



Wager and Brown Workshop on Layered Igneous Rocks

Sunday 28th June 2026

Abstract Volume

Wager and Brown Workshop on Layered Igneous Rocks 2026. Perth, Western Australia, Australia. 2026. 18 pp.

Organising Committee: Barnes S. J., Latypov R., Schoneveld L., Smith W.,

Design, editing and layout: Schoneveld L.

Perth, Western Australia 2026

Table of Contents

Secondary Nucleation: An Overlooked Mechanism of Crystal Formation in Igneous Systems.....	1
Rais Latypov, Sofya Chistyakova, Stephen J. Barnes, Belinda Godel, Giada Iacono-Marziano, Willem Kruger	
Petrogenesis of the Main Zone-Upper Zone Transition in the Western Bushveld Complex Based on Plagioclase and Strontium Isotopic Compositional Variation.....	1
Stephen Prevec, Petele Lehloenyana, Freddie Roelofse	
Effects of post-cumulus processes on chromite compositions in layered intrusion cumulates and implications for the origins of chromitite layers.....	3
Steve Barnes, Michael Langa, Will Smith	
Evidence for percolation of sulfide-rich crystal slurries in the Stillwater Complex, Montana.....	4
WD Maier, D Grobler, A Brits, MC Jenkins, M Zientek	
Fine-scale textural and mineralogical variability in the PGE-rich B chromite zone, Stillwater Complex, USA revealed by high-resolution XRF mapping.....	5
M. Christopher Jenkins, Stephen J. Barnes, Michael L. Zientek, and William D. Smith	
Evaluation of the economic potential of Platinum Group Element (PGE) deposits: the case of the Platinova Reefs at Skaergaard.....	6
Raymond Goldie	
PGE reefs in the upper portion of the Koitelainen layered intrusion, Finland.....	7
Wolfgang Maier, Piotr Skotnicky, Petri Peltonen, Sarah-Jane Barnes, Eero Hanski, William D Smith, Duncan Muir	
An assessment of olivine-rich rocks of the layered mafic intrusions of the Duluth Complex as source rocks for geological hydrogen.....	8
Joyashish Thakurta and Cory Paliewicz	
The Rhiw layered intrusion, Wales: petrogenesis, marginal chill differentiation, and early sulfide saturation.....	9
Anton Kutyrev, Wolfgang D. Maier, Thomas Blenkinsop	
Fe-Ti oxide crystallisation in the T-Zone crystal mush as a trigger for stratiform PGE mineralisation in the Bushveld Complex.....	10
Ben Hayes, Scott MacLennan, Robert Bolhar	

Table of Contents Continued...

Basal Olivine-Rich Zones in Sills and Layered Intrusions: Origin by Slurry Injection, Flow Segregation, or Crystal Settling.....11

H. Richard Naslund

The Merensky Reef and the Platreef: sill-like and dyke-like intrusions of sulphur-rich Upper Zone magma12

Johan Kruger

Surface energy and phase boundary energy: What's the difference?.....13

Alan Boudreau

Regional geology and chemistry of orthopyroxene argue against the formation of the Bushveld Complex from externally-derived crystal-rich slurries.....14

Rais Latypov, Sofya Chistyakova

Secondary Nucleation: An Overlooked Mechanism of Crystal Formation in Igneous Systems

Rais Latypov¹, Sofya Chistyakova¹, Stephen J. Barnes², Belinda Godel², Giada Iacono-Marziano³, Willem Kruger¹

¹School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa;

²CSIRO Mineral Resources, Kensington, Perth, WA 6151, Australia.

³ISTO, UMR 7327 CNRS-Université d'Orléans-BRGM, 1A rue de la Ferrollerie, 45071 Orléans Cedex 2, France
rais.latypov@wits.ac.za

Abstract

Understanding where and how crystals nucleate and grow in magmatic systems is critical for constraining many fundamental questions in igneous petrology. In mafic layered intrusions, a large body of field, textural, and chemical evidence indicates that magma chambers develop from margins inward through solidification fronts. These fronts grow and propagate inward via processes that likely involve repeated nucleation and growth of new crystals on pre-existing ones directly at the floor, walls, and roof of magma chambers. What remains unclear, however, is the physical mechanism responsible for this in situ nucleation and growth of crystals at the crystal–liquid interface of solidification fronts. Here we argue—surprising as it may seem—that this mechanism has been entirely overlooked in igneous petrology. At present, only two nucleation modes are recognized: homogeneous nucleation, occurring spontaneously within a pure bulk melt and requiring high supercooling, and heterogeneous nucleation on pre-existing surfaces (e.g., impurities or chamber sidewalls), thereby reducing the required supercooling and facilitating crystallization. In industrial crystallization, these are regarded as modes of primary nucleation, as they occur without requiring pre-existing crystals of the same substance in the liquid to initiate the process. There is, however, another class of nucleation – never explicitly recognized in igneous petrology – referred to as secondary nucleation, which requires even lower supercooling because it is induced by crystals of the same substance already present in the melt. In industrial crystallization, secondary nucleation is considered a dominant process, typically resulting in crystal proliferation, i.e., a rapid and explosive burst of new crystal formation. By efficiently consuming supersaturation, secondary nucleation suppresses the buildup of supercooling required for primary nucleation, rendering the latter effectively negligible. Induced by pre-existing parent crystals that catalyse further nucleation of the same minerals, it is expected to play a decisive role at the crystal–liquid interface of solidification fronts in evolving magma chambers. We therefore propose that secondary nucleation is likely the dominant mechanism of crystal formation in magma chambers, promoting their development via in situ crystallization from the margins inward through inward-propagating solidification fronts.

Petrogenesis of the Main Zone-Upper Zone Transition in the Western Bushveld Complex Based on Plagioclase and Strontium Isotopic Compositional Variation

Stephen Prevec¹, Pelele Lehloeny^{1,2}, Freddie Roelofse²

¹ Rhodes University, South Africa;

² University of the Free State, South Africa

s.prevec@ru.ac.za

Abstract

A sample suite across the contact between the uppermost Main Zone and the basal Upper Zone in the western limb of the Rustenburg Layered Suite, including the Pyroxenite Marker (PM) has provided the basis for a mineral chemical and isotopic study of this postulated magmatic interface zone. A key feature is the compositional reversal across the upper 300 m or so of the Main Zone, which has inspired a range of innovative magmatic recharge processes to explain in the literature. Novel findings of this study include the observation of a prominent spike in radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ across the PM not noted in Sr or Nd isotopes at this horizon elsewhere, and an apparently gradual transition in $^{87}\text{Sr}/^{86}\text{Sr}$ from the Main to Upper Zones, in marked contrast to the stepwise isotopic compositional shift reported in some previous work, and as conventionally reported. This evidently does not represent a crustal contamination event corresponding to a new influx of magma, as no high field strength or large ion lithophile elements show corresponding enrichment. This is consistent with the absence of a similar peak in other equivalent sections. In fact, elsewhere the PM interval is isotopically characterized by erratic or variable compositions, consistent with locally open system behaviour. In this case, the apparently $^{87}\text{Sr}/^{86}\text{Sr}$ enrichment can be explained by a depletion in Rb, resulting in undercorrection for age decay for the initial ratio calculation. The gradational change in isotopic composition commencing below the PM may suggest that the PM itself does not represent a new magma influx (i.e., of a ferrogranitic Upper Zone magma). An alternative model for the Upper Main Zone involving symmetrical bottom up and top down crystallization (over a 600 m interval) is also examined.

Effects of post-cumulus processes on chromite compositions in layered intrusion cumulates and implications for the origins of chromitite layers

Steve Barnes¹, Michael Langa², Will Smith¹

¹ CSIRO Mineral Resources, Kensington, WA

² Harquail School of Geosciences, Laurentian University, Sudbury, Canada

steve.barnes@csiro.au

Abstract

In several studies of chromite-rich cumulates in layered intrusions, the Cr/Al ratio of cumulus chromite has been shown to vary significantly at short range within cm-dm scale layering. In the example of the G-H Chromitite section of the Stillwater Complex, Cr/Al shows a close relationship to chromite mode in the rock, being significantly higher in the most chromite-rich rocks compared with immediately adjacent layers. Systematic relationships between Cr/Al and mode are also observed in Bushveld Complex cumulates. This is a critical observation for models of chromitite genesis that involve mechanical sorting of chromite from olivine and/or orthopyroxene in gravity flows, as there is no plausible mechanism for sorting small chromite grains on the basis of subtle variations in composition. A possible explanation could be in the combined effects of subsolidus re-equilibration and trapped liquid reaction, which are known to have major mode-dependent effects on the Mg/Fe ratio of chromite. To test this possibility, a series of model calculations has been carried out solving for conservation of mass in a closed system, known relationships between distribution coefficients, composition and temperature, and mineral stoichiometry. The results indicate that, while Mg/Fe ratios are indeed predicted to be highly mode-dependent, the Cr# (defined as atomic Cr/[Cr+Al]) is insensitive to postcumulus effects for chromite proportions more than about 20%. The difference in Cr# between rocks with 50% and 80%+ chromite, and the short range cyclicity of Cr# within individual massive chromitite layers, cannot be explained by post-cumulus processes and therefore must be reflecting primary liquidus compositions. This argues in favour of in-situ boundary layer crystallisation models over mechanical deposition and hence supports models of in-situ growth of chromitites from large convecting magma bodies.

Evidence for percolation of sulfide-rich crystal slurries in the Stillwater Complex, Montana

WD Maier¹, D Grobler², A Brits², MC Jenkins³, M Zientek³

¹ *School of Earth and Environmental Sciences, Cardiff University, UK*

² *Stillwater Critical Minerals, Vancouver, Canada*

³ *United States Geological Survey, Spokane, USA*

maierw@cardiff.ac.uk

Abstract

In the basal portion of the Stillwater Complex, within Peridotite zone and Basal series rocks, sulfides locally form centimetre- to rarely decimetre-wide massive veins traversing net-textured sulfides. The silicate mineral assemblage between the net-textured sulfides typically lack sulfides but locally contain what look like sulfide inclusions in two dimensions but in reality represent the matrix to amoeboidal olivine grains. We interpret these textures to reflect the percolation of sulfide melt through incompletely solidified crystal mushes. This process is possibly initiated by the density contrast between sulfide melt and silicate melt, and the low viscosity and high heat capacity of sulfide melt, enabling the sulfide to dissolve the host rocks thereby creating a path for the sulfide liquid to percolate downwards. The preferred occurrence of net textures in peridotites reflects the enhanced wettability of olivine relative to other minerals. Sulfide melt percolation is consistent with the observation that sulfide enrichments may occur in any rock type, including some metasedimentary layers. The latter may have acted as traps to migrating sulfide melt, as suggested by sulfide concentrations at their top and bottom contacts. Sulfide melt percolation could also explain the relatively low proportion of chalcopyrite in some massive sulfide pods and the knife-sharp contacts of decimetre- to metre-sized sulfide lenses within sulfide-poor silicate host rocks. Drill core CM2025-02 contains decametric sulfide-rich pyroxenite layers within fine grained gabbro, with the intrusive nature of the former indicated by their sharp boundaries and decreased grain size at the margin, whereas the adjacent gabbro has a narrow alteration corona characterised by K-loss. We interpret these textures to result from downward percolation of sulfide liquids from higher up in the complex.

Fine-scale textural and mineralogical variability in the PGE-rich B chromite zone, Stillwater Complex, USA revealed by high-resolution XRF mapping

M. Christopher Jenkins¹, Stephen J. Barnes², Michael L. Zientek¹, and William D. Smith²

¹ *U.S. Geological Survey, Geology, Minerals, Energy, and Geophysics Science Center, Spokane, Washington, USA;*

² *CSIRO, Mineral Resources, Kensington, Western Australia*

mcjenkins@usgs.gov

Abstract

Several samples preserving fine-scale layering were collected from the PGE-rich B chromite zone in the Verdigris Creek area of the Stillwater Complex, with the goal of documenting centimeter- to millimeter-scale variability in textures and the distribution of PGE-bearing phases. Select rocks were mapped using CSIRO's benchtop Maia Mapper XRF system and by high-resolution Maia μ XFM mapping at the Australian Synchrotron. Elemental maps demonstrate that textures vary dramatically over centimeter length scales, even within single hand specimens. The rocks are poikilitic harzburgites with highly variable chromite modal proportions from layer to layer. Orthopyroxene oikocrysts are commonly sandwiched between chromite-rich layers or terminate against them, although rare examples transgress layering. In some layers, textures become markedly more pegmatoidal and closely resemble harrisite-style growth textures described from the Rum Layered Suite, suggesting localized departures from typical adcumulate or mesocumulate fabrics. High-resolution mapping further identifies Pd- and Pt-rich phases occurring both within chromite-rich layers and in adjacent silicate-rich domains, indicating that chromite abundance exerts less control on the distribution of these phases than previously assumed for the B chromitite horizon. Silicate phases show no detectable chemical zoning in mapped domains. Chromite textures also vary strongly over centimeter scales, including the presence of very large grains that appear inclusion-rich in two-dimensional section, and domains within single chromitite layers that exhibit a sintered texture. Collectively, these observations highlight extreme small-scale heterogeneity within the B chromite zone and underscore the need to integrate high-resolution mapping with traditional stratigraphic interpretations of PGE-enriched chromitite formation.

Evaluation of the economic potential of Platinum Group Element (PGE) deposits: the case of the Platinova Reefs at Skaergaard

Raymond Goldie¹

¹ *Independent Analyst and Director*

raymondgoldie@outlook.com

Abstract

According to Geusebroek (2022)^[1], the Platinova Reefs of the Skaergaard intrusion in Greenland contain Indicated Resources of 158.95 Mt grading 1.57 g/t palladium, 0.53 g/t gold and 0.12 g/t platinum; or, as a rule-of-thumb, 2.23 g/t of “palladium equivalent”. The recent increase in the price of gold has spurred re-evaluation of the economic potential of the Reefs, and improvements in the cost and ease of assaying since the Reefs were discovered in 1988 have facilitated the analysis of a greater number of elements than were previously considered. In particular, “TABSS” elements (tellurium, arsenic, bismuth, tin and antimony) can and should now be assayed routinely because, although they are pathfinders for PGE, TABSS may reduce a project’s prospects for eventual economic extraction of PGE. On the other hand, ruthenium, rhodium, osmium and iridium could be assayed as potential contributors to revenues from the Reefs.

Misunderstandings about rules-of-thumb used to evaluate PGE projects have resulted in expensive outcomes for Australian investors. Rather than calculating “palladium equivalents”, geologists who seek a single number to represent the chemical composition of mineralization could analyse historic records of operating mines and consult with metallurgists at processing plants in order to prepare estimates of a Net Smelter Return (NSR) per tonne of mineralization^[2].

References:

^[1] Geusebroek P A 2022 NI43-101 Independent Technical Report Skaergaard Project

<https://share.google/JijW7jCAEjJOSBvm1>

^[2] Goldie R 2023 Net Smelter Returns (NSRs) and alternative measures of the value of polymetallic mineralization *Mineral Economics* DOI:10.1007/s13563-023-00400-3

PGE reefs in the upper portion of the Koitelainen layered intrusion, Finland

Wolfgang Maier¹, Piotr Skotnicky¹, Petri Peltonen², Sarah-Jane Barnes³, Eero Hanski⁴, William D Smith⁵, Duncan Muir¹

¹*Cardiff University, UK,*

²*University of Helsinki,*

³*Universite du Quebec a Chicoutimi,*

⁴*Oulu University,*

⁵*CSIRO, Kensington, Western Australia*

mierw@cardiff.ac.uk

Abstract

The Koitelainen intrusion of northern Finland is a ~200 km² mafic-ultramafic layered body. In its Upper Zone it contains a ~70-m-thick interval of elevated PGE and Au contents in disseminated magnetite gabbro and its leucogabbroic footwall. The mineralisation contains up to 1ppm Pd, 0.5ppm Pt and 0.4-0.5ppm Au, whereas concentrations of Ir, Os, Ru and Rh are < 10 ppb in total. The mineralization is of the offset style, with IPGE peaking before Pd and Pt, Au and finally Cu. The PGE occur mainly in the form of platinum-group minerals (PGM), predominantly arsenides, hosted in magmatic and metamorphic silicates. We suggest that the mineralisation is of originally magmatic origin. Sulfide saturation was triggered by the onset of magnetite crystallisation. Some of the sulfide melt percolated into the footwall rocks. The sulfides were subsequently partially or completely resorbed by percolating fluids, but the noble metals were relatively immobile.

An assessment of olivine-rich rocks of the layered mafic intrusions of the Duluth Complex as source rocks for geological hydrogen

Joyashish Thakurta¹ and Cory Paliewicz¹

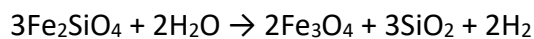
¹*Natural Resources Research Institute, University of Minnesota, USA*

thakurta@d.umn.edu

Abstract

The Mesoproterozoic Duluth Complex in northeastern Minnesota, USA represents one of the largest mafic-ultramafic layered intrusive bodies on Earth and a massive, yet underexplored, reservoir for geological hydrogen. While the complex is globally recognized for its significant Cu-Ni-PGE resources, rocks from the troctolitic and anorthositic series contain vast volumes of olivine-rich rocks capable of hosting low-temperature serpentinization.

Previous studies on olivine composition in troctolite and olivine gabbro cumulate rocks of the major layered intrusions of the complex provide the following ranges: Partridge River: Fo₆₀₋₇₅; South Kawishiwi: Fo₇₀₋₈₀; Sonju Lake Fo₇₉₋₁₀ and Bald Eagle: Fo₆₈₋₈₂. In spite of such wide ranges in Mg-Fe composition across stratigraphic horizons of layered units, it is evident that olivine, in many parts of the intrusive layers, is substantially more enriched in Fe than most other mafic-ultramafic rocks in the Midcontinent Rift System (MRS) and elsewhere. Thermodynamic modeling suggests that the more ferroan nature of olivine may lower kinetic barriers and enhance the total hydrogen yield compared to more magnesian analogues. This provides a critical geochemical advantage for hydrogen generation. The oxidation of Fe²⁺ during the serpentinization of olivine is the primary driver of hydrogen production via the reaction:



Furthermore, the structural architecture of the MRS, in conjunction with the Duluth Complex, provides the necessary faults and fractured rocks to facilitate fluid circulation and gas migration which are necessary for an active hydrogen generating system.

Integrating mineralogical and petrological data we evaluate high-potential targets which display continuous differentiation trends reaching highly fayalitic olivine. As the global energy transition accelerates, the Duluth Complex is positioned to pivot from a traditional Ni-Cu-PGE-rich district to a premier candidate for both natural hydrogen and stimulated subsurface production, leveraging existing infrastructure to lead the emerging hydrogen economy."

The Rhiw layered intrusion, Wales: petrogenesis, marginal chill differentiation, and early sulfide saturation

Anton Kuttyrev^{1,2,3}, Wolfgang D. Maier³, Thomas Blenkinsop²

¹ School of Geosciences, University of the Witwatersrand, 1 Jan Smuts Avenue, Johannesburg 2050, South Africa

² African Research Centre for Ore System Science (CORES), School of Geosciences, University of the Witwatersrand, 1 Jan Smuts Avenue, Johannesburg, South Africa

³ School of Earth and Environmental Sciences, Cardiff University, Main Building, Park Place, Cardiff, Wales CF10 3AT, UK

anton.kuttyrev@wits.ac.za

Abstract

The origin of layered mafic-ultramafic intrusions in convergent-margin settings remain less constrained than their continental counterparts. We present new field observations, whole-rock major and trace element data, platinum-group element (PGE) geochemistry, zircon U-Pb geochronology, and thermodynamic modelling for the Rhiw layered intrusion, Wales. This study focuses on the well-exposed south-western part of the intrusion, where a 265 m-thick section begins with a 0.9 m differentiated marginal chill, continuing upward through a \approx 150 m-thick predominantly ultramafic unit, and then gabbroic lithologies. Both peridotite and gabbro commonly contain abundant composite clinopyroxene-hornblende oikocrysts, locally forming an interconnected framework at outcrop scale. The south-western sequence shows subduction-related trace element characteristics, including pronounced negative Nb and Ta anomalies. In contrast, basaltic rocks exposed in the central part of the intrusion are geochemically distinct from the main layered sequence and display an enriched intraplate-like trace-element signature lacking the negative Nb-Ta anomalies of the main sequence. Thermodynamic modelling is used to test whether the south-western section represents the full stratigraphy of the intrusion or a marginal series developed along the edge of a larger body concealed beneath the sea.

New zircon data yield an emplacement age of 452.0 ± 6.1 Ma, placing Rhiw in the Late Ordovician and linking it to the volcanism in Snowdonia. PGE abundances are relatively low throughout the sequence. The most magnesian analysed sample, an amphibole wehrlite with 31.7 wt% MgO, contains 13.8 ppb total PGE, whereas most other ultramafic rocks contain 1.3 to 4 ppb PGE and the gabbroic rocks contain 0.4 to 1.3 ppb. Cu/Pd ratios are correspondingly very high, two orders of magnitude or more above the primitive mantle. These data, compared with the global database of arc volcanic rocks, indicate that Rhiw records the crystallisation of arc-related magma that had already undergone effective chalcophile element depletion prior to emplacement.

Fe-Ti oxide crystallisation in the T-Zone crystal mush as a trigger for stratiform PGE mineralisation in the Bushveld Complex

Ben Hayes¹, Scott MacLennan¹, Robert Bolhar¹

¹ School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa

ben.hayes@wits.ac.za

Abstract

Ore-forming processes leading to stratiform PGE reefs in layered intrusions are generally thought to require segregation of a sulfide melt, followed by its upgrading in metals. The mechanisms triggering sulfur saturation and sulfide melt segregation in the magma chamber are, however, less well understood. We studied stratiform PGE mineralisation at the Waterberg Project, a northern extension of the Paleoproterozoic (2.06 Ga) Bushveld Complex into the Southern Marginal Zone of the Limpopo Belt. T-Zone mineralisation occurs in a ~20 m thick package of gabbro-norites and anorthosites at the boundary between the troctolite-gabbro-norite-anorthosite (TGA) sequence and the Upper Zone. Magmatic sulfides are intergrown with ilmenite between plagioclase laths, indicating co-crystallisation from the pore melt of the crystal mush. Ilmenite is enriched in Mn and, along with the presence of biotite, indicates both a H₂O-rich and low fO_2 pore melt. Negative Cu-Ni-Co-Zn anomalies in ilmenite reflect partitioning of these chalcophile elements into the co-crystallising sulfide melt. Positive V anomalies confirm ilmenite crystallised prior to magnetite. Trace element inversion models demonstrate that melts in equilibrium with T-Zone ilmenite are comparable to the B3 melt, the inferred parent melt of the Upper Zone. Forward models constrain ilmenite saturation to 40–60% crystallinity in the mush. Ilmenite crystallisation lowered melt FeO and fO_2 , reducing sulfur solubility and triggering sulfur saturation locally in the pore melt. Rayleigh fractionation modelling demonstrates that differentiation during TGA crystallisation generated high concentrations of Pd, Cu and Au in the residual melt. R-factors of 100–1000 are required to produce observed PGE grades, achievable via percolative melt flow through the partially molten mush. These results demonstrate that stratiform PGE reefs can develop at any stratigraphic level in a layered intrusion, with Fe-Ti oxide crystallisation locally acting as a metallogenetic trigger.

Basal Olivine-Rich Zones in Sills and Layered Intrusions: Origin by Slurry Injection, Flow Segregation, or Crystal Settling

H. Richard Naslund¹

¹*Department of Earth Sciences, SUNY, Binghamton, New York 13902*

naslund@binghamton.edu

Abstract

Basal olivine-rich horizons are a common feature in sills and layered intrusions. In some intrusions olivine-zones appear to have resulted from injection of an olivine-phyric slurry into an existing magma chamber, in which the denser slurry underflows the existing magma. To form a basal olivine zone, the slurry must have been injected simultaneous with or shortly after the initial filling before a significant lower series formed. Flow segregation causes phenocrysts to be concentrated in the higher velocity center of flowing magma. In olivine zones formed by slurry injection the % olivine increases from the base upward reaching a maximum % in the center of the slurry and then decreasing upward above the center of the slurry. The largest crystals occur in the center of the slurry with the highest olivine abundances. Post emplacement olivine-magma re-equilibration (a static re-equilibration) results in more re-equilibration (lowest Mg#) at the zone margins with lower olivine abundances. In some cases, multiple slurry pulses can be identified.

In some intrusions basal olivine-rich zones appear to be the result of crystal settling from a relatively homogeneous olivine-phyric magma. Such basal zones have increasing olivine abundances upward as settled crystals are captured by the crystallization front progressing upward from the base, and a relative sharp upper boundary. Average olivine grain-size decreases upward in such zones with the smallest average grain-sizes in the olivine-rich tops of the zone. Olivine re-equilibration occurs during settling (a dynamic re-equilibration) such that the olivine crystals at the top of the zone, which have fallen farther and slower than those at the base, are the most re-equilibrated (lowest Mg#). Olivine-phyric magmas from depth re-equilibrate in the upper crust owing to the pressure-temperature effect on olivine-magma Fe/Mg equilibrium.

Examples from the Palisades Sill, Victoria Island Sills, Skaergaard intrusion, and published literature.

The Merensky Reef and the Platreef: sill-like and dyke-like intrusions of sulphur-rich Upper Zone magma

Johan Kruger¹

¹ *GeoActiv (Pty) Ltd, South Africa*

johan@geoactiv.co.za

Abstract

Isotope and field data, show that the Merensky reef is a sill-like intrusion on the unconformity between the Critical and Main Zones, and the Platreef a discordant inclined dyke-like intrusion marginal to the Main Zone of the BC. Both these reefs are sulphur-rich, compared to the sulphide devoid Critical and Main Zones. The Upper Zone is the only S-rich magma and is inferred to be the source of the Merensky and Platreef.

The Critical Zone – Main Zone unconformity and the origin of Potholes: This unconformity is at the base of the Main Zone excluding the Merensky cyclic unit. The unconformity was created during the influx of the Main Zone magma which caused the Lower and Critical Zone cumulates and the underlying sediments to be warped into long wavelength folds. In the northern (Platreef areas), the Main Zone magmas directly impinged on the floor rocks as a steep contact with no Critical Zone present. The areas over upfolds have the top of the Critical Zone eroded into an unconformity. Potholes are a Main Zone phenomenon. The plagioclase eroded off the domes mixed with the incoming magma and caused the continuous upward change in isotopic character above the Bastard Cyclic Unit. The Bastard Reef and the BCU with its thin basal chromite stringer are the first layers deposited on this unconformity from the Main Zone magma.

The Bastard and Platreef unconformities “prepared the ground” for the intrusion of sulphur-rich Upper Zone magma. These intruded firstly along the Platreef and then spread out along the base of the Bastard Cyclic Unit and deposited the Merensky Reef and Merensky Cyclic unit with high PGM on the top chromite stringer. The pegmatoidal nature is explained as the metamorphic action of the Merensky magma on the remnant footwall Bastard pyroxenite.

Surface energy and phase boundary energy: What's the difference?

Alan Boudreau¹

¹Duke University, Durham NC USA

boudreau@duke.edu

Abstract

The Gibbs free surface energy (or simply the surface energy, s) is the excess free energy that arises from the mismatch and unsatisfied bonds and local lattice distortions at the surface of a phase (and especially minerals) that contributes a positive contribution to the total free energy of that phase. The phase boundary Gibbs free energy (boundary energy, γ) is that excess positive free energy that is present at the contact of two phases. Both play an important role in the crystallization of rocks ranging from high temperature igneous to sedimentary rocks. However, an explicit description of the relationship between the two is rarely noted in the geologic literature.

Ignoring deformational effects, the energy to create two surfaces in contact can be considered the sum of the two surface energies in vacuo ($\sigma_{iv}^{\alpha} + \sigma_{iv}^{\beta}$) less the binding energy (Ba-b) gained when the two surfaces are brought together, and new bonds are formed. The boundary energy, $\gamma_{\alpha-\beta}$, is then:

$$\gamma_{\alpha-\beta} = (\sigma_{iv}^{\alpha} + \sigma_{iv}^{\beta}) - B_{\alpha-\beta}$$

The boundary energy can then be shown to be the sum of the residual or uncompensated in vacuo surface energy of both grains, $\sigma_{\alpha-\beta}^{\alpha}$ and $\sigma_{\alpha-\beta}^{\beta}$:

$$\gamma_{\alpha-\beta} = \sigma_{\alpha-\beta}^{\alpha} + \sigma_{\alpha-\beta}^{\beta}$$

Using these definitions, one can derive common expressions such as the Ostwald-Freundlich equation that define solution concentration as a function of mineral grain size. Owing to the independent nature of surface energies and the boundary energy, they can affect the pattern-forming behavior of the system (e.g., periodic precipitation or mineral clustering) that may not be evident from consideration of either alone.

Regional geology and chemistry of orthopyroxene argue against the formation of the Bushveld Complex from externally-derived crystal-rich slurries

Rais Latypov¹, Sofya Chistyakova¹

¹*School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa*

rais.latypov@wits.ac.za

Abstract

There is general agreement that the Bushveld Complex is a classic example of an open-system magma chamber that grew incrementally through several major and numerous minor replenishment events, with parental magmas sourced from deep crustal to mantle reservoirs. A central point of debate is whether these replenishing magmas were crystal-rich (i.e., crystal slurries) or effectively crystal-free (ranging from normal to superheated melts). We address this question using regional geology and the chemistry of cumulus orthopyroxene in the Bushveld Complex. Regional geology constrains the floor of the Bushveld Complex to a depth of ~10 km (~3 kbar), with the underlying well-exposed volcano-sedimentary succession extending to a depth of ~20 km (~6 kbar) above the granitic basement. If upper- to middle-crustal staging chambers had existed within this preserved crustal column, one might reasonably expect intrusive remnants of such chambers to be preserved; however, no such evidence is observed. Recent seismic and gravity imaging has identified a deep staging chamber only at depths of ~40–45 km, corresponding to pressures of ~10 kbar, thereby suggesting the most plausible lower crustal pressure conditions under which the proposed crystal slurries may have formed. Experimental crystallization of Bushveld-type magmas at ~10 kbar produces orthopyroxene enriched in Al₂O₃ (~3.5–7.0 wt%) and Cr₂O₃ (~1.7–2.2 wt%), providing a quantitative benchmark for high-pressure orthopyroxene. In contrast, cumulus orthopyroxene across the Bushveld Complex is systematically low in Al₂O₃ (<1.5 wt%) and Cr₂O₃ (<0.5 wt%), irrespective of stratigraphic position or the presence of chromite. Potential post-cumulus re-equilibration capable of lowering Al₂O₃ in high-pressure orthopyroxene is examined in detail but found to be inconsistent with the petrographic and chemical features of Bushveld orthopyroxene. We therefore conclude that orthopyroxene—and by inference, all other co-crystallizing minerals— were not derived from a deep staging chamber but rather formed directly within the shallow Bushveld magma chamber itself. These results impose a fundamental mineral-chemical constraint on petrogenetic interpretations and effectively rule out models invoking external crystal-rich slurries for the petrogenesis of the Bushveld Complex. They further indicate that the chromite, platinum, and magnetite reefs likely formed from crystal-free melts *in situ* within a shallow, largely molten Bushveld magma chamber.