MgO (such as Fo-Fa-SiO2) reveals that indeed, a magma starting at composition (A) in this diagram will evolve to the Opx-Ol peritectic line; what will happen here depends on the original composition, and on whether the olivine crystals stay in the liquid or settle away from it. In any case, as the Opx field pinches towards the Fe-rich side, the liquid will eventually reach again the Ol field or the Ol-SiO2 cotectic, therefore resulting in the formation of Fe-rich olivine together with quartz: a noticeable, but very uncommon exception to the common rule stating that olivine and quartz never exist together in a rock.

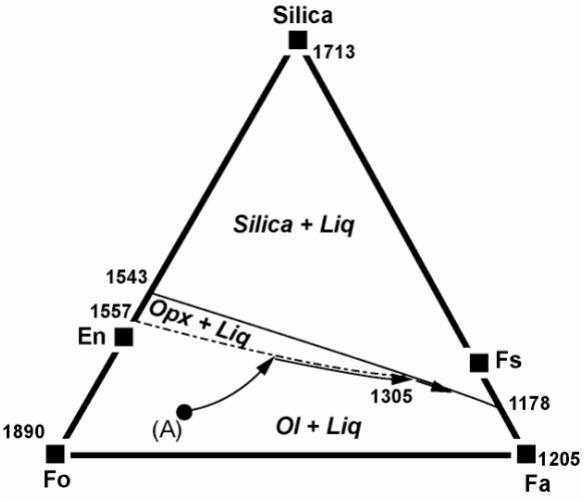

Figure 6: Possible evolution of Bushveld-type magmas in a forsterite-fayalite-silica diagram. The path does not correspond to any sample in particular, but explains how Fe-rich olivine can (re)appear at the top of a differenciation sequence. Modified after Winter (2002)

3.4. Conclusion

Petrographic studies reveal the existence of at least two (possibly three) different batches of magma. The first one is in the olivine field, and emplaces to form the lower and critical zones. The second one has plagioclase as a liquidus phase; it forms the main zone. Without being possible to demonstrate with our data, it can be proposed that the upper zone formed from a third (different?) batch of magma.

The existence of magmatic cycles in the critical zone, however, strongly suggest that this zone might, itself, be made of more than one magma injection.

4. Major elements geochemistry

Major elements chemistry mostly confirm the petrographical conclusions.

4.1. Lower and critical zones

The composition of samples from the critical zone plot as a complex pattern, that is U-shaped in the SiO_2-FeO+MgO diagram, and more simple in the others.

In binary diagrams, fractional crystallization of cumulates with single compositions result in linear trends, pointing directly away from the cumulate's composition. If the cumulate does not change throughout the differentiation, a simple segment is expected. The U-shaped pattern observed in the critical zone implies that three successive cumulates formed.

Plotting the composition of individual mineral phases in binary diagrams shows that each segment can be interpreted as resulting from the composition of one single mineral phase. In the SiO2 vs. MgO+FeO diagram (which is the most interesting here), olivine plots in the upper left corner; olivine fractionation of a liquid somewhere around 45% FeO+MgO and 40-45 % SiO2 (A) will result in a trend with compositions evolving straight away from the olivine "point", corresponding to the upper most segment. After some olivine has been formed, the composition of the remaining magma arrives to composition (B). Fractionnation of orthopyroxene from (B) will create a nearly vertical trend, corresponding to the right-hand segment of the "U", until composition (C). Finally, fractionation of plagioclase out of (C) will move the composition to the left, resulting in the lower "leg" of the U-pattern. Collectively, the geochemical pattern observed here is consistent with the successive fractionation of olivine, orthopyroxene and plagioclase – a sequence predicted by phase diagrams and consistent with petrological information in the critical zone.

In other diagrams, this evolution is less obvious because more than one mineral phase plot together – identifying the contribution of each is therefore not possible. It can be noted, however, that none of the data available contradicts the model proposed above; fractionation of olivine, orthopyroxene and finally plagioclase can account for the trends observed in all diagrams.

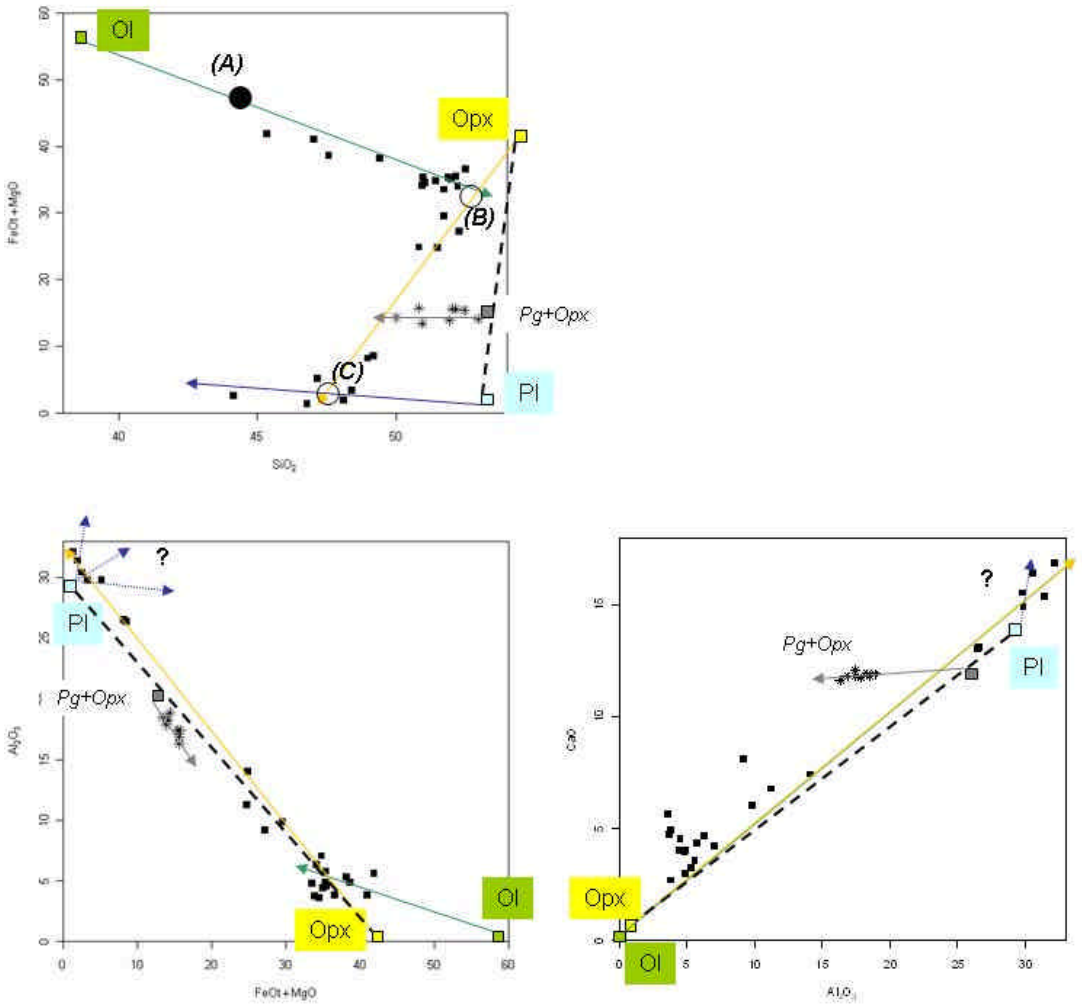

Figure 7: Major elements geochemistry of Bushveld samples. In the critical zone (squares, with trends drawn in colour), the successive precipitation of olivine (green), ortopyroxene (yellow) and plagioclase (blue) can explain the different compositions observed. A different, simpler evolution can account for the evolution in the main zone (stars); there, co-precipitation of orthopyroxene and plagioclase (composition along the dashed line, grey square, controlling the grey trend) defines trends similar to these observed for main zone norites. Data J. Miller (pers. Com.) and Nex (. 2002).

It must be stressed that the samples used to construct this diagram come from different cycles within the critical zone – not from a single one, but from a collection of cycles. This emphasizes the fact that all cycles of the critical zone actually are very similar to each other in terms of chemistry and petrology; in other words they evolved all from a similar magma.

4.2. Main zone

The data we have for the main zone shows strikingly different features. Firstly, there is not such a large compositional spread as in the critical zone, consistent with the fact that the main zone is mostly gabbro-norites, with little or no other rocks. Secondly, the samples from the main zone only partially overlap the compositional range for the critical zone, again emphasizing the different nature of the parental magmas in both parts. Thirdly, the trend defined by the main zone magmas is not consistent with fractionation of any single mineral; it could be related to the fractionation of plagioclase+pyroxene together (again, in good agreement with petrology). Finally, the differentiation

trend (if it is one) is actually very short, compared to what happens in the critical zone; this implies that differentiation was only a minor process here, and that most main zone magmas are primarily melts chilled in place, with little fractionation.

4.3. Conclusion

Major elements chemistry confirms the petrological data: there is a first order diference between the critical and the main zons. The critical zone is made of a relatively mafic magma (able to form olivine as the first mineral crystallizing), that differentiated and formed cumulates; several cycles of differentiation (and, probably, of magma recharge) resulted in the layering of the critical zone. In contrast, the main zone appears as being made of one single batch of a more felsic magma (plagioclase in the liquidus), that did not, or not much, differentiate and mostly chilled in place.

Table 1 (Eales and Cawthorn 1996) shows the (calculated) composition of the parental magmas of both the main and the critical zone (the way this composition was calculated is beyond the scope of the present exercise). It nicely evidences the difference between the two parental magmas. Note how their composition fits with the "theoretical" parents magmas determined graphically.

5. Isotope geochemistry

5.1. Global evolution

Observation of the diagram figure 8 shows that the large scale pattern of Sr isotopic evolution from the bottom to the top of the Complex confirms our petrological and geochemical conclusions. The ISr values are variable but low (.705 to .706) in the lower and critical zone; they are still variable, but higher in the lower part of the main zone (between .708 and .709); and they are constant in the main and upper zones, at resp. .7085 and .7075.

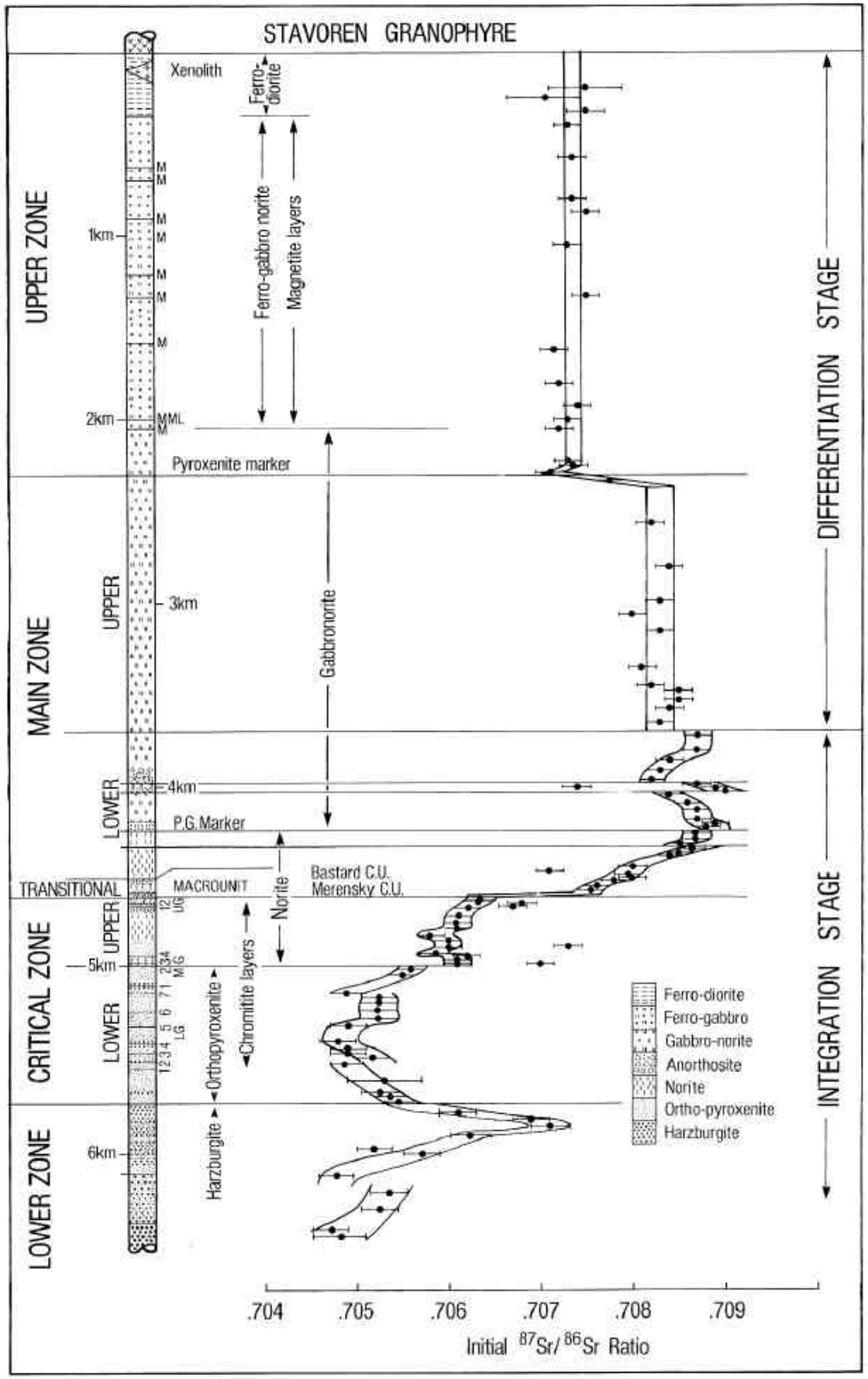

Figure 8: Evolution of the Sr initial isotopic ratio (recalculated at 2.05 Ga) along a vertical section in the Bushveld complex (Eales and Cawthorn, 1996). Comments in text.

At this scale, this confirms the existence of a few batches of magmas, with different compositions; we had previously demonstrated that the parent magmas in each zone was chemically different, we now see that the different parent magmas also had different isotopic compositions, and therefore came from different sources.

The differences, however, are not huge. While they are larger than the analytical error (from the graphic, it would be around ± 0.0002, i.e. .7080 ± 0.0002 = from .7078 to .7082), the total spread of data is between .7045 and .7085, which is well within the range of mantle values; the continental crust in the Kaapvaal craton at the same period (2.05 Ga) was typically between .705 and .725.

5.2. Details of the lower and critical zone

Again, details of the isotopic evolution in the critical zone show a much more complex behavior, just as could be seen with petrography and major elements geochemistry. In this part of the Complex (and isotopes suggest that the lower part of the main zone actually belongs to this group, rather than to the upper half of the Complex), the Sr isotopic ratios are characterized by very unstable values, irregularly rising and dropping. Since fractional crystallization does not change the initial Sr ratios, this evolution must be related to successive venues of magmas with slightly different isotopic compositions – similar, but not identical. This confirms the conclusion drawn by the cyclic nature of this part of the Complex.

6. Meaning of the magmatic cycles and of the chromitites layers in the lower and critical zones

The critical zone (in fact, the lower zone, and the bottom of the main zone, show very similar features) is made of a succession of lithological cycles. Each cycles, from bottom to top, is composed of

- Ultramafic cumulates (dunite/harzburgite/pyroxenite in this order, in a "complete" cycle);
- Norites;
- Anorthosites.

A 10—100 cm layer of chromitite marks the top of the sequence, and is followed by a new cycle, starting again with ultramafic cumulates. The photo fig. 9 shows the chromitite unit UG3 of the critical zone on Mandaagshoek; it is above anorthosite, and below (in this case) pyroxenite.

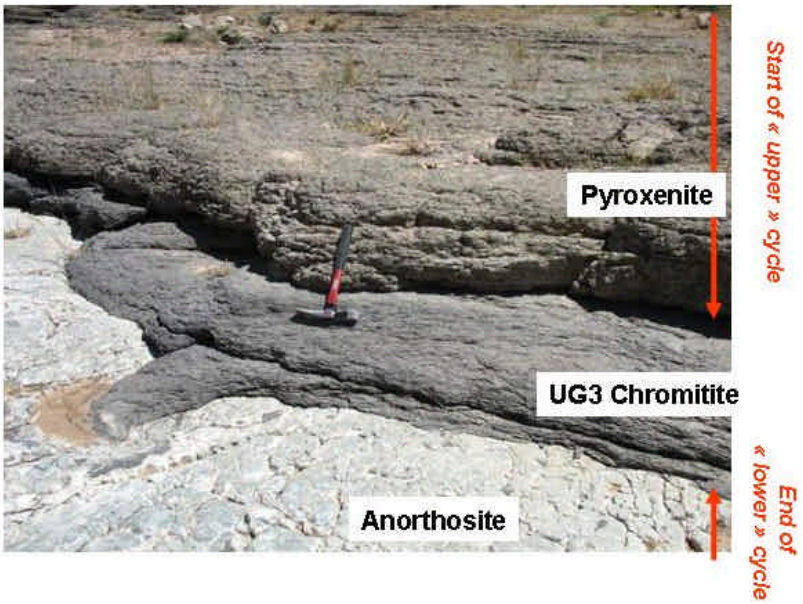

Figure 9: Outcrop of UG3 chromitite, farm Mandaagshoek, near Burgersfort (MP)

As suggested by petrography and isotopes, each cycle could correspond to a new magma injection; the recharge of fresh, undifferenciated magma into the magma chambers "moves back" the composition into the orthopyroxene, or even the olivine stage.

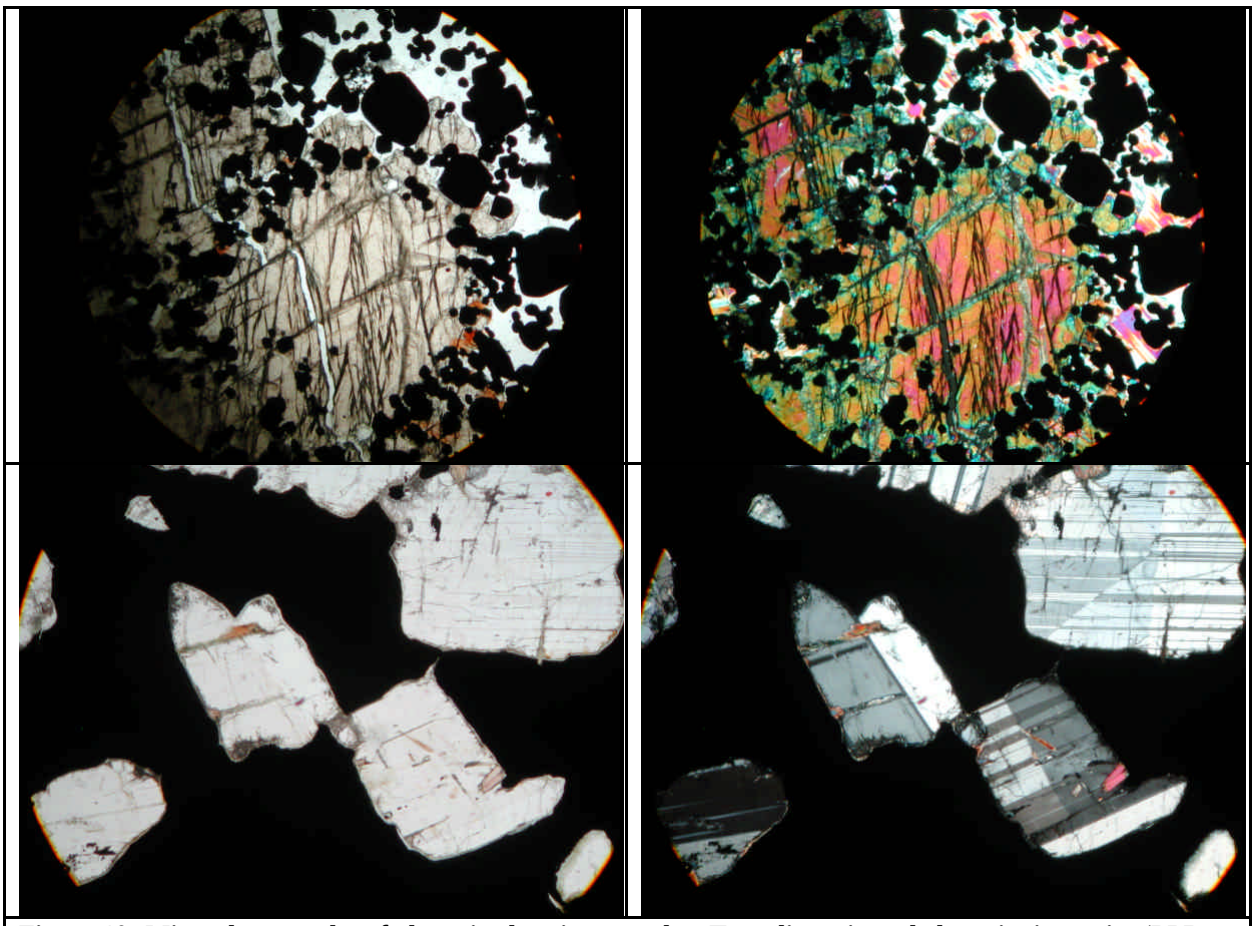

Figure 10: Microphotography of chromite-bearing samples. Top: disseminated chromite in norite (PPRust mine). Bottom: Interface between a chromitite and an anorthosite layer; the sample is made of chromite and anorthite. In each set, left is PPL and right XPL.

The existence of chromitites layers actually supports this model. In the SiO2-Fo(rsterite)-chromite diagram (Figure 11) it is possible to see that a magma with an initial composition in the olivine field (A) will evolve firstly to the olivine+chromite cotectic (forming dunite with disseminated chromite); then to the orthopyroxene+chromite cotectic, crossing the Fo-En peritectic line. It will then form pyroxenite with disseminated chromite. If at this stage fresh magma, of the initial composition, is injected into the magma chamber, it mixes with the differenciated magma (B) and produces a mixture of composition (C) that –depending on the proportions and the degree of differenciation—can have a composition within the chromite field. In this case, pure chromite is formed until the magma moves back to the olivine-chromite (in this case) cotectic, where a new cycle starts.

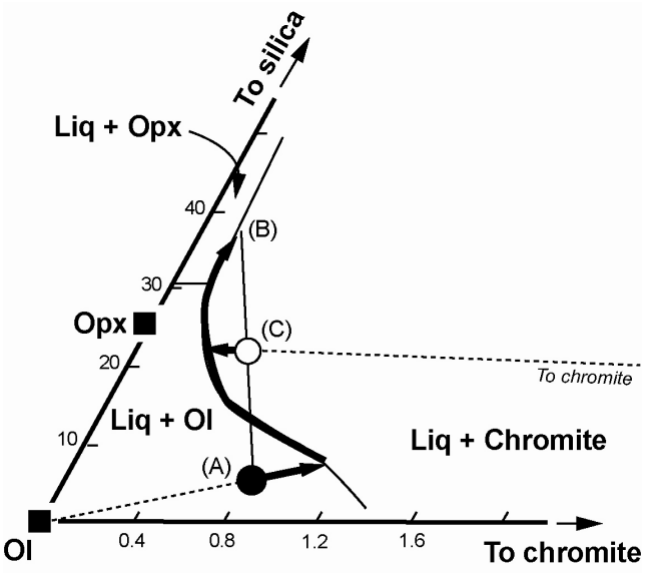

Figure 11: Possible evolution of chromite-rich magmas from the critical zone. Magma recharge can result in the formation of a chromitite layer (comments in text). Modified after Eales and Cawthorn (1996).

7. Discussion

7.1. A model for the accretion of the Bushveld complex

The data presented here allows to propose a model for the emplacement of the Bushveld complex.

- The lower and critical (and lower main) zones are formed by the successive accretion of small batches of a magma of constant composition – with olivine on the liquidus. Each successive batch evolves by fractional crystallization and crystals separation, forming a succession of ultramafic cumulates, norites and anorthosites. Mixing of the recharged magma with the residual magma, in the magma chamber, results in the formation of successive cycles, separated by chromitite layers.
- The (upper) main zone, in contrast, is formed by one large batch of a different magma (with plagioclase as the first liquidus phase). It is very homogeneous, and mostly evolves by in-situ crystallization, with little crystal settling.
- The upper zone apparently corresponds to another big batch of magma, that undergoes some fractionation and crystal settling, resulting in a pile of progressively more differenciated rocks.
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7.2. Comments and criticisms

Several observations (within the scope of this paper – and more if taking into account other data!) do not fit in this model, for instance:

- The existence of multiple cycles in the critical zone would imply as many successive magma injections (several tens). How realistic is this?
- The details of the layering are not always consistent with a magma recharge driven cyclicity (see photo); for instance, the branching chromitite layers in anorthosites at Dwars River implies more complex processes. In other places, the layering correspond to changes in mineral proportions (but not in their nature), inconsistent with pure fractionation.
- The upper zone itself shows some cyclicity, and several layers of pure magnetite, that point to processes more complex than pure in-situ fractionation.
- The idea that the main and upper zone were formed by single magma batches is also surprising, as it would imply that, at this time, there was a several kilometers-thick liquid layer in the crust. Whether such a large body of liquid is physically sustainable is open to question

Figure 12: Some features of the Bushveld complex poorly explained by the model presented here. Top left: repeated alterance of chromitite and anorthosite layers (Dwars River, Critical zone), with bifurcating chromitite layers and "xenolith" of anorthosite in chromitite. Top, right: Modal layering in the main zone (near Dwars River), materialized by changing mineral proportions. Bottom, left: The Main Magnetite Layer in the Upper zone, at Magnet Heights. Its existence does not fit into a simple fractionation scheme. Bottom, right: field appearance of the MML, with euhedral magnetite and intercumulus plagioclase.

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8. Conclusion

The Bushveld complex appaeras to be the product of the accretion of individual magma batches, that can mix with residual liquids present in the magma chamber. Following their emplacement, magma batches evolve, dominantly by fractional cruystalization.

Magma batches can be small (such as in the lower and critical zones, where they correspond to several tens of meters of stratigraphy); or larger, in the main and upper zone (several kilometers).

As a whole, the Bushveld complex "mimics" a series differenciating by fractional crystallization, with ultramapfic cumulates in the lower zone, followed by norites, gabbros and finally diorites. However, closer examination shows that this is only apparent; the complex is really made of a succession of – progressively more differenciated—batches of magma.

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