Parental magma of the Bushveld Main Zone : constraints from in-situ trace elements of cumulus minerals

Sheng-Hong Yang[1], Wolfgang D. Maier[1,2] , Bélinda Godel[3], Sarah-Jane Barnes[4], Eero Hanski[1], Hugh O'Brien[5]

1. Oulu Mining School, University of Oulu, Finland
2. School of Earth & Ocean Sciences, Cardiff University, UK
3. CSIRO Earth Science and Resource Engineering, Australian Resource Research Centre, Australia
4. Science de la Terre, Université du Québec à Chicoutimi, Chicoutimi, QC, Canada
5. Geological Survey of Finland, Espoo, Finland

Outline

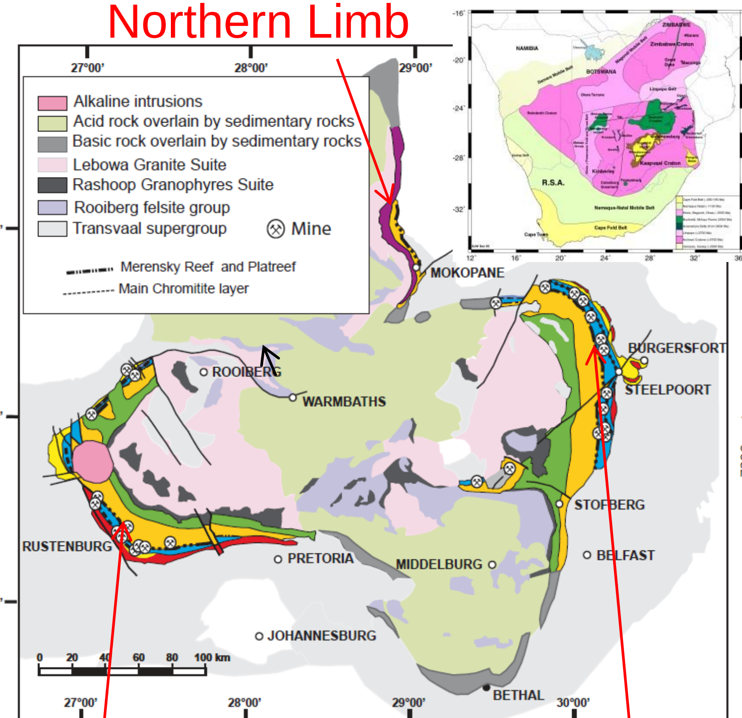
- Geological background of the Bushveld complex

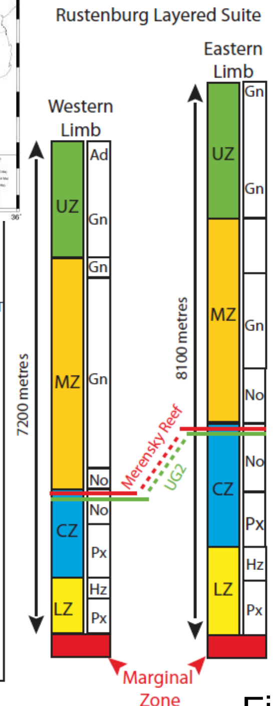
- Key processes :
  - Crystal fractionation of main magma,
  - Crystal fractionation of trapped liquid,
  - Trapped liquid shift

- Constraints on the parental magma of Bushveld Main Zone

Bushveld complex World largest Cr, PGE, V deposit

Northern Limb





Upper Zone (V)

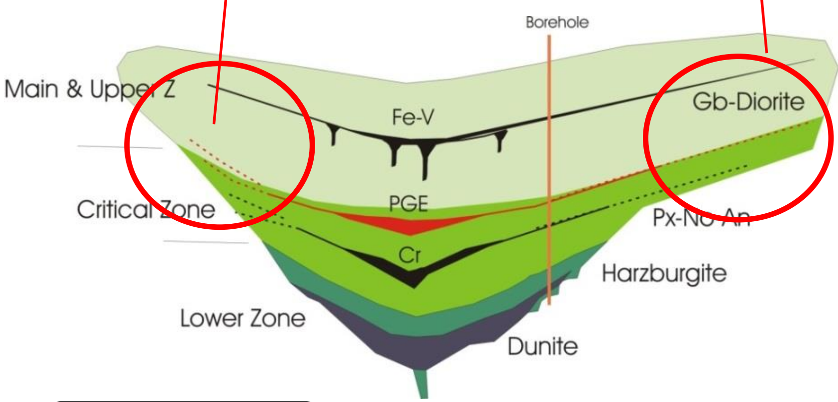
Main Zone

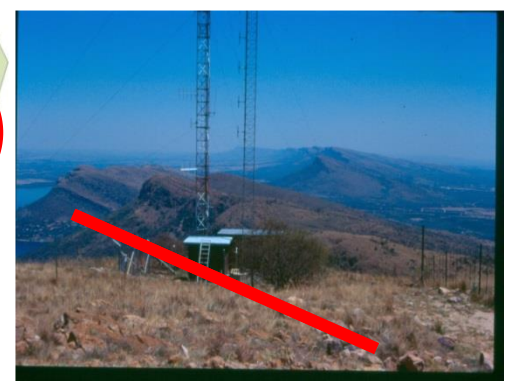
Critical Zone (Cr, PGE)

Lower Zone

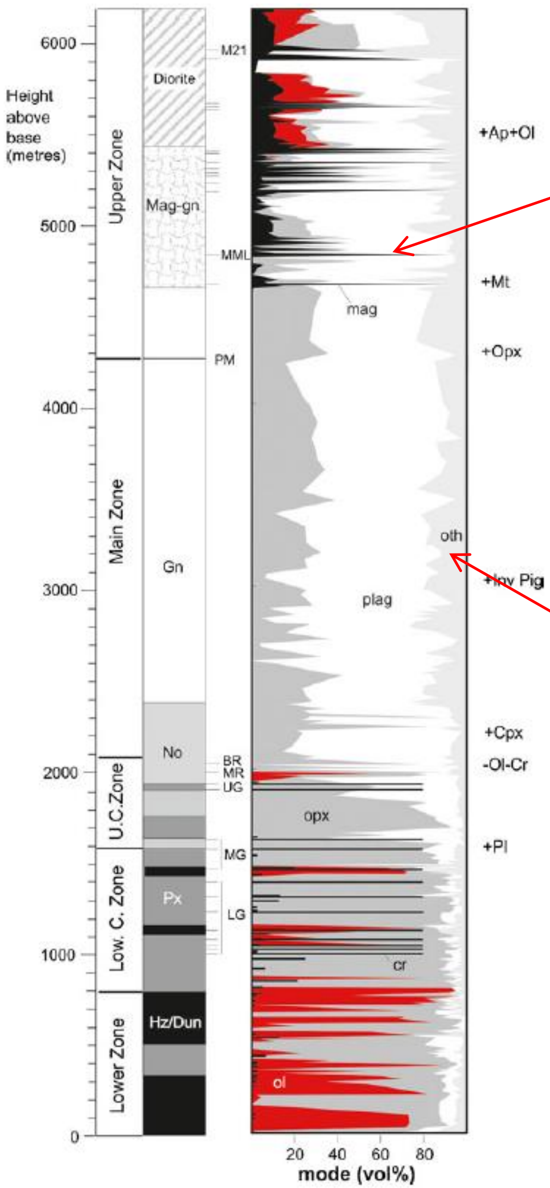
Marginal Zone

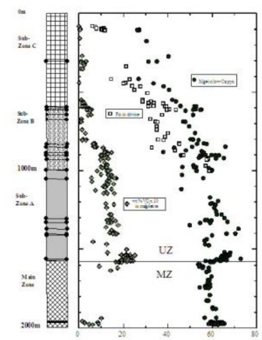
Figure from Godel, 2015





Only western and eastern margin crop out





Upper Zone

Magnetite gabbronorite Anorthosite

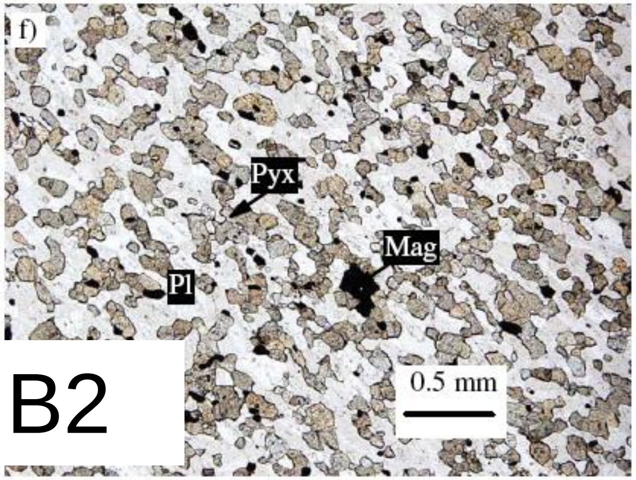
Maier et al., 2013,

Main Zone

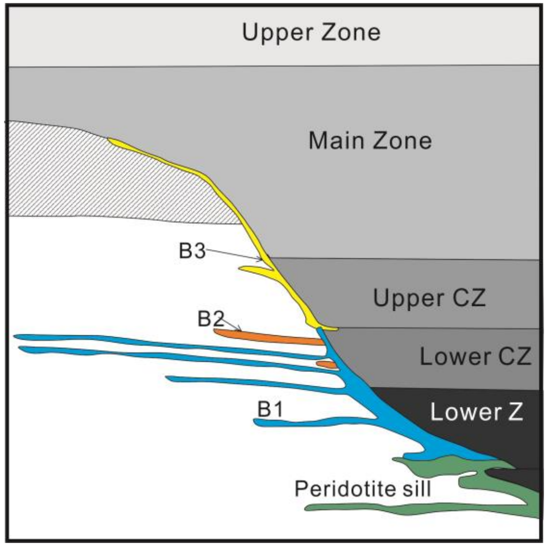
gabbronorite

3 types of marginal rocks, potentially represent parental magmas of Bushveld

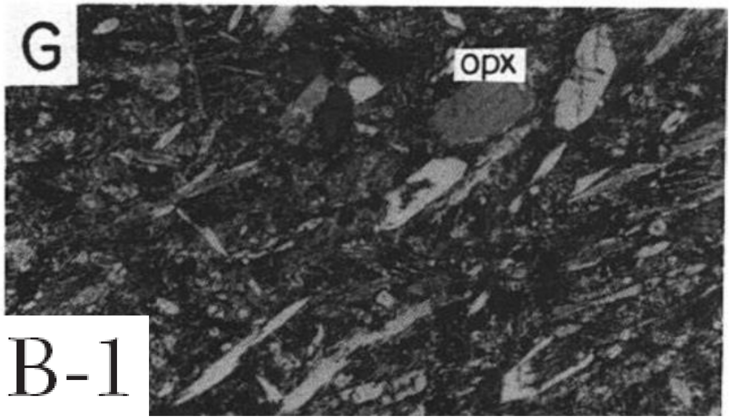
- B1 micro-orthopyroxenite
- B2 microgabbro
- B3 microgabbro

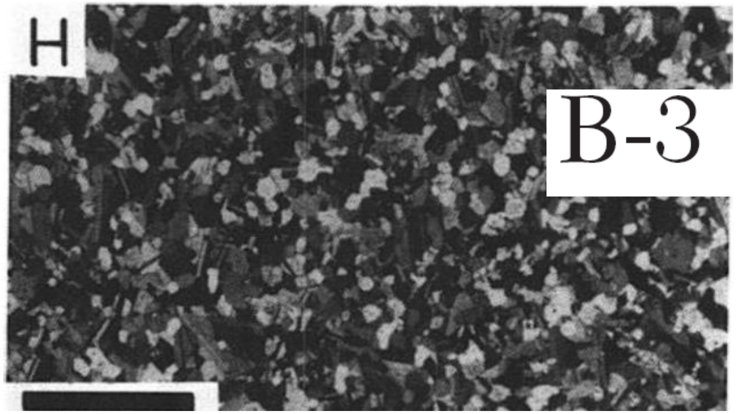


Barnes et al., 2010



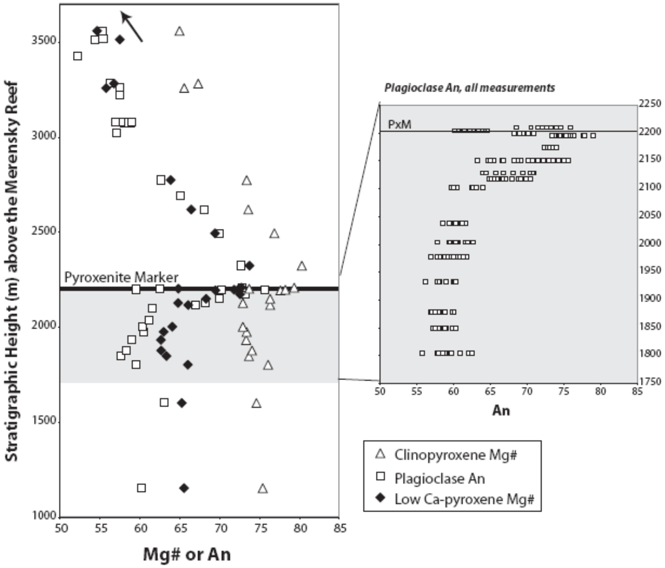
Modifed afrer Harmer and Sharpe, 1985

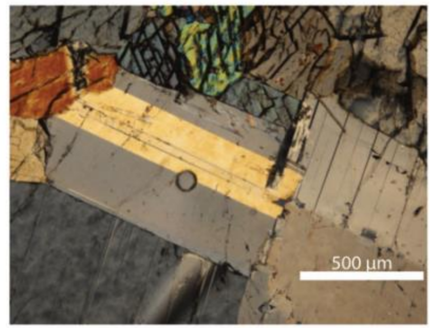


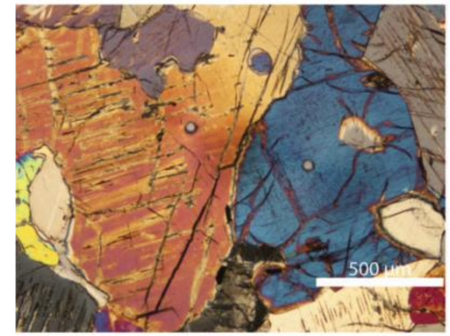


Harmer and Sharpe, 1985

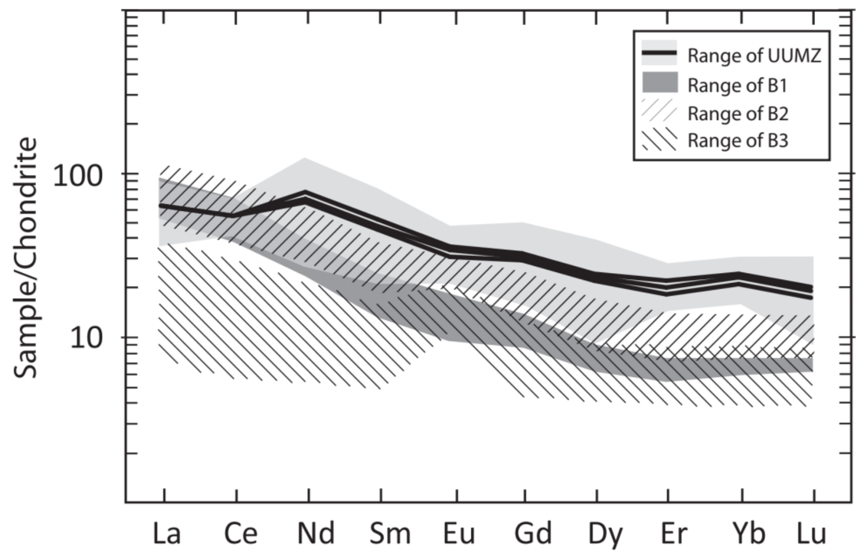
Constraints on the parental magma using in-situ trace elements of cumulus minerals, upper zone







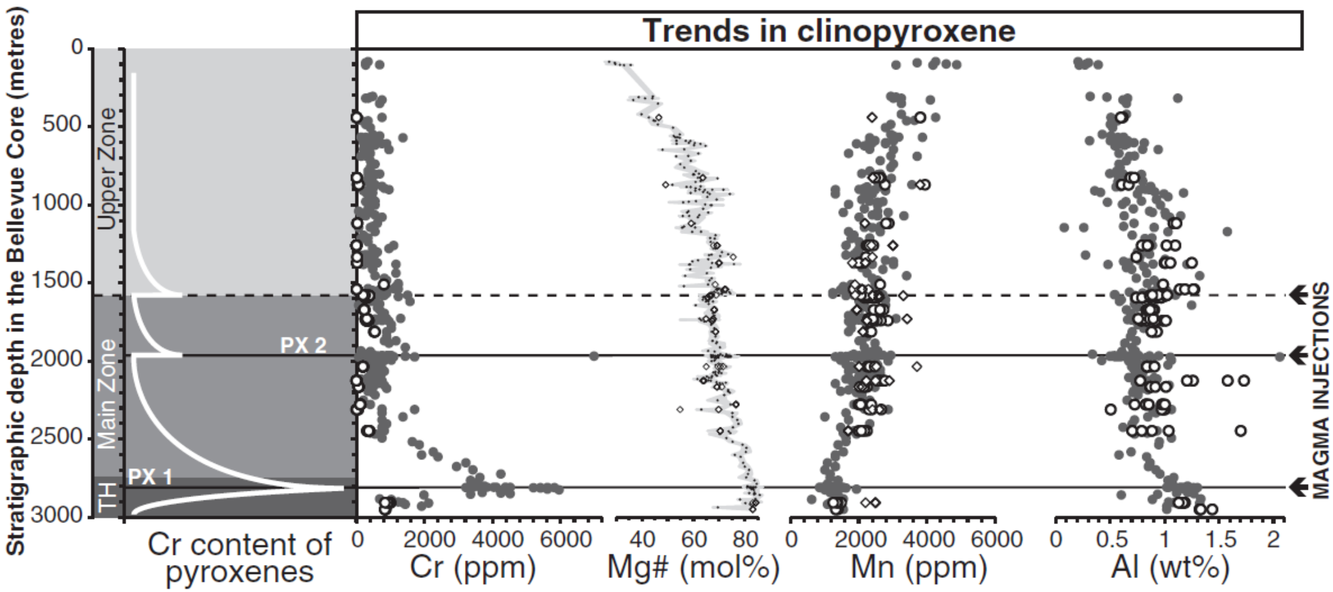
- At the pyroxenite marker, there is a large magma recharge event
- **Assuming core of minerals preserve the original composition**
- The feeding magma composition is closed to B2 type marginal rocks



VanTongeren & Mathez (2013)

Problems using in-situ trace element of cumulus:

Only Cr in pyroxene preserved the original composition,
but all other elements have been modified！！



eral basis, and show that the Cr content of pyroxene is the only proxy that records three cryptic magma injections, coincident with two pyroxenite horizons and the UZ–MZ boundary. On the

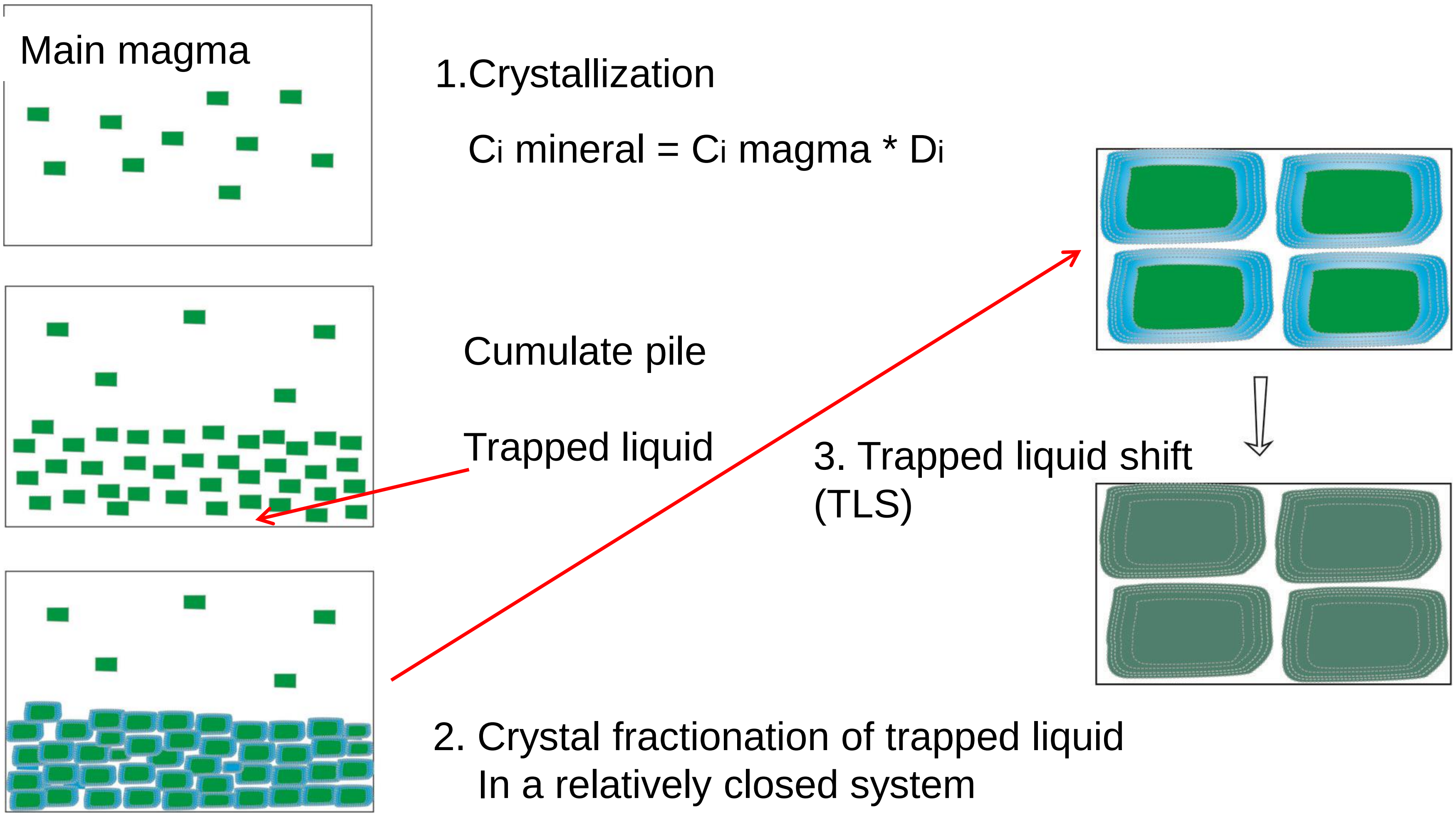
Tanner et al., 2014

Questions ?

- Are all elements modified except Cr ?
- To what extent does TLS affect the trace elements
- What useful information can we get from in-situ trace element of cumulus minerals ?

Three key processes

1. Crystallization from main magma (forming cumulus core)
2. Crystallization of trapped liquid (forming overgrowth rim)
3. Trapped liquid shift (diffusion driven homogenization)



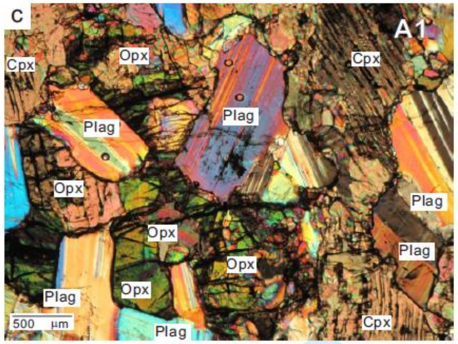
Cumulus minerals in Main Zone

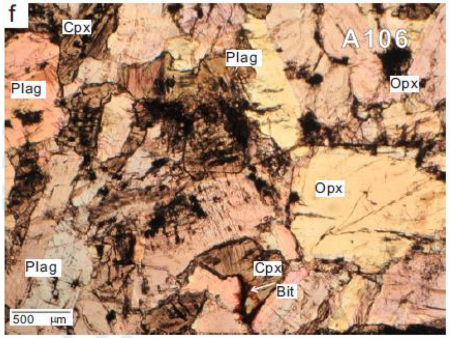
- Plagioclase
  40-50%

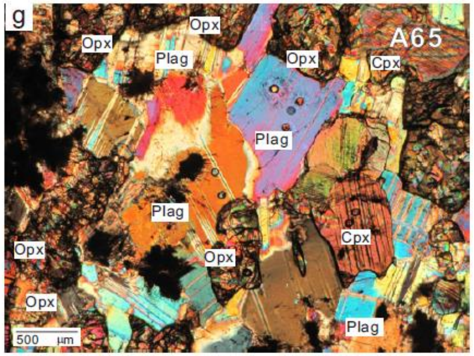
- Orthopyroxene
  15-20%

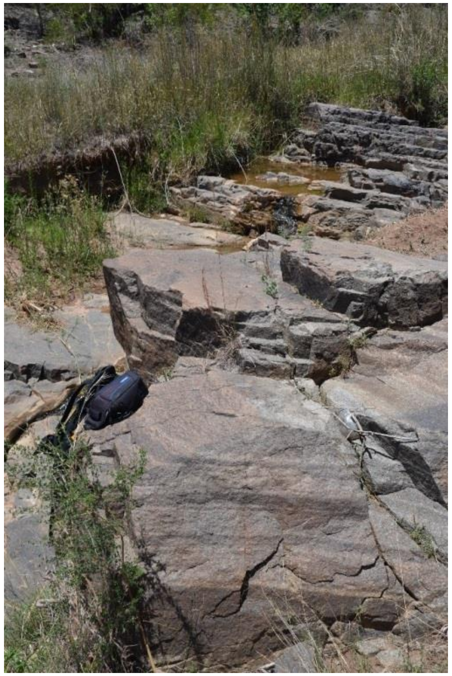
- Clinopyroxene
  20-30

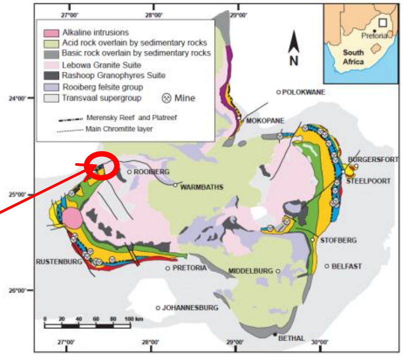
- Biotite, quartz, K-feldspar
  <5%
  representing final evolved liquid



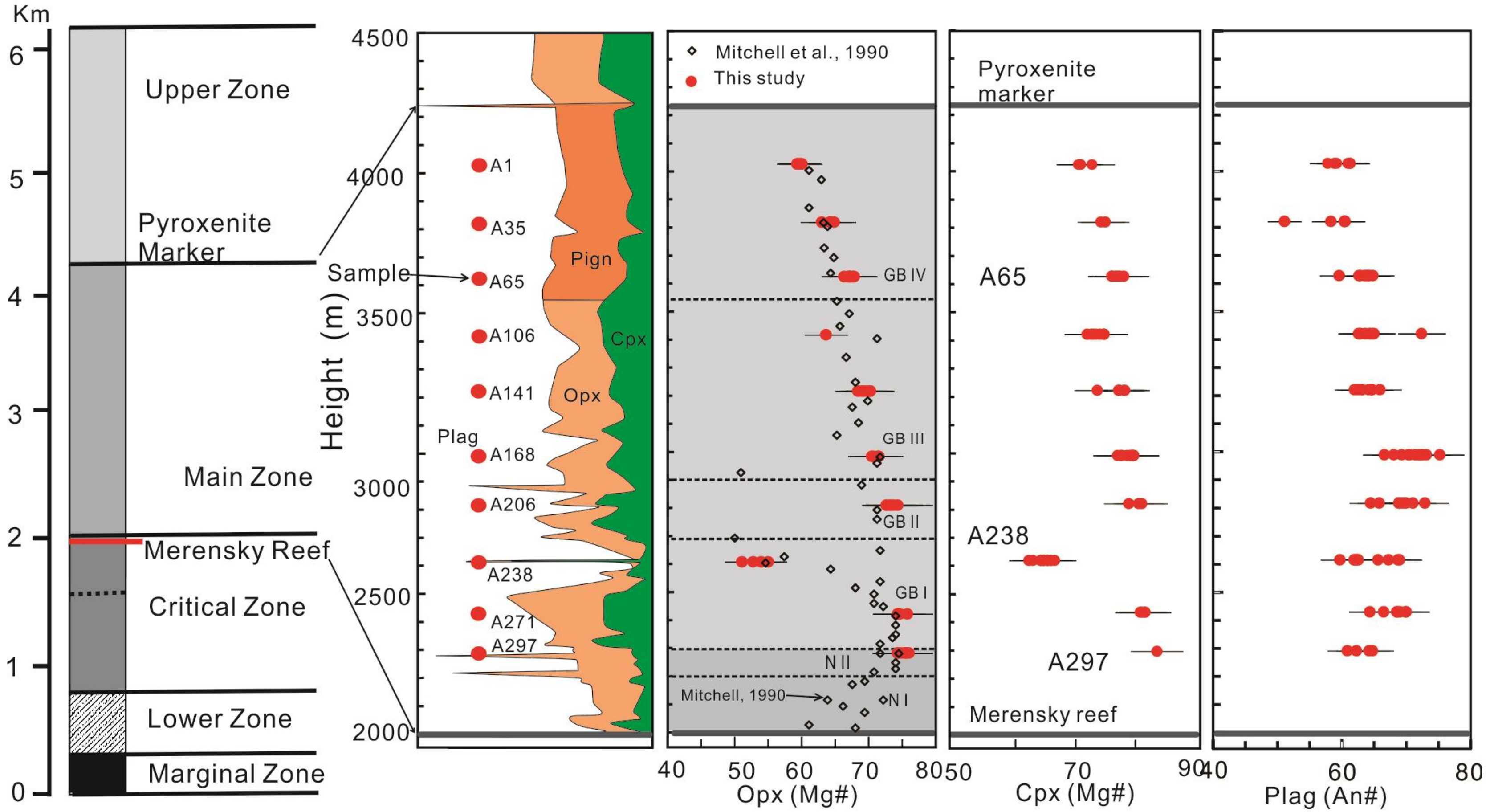








Sample, drill core,
NW bushveld

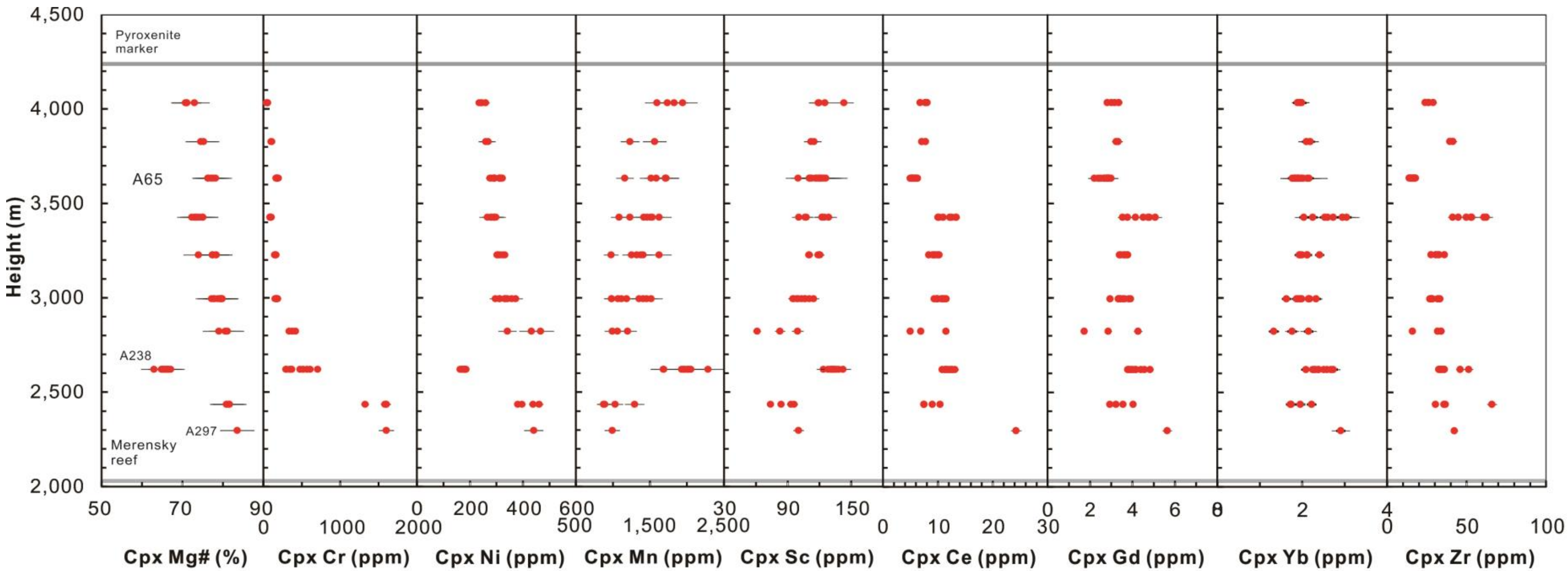


A general upward crystal fractionation trend

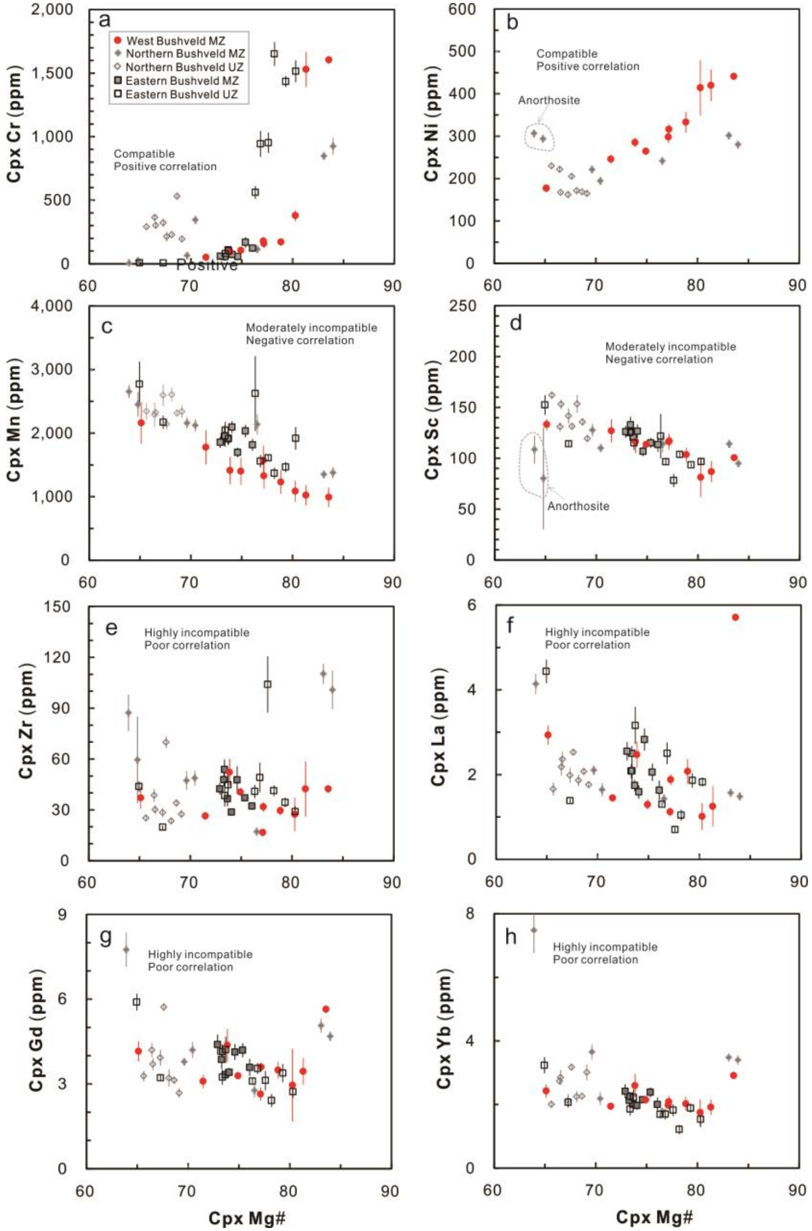
Yang et al., 2019

Clinopyroxene, compositional variation

- Mg# progressively decrease upwards， reflecting crystaliation fractionation of main magma
- Cr, Ni decrease upwards, Mn, Sc increase upward, consistent with crystal fractionation trend
- Other incompatible elements not consistent with fractionation trend



Yang et al., 2019

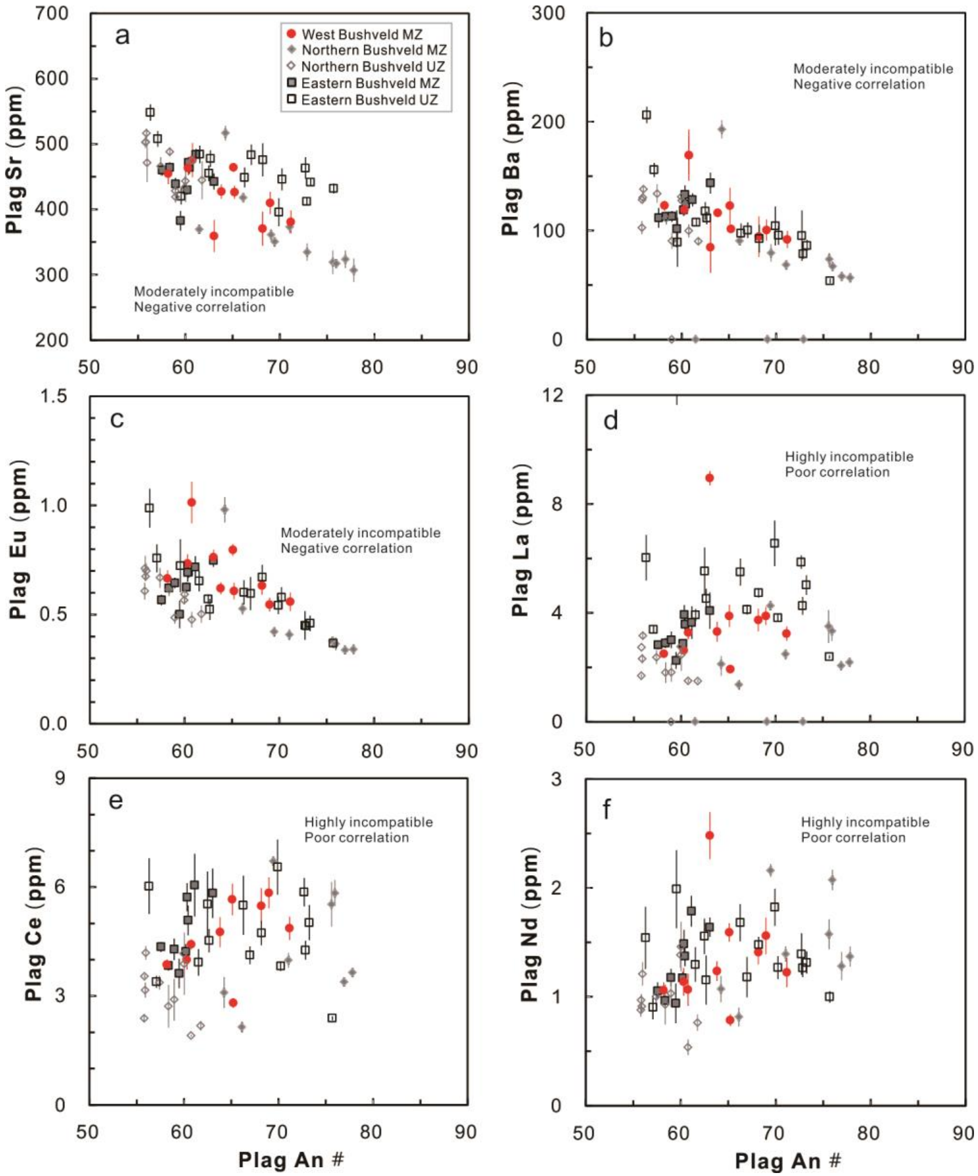


Clinopyroxene

Trace elements vs Mg#

- Cr, Ni, positive correlation
- Mn, Sc, negative correlation
- La, Gd, Yb, Zr, randon distribution

Yang et al., 2019



Plagioclase

Trace elements vs An#

- Sr, Ba, Eu, negative correlation
- La, Ce, Nd, randon distribution

Yang et al., 2019

These elements are dominated by crystal fractionation

- **Cr Ni (in pyroxenes)**
- **Mn Sc (in pyroxenes)**
- **Sr Ba Eu (in plagioclase)**

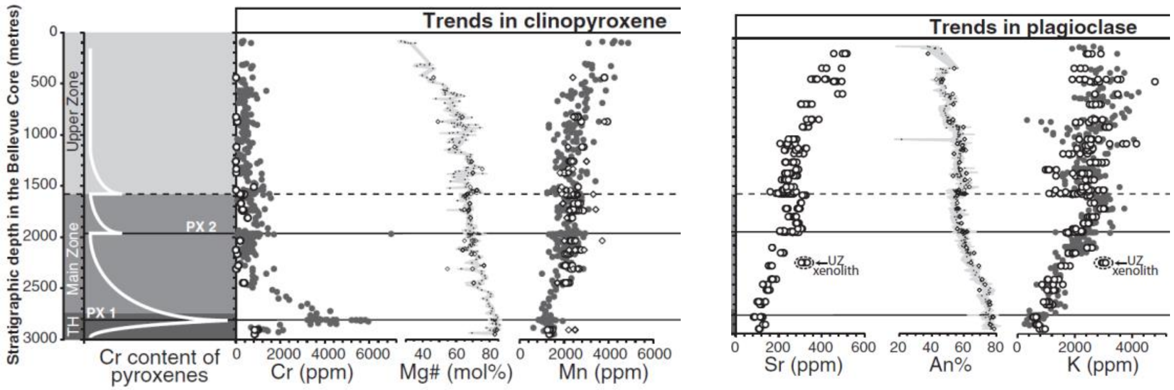
Crystal fractionation is not the dominant process

- **Highly incompatible elements, REE, Zr Hf, Y**

Yang et al., 2019

Northern Bushveld

Similar trend has been observed for northern Bushveld



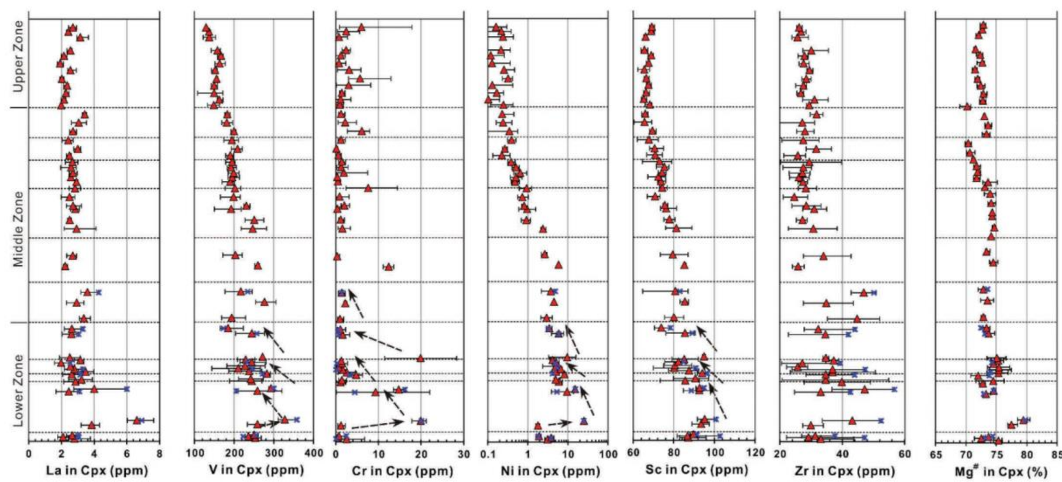
Cpx

- Mg# decrease upwards
- Cr decrease upwards,
- Mn increase upwards

Plagiocalse

- An# decrease upwards
- Sr decrease upwards,

Tanner et al., 2014

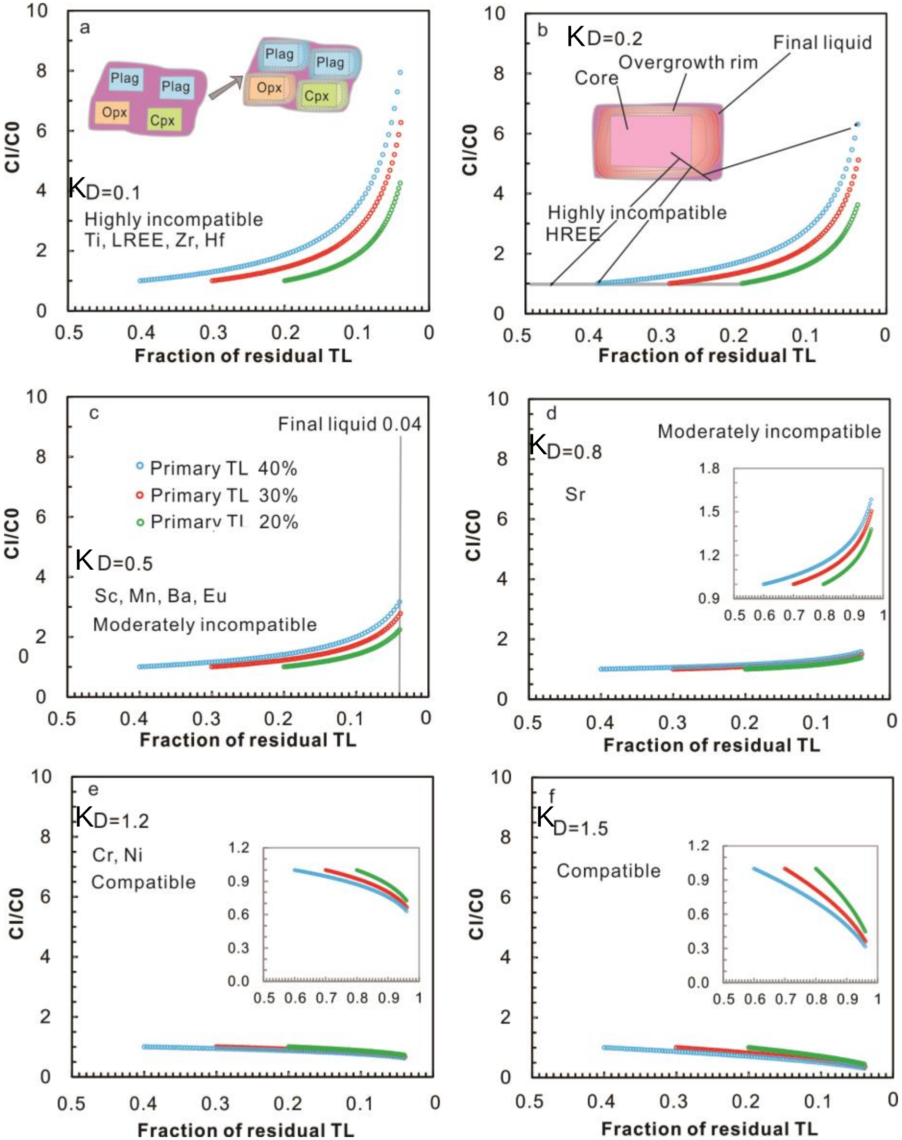


Similar trend in Panzhihua, China

Chen et al., 2017

Modelling calculation on compositional evolution of trapped liquid

$$C_{Liq} = C_0F^{(D-1)}$$



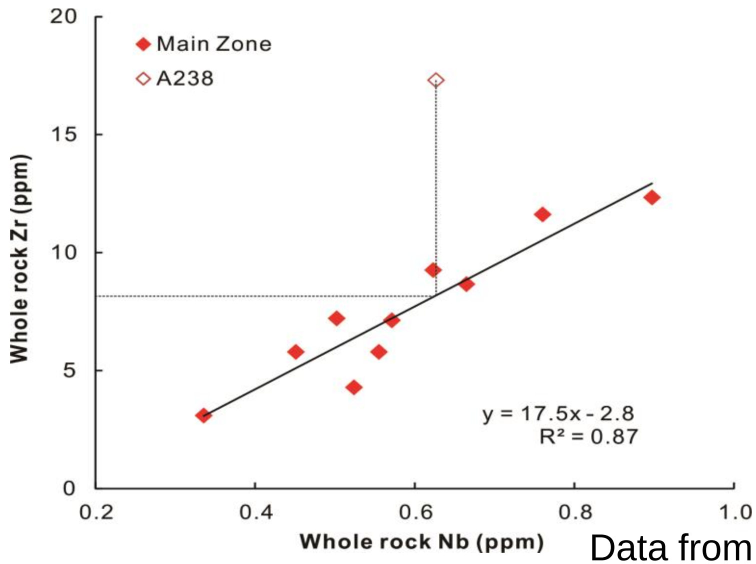
Modelling: enrichment in the rim depending on the bulk partition coefficient

Element	KD,	CL/C0
• Cr, Ni,	1.2	~ 0.7
• Sr, Mn,Sc, Ba, Eu	0.5-0.8	1.5-3
• REE, Tl, Zr, Hf, Nb, Ta	0.1-0.2	3-8

Highly incompatible elements, enrichment in the rim is the highest

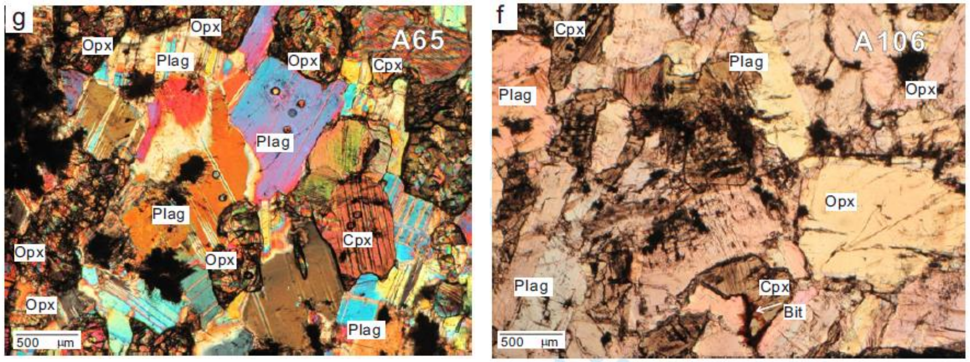
Yang et al., 2019

Is trapped liquid present in the Main Zone ?



Data from Maier et al., 2013

- Some extremly incompatible elements, Nb, Ta, < 0.05 ppm in 3 cumulus minerals
- But, 0.3-0.9 ppm Nb in whole rock, hosted in trapped liquid
- Very good positive correlation between different highly incompatible elements, controlled by the amount of trapped liquid

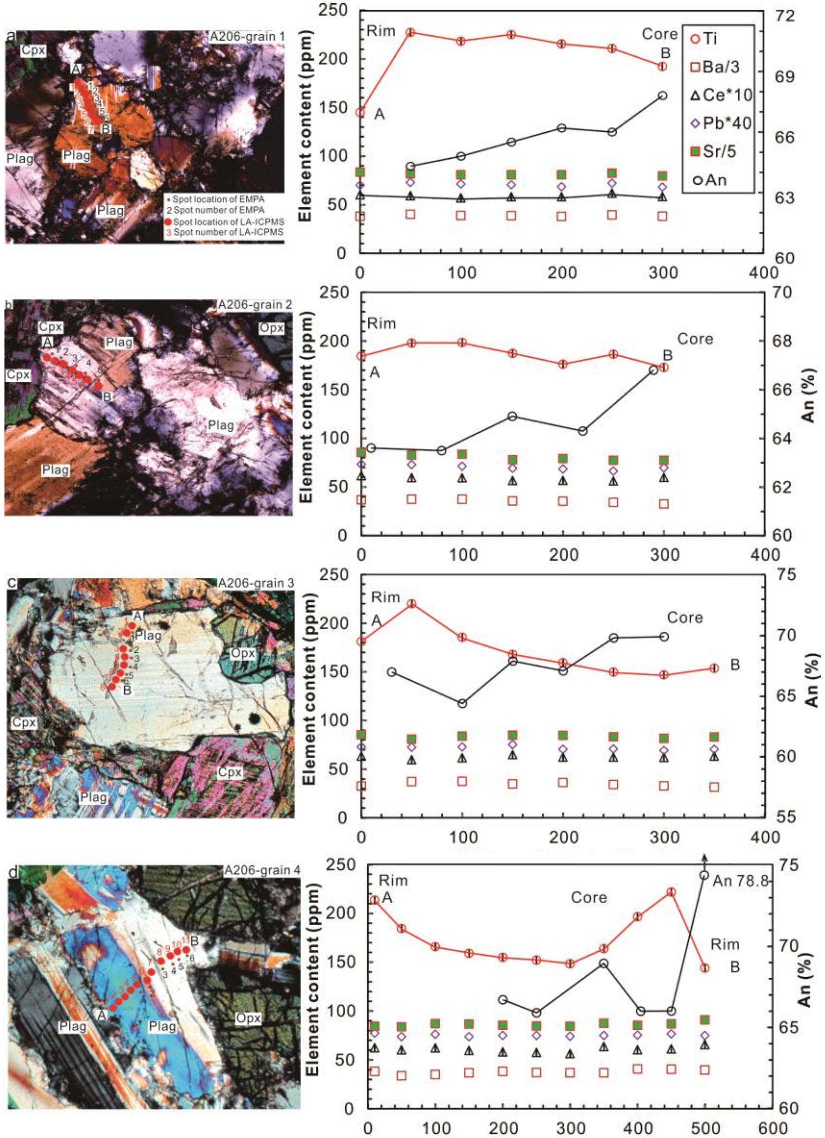


- Cumulus minerals subhedral
- Quartz, biotite, zircon, crystalized from evolved trapped liquid

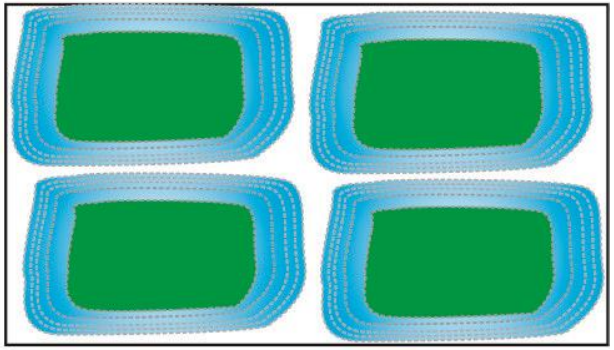
There is different amount of trapped liquid in the Main Zone rocks

Yang et al., 2019

Crystallization of trapped liquid

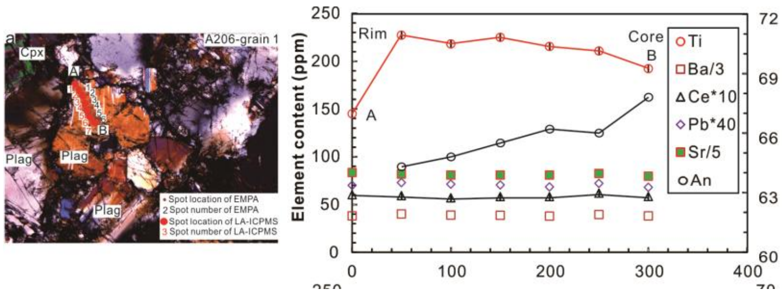


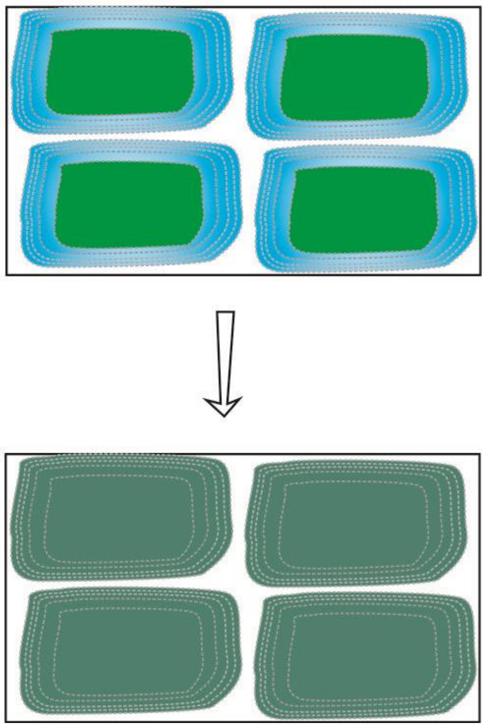
- Except the outermost rim, An# decrease outward, Ti increase outward from core to rim, zoning
- Crystal fractionation of trapped liquid in a relatively closed system



Yang et al., 2019

Trapped liquid shift process





- LREE has similar compitability as Ti, Ce has much weaker enrichment in the rim
- Very possible LREE had core-rim variation similar as Ti, but modified by diffusion
- Why zonation of Ti preserved？

Diffusion rate positively correlate with valence (Cherniak, 2003)
$A^{3+} < A^{2+} < A^{1+}$

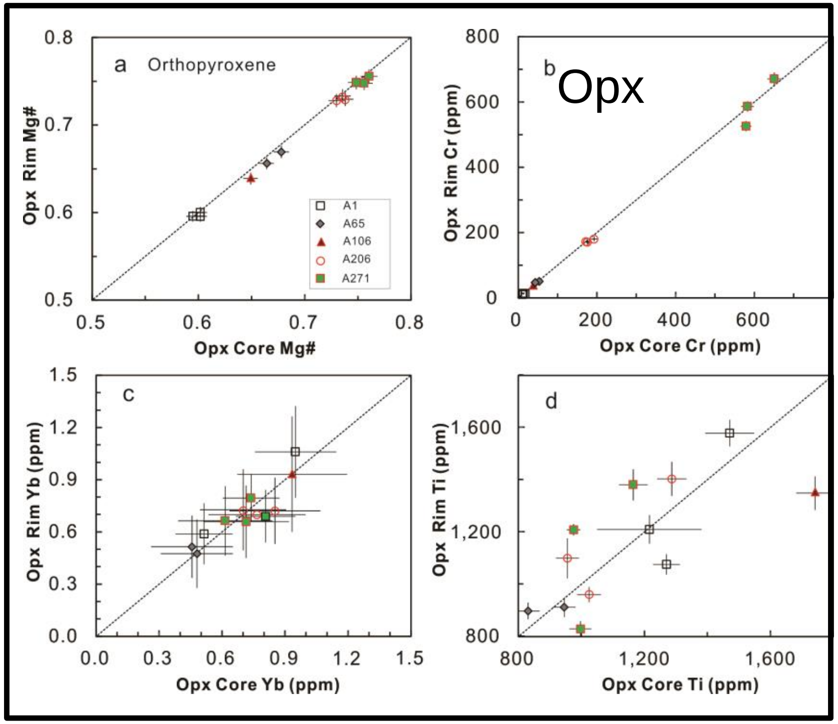
Ti^{4+}, REE^{3+}， Ti difffuse slower than REE

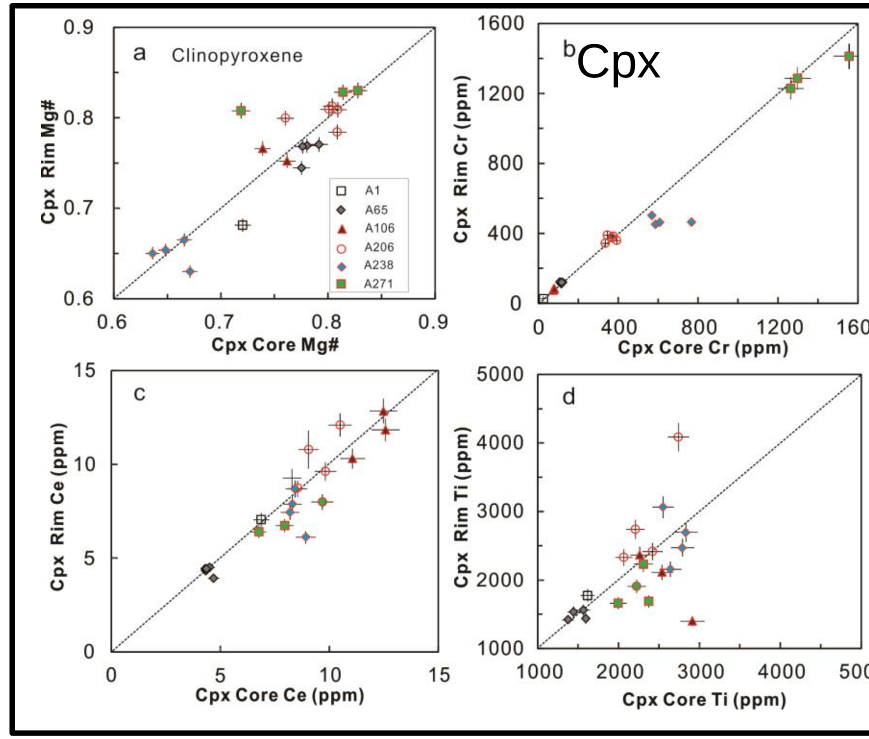
This is trappd liquid shift

For highly incompatible elements, trapped liquid shift may have modified the core of cumulus minerals

Caution must be paid using core composition to calculate melt composition

Core-rim Variation of Cpx and Opx



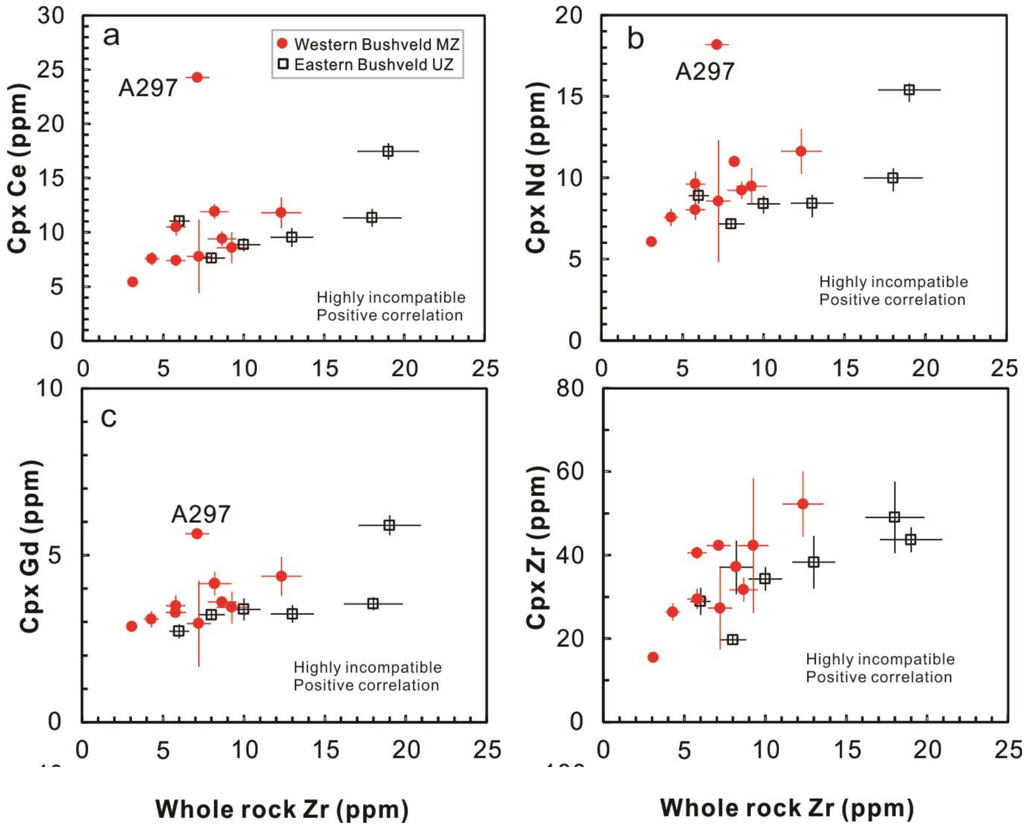


- For most elements (e.g. REE), there is no difference between Core and rim in Opx and Cpx
- Trapped liquid shift also occurred in these two minerals

Yang et al., 2019

Test the model, correlation between amount of trapped liquid with incompatible elements

Clinopyroxene

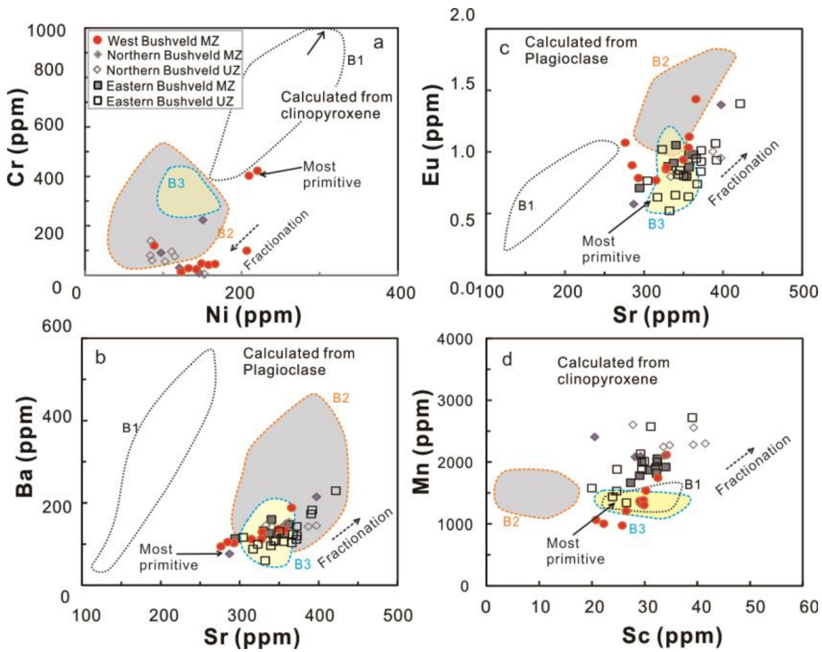


- **Positive correlation observed between highly incompatible elements and whole rock Zr**
- **Similar trend observed in plagiocalse**

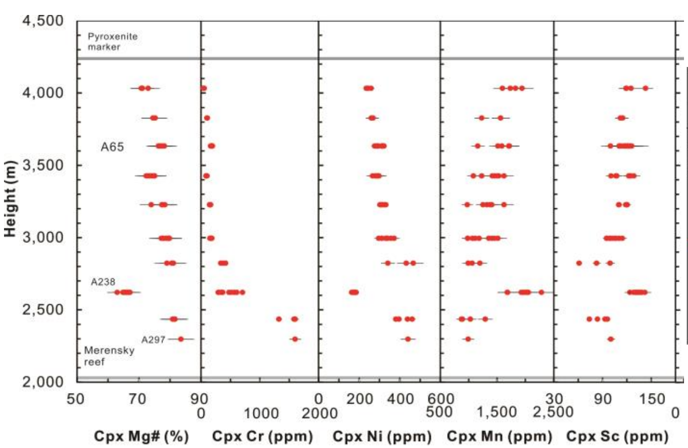
The rocks with lowest amount of trapped liquid, the cumulus minerals least modified by trapped liquid shift !!!

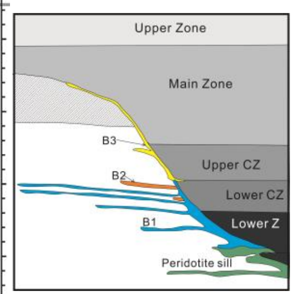
Yang et al., 2019

Compatible and moderately incompatible elements



Partition coefficients from Bédard, 2001

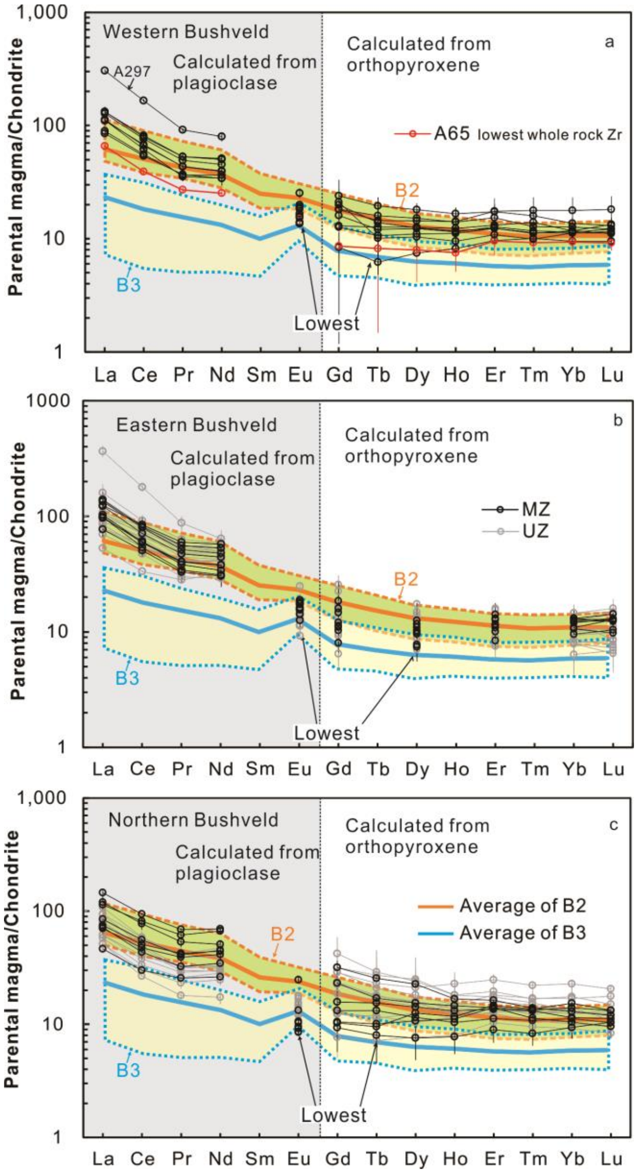




- Cr, Ni, Mn, Sc, Sr, Ba, Eu
- Dominated by crystal fractionation from main magma reservior
- Least modifed by TLS
- The most primitive samples approaching the parental magma
- Cr, Ni, lower than B1, similar to B2, B3
- Eu, Sr, lower than B2 similar to B3
- Mn, Sc higher than B2, similar to B3
- **Generaly show more affinity to B3**

Yang et al., 2019

Highly incompatible elements (REE)



- LREE from plagioclase, HREE from orthopyroxene
- Lowest whole rock Zr sample approaching the real composition (red line)
- Eastern, Western, Northern Bushveld show similar composition
- Lowest HREE within B3, lower than boundary of B2
- Eu in B3
- Lowest LREE in the lower boundary of B2
  - **The lowest value is higher than real value**

1. Some degree of trapped liquid shift (though low)
2. Crystal fractionation of main magma

Considering all factors,
parental magma more likely B3 composition

Yang et al., 2019

Summary

- Not all elements modified by trapped liquid shift, compatible and moderately incompatible elements less modified by trapped liquid shift than highly incompatible elements
- Crystallization of trapped liquid well preserved by zonation of Ti in plagioclase
- Lack or weak zonation of REE and other highly incompatible elements prove the presence of trapped liquid shift, even in the core of cumulus minerals
- Trapped liquid shift is also dependent on the amount of trapped liquid
- Based on the above, calculated parental magma of Main Zone of Bushveld has more affinity of B3 than B2, B1

Yang et al., 2019

- *Recent study on smaller intrusions (10s km) show clear nice zonation of highly incompatible elements (e.g., REE, Zr, Ti) in plagioclase and pyroxenes, indicating TLS is much less due to faster cooling in smaller intrusions.*

Thanks for your attention!