A Semi-Quantitative Model for the Formation of Great Dyke-Type Platinum Deposits

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The uppermost parts of the ultramafic sections of some layered intrusions host significant deposits of the platinum-group elements (PGE). The type example of this class of PGE deposit is the Great Dyke of Zimbabwe. The Munni Munni deposit has a similar occurrence (e.g., Hoatson and Keays, 1989). In the Stillwater Complex of Montana there are local shows of PGE-sulfide enrichments at the top of the Ultramafic series but they are not laterally continuous (fig. 1).

These deposits have a number of common features:

1) Each is characterized by a lower sequence of ultramafic rocks consisting mainly of pyroxene and olivine overlain by mafic rocks containing 50 to 60 % plagioclase. The transition is sharp (commonly on the scale of a few grain diameters) and results in a marked density change in the rock.

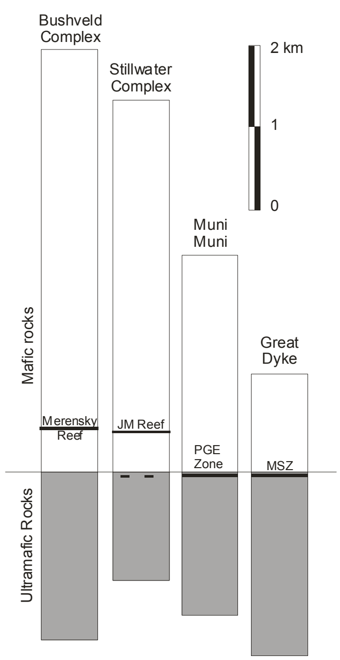

Figure 1. *Locations of major PGE zones in several layered intrusions. Those that occur just below the mafic-ultramafic contacts are the subject of this report.*

2) The PGE-sulfide mineralization is commonly found *below* the ultramafic-mafic contact. In addition, there are typically significant stratigraphic "offsets" between the maximum concentrations of the PGE, base metals and sulfur.

3) At discrete horizons, just below the ultramafic-mafic boundary, the rocks have higher incompatible trace-element concentrations, greater modal proportions of interstitial minerals, and more evolved mineral compositions. These features are interpreted to reflect a marked enrichment in crystallized interstitial liquid in these rocks.

A number of investigators have suggested that these zones are the result of a complex interplay of extreme fractionation, magma mixing, and sulfide saturation with variable "R-values" (e.g, Barnes, 1993; Hoatson and Keays, 1989).

Here we suggest that the first order features of these deposits are explained by compaction in a crystal pile, in which the bulk solid density shows an abrupt change, and fluid redistribution of the ore-element component. We have modeled these processes in previous works (e.g., Meurer and Boudreau 1996; Boudreau 1999) and in combination they can explain why the tops of ultramafic zones are particularly prone to PGE enrichment. The models propose that compaction of a density-stratified crystal pile leads to an increase in porosity and enrichment of the uppermost parts of the ultramafic section in evolved liquids. As the cumulates below degas, allowing ore components to migrate upward as a chromatographic front, these liquid- and iron-rich zones can become traps that either physically retard the upward movement of the exsolved fluids or cause them to precipitate of PGE-sulfides. In either case, they can result in one or more PGE-enriched horizons.

Compaction at Ultramafic-Mafic Boundaries

Compaction in a crystal pile is driven by density differences between the bulk solid assemblage and the interstitial liquid. As discussed by Meurer and Boudreau (1996), the transition from the ultramafic to mafic assemblage typically involves a change in density from approximately 3.3 g/cm^3 to 3.0 g/cm^3. Compared with a typical liquid density of 2.7

g/cm^3, the liquid-solid density contrast in the ultramafic section is about twice that of the overlying mafic section. For other parameters being equal, this means that the ultramafic zone will compact faster than the mafic section. The results of numerical simulations show that sharp density changes can produce uneven distributions of pore liquid at the tops of ultramafic sections. In this case, interstitial liquid tends to collect as porosity waves that propagate from the interface (fig. 2). Comparison of modeled liquid distributions with incompatible trace-element concentrations from the Jimberlana and Munni Munni intrusions shows a good match. These results demonstrate that the trace-element trends can be accounted for by compaction without any other changes in the crystallization conditions other than the magma becoming saturated in plagioclase. This model can explain the high abundance of incompatible elements that occurs just below the ultramafic-mafic boundary in a number of intrusions including the Great Dyke of Zimbabwe, and the Jimberlana and the Munni Munni Complex of Australia.

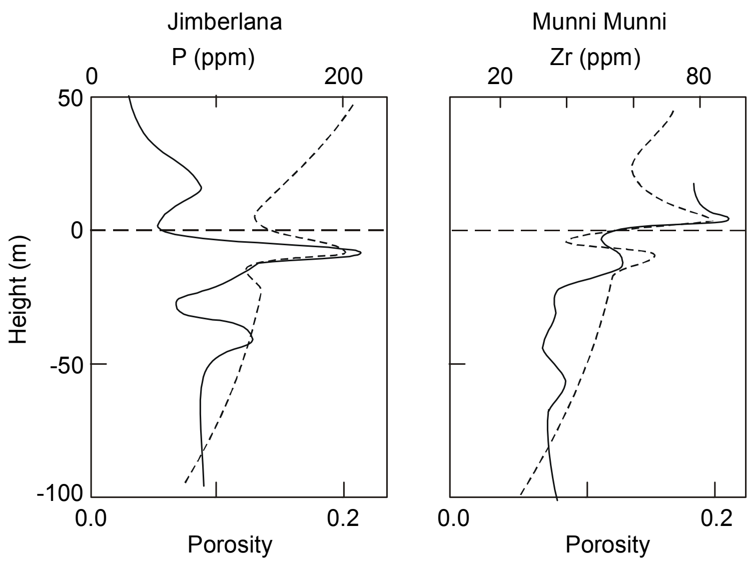

Figure 2. *Comparison of predicted liquid distributions at 1000 yr and 1250 yr with incompatible-trace-element concentrations in the Jimberlana (P) and Munni Munni (Zr) intrusions. The vertical scale represents the height in meters relative to the ultramafic-mafic transition. The model is dimensional so the results can be directly compared to actual stratigraphic thicknesses. The horizontal scale for the trace element data (upper scale) is in ppm while the horizontal scale for the simulation results (lower scale) is for porosity. The dashed line depicts the results of the simulation and the solid line is the observed trace-element abundance. The simulations accurately predict the relative positions and wavelengths of the incompatible-trace-element peaks for both intrusions and the presence of two peaks in the Munni Munni intrusion. The increasing porosity at the top of the dashed model curves reflects the gradient toward crystal-free liquid.*

Metal Transport During Degassing of Interstitial Liquids

Using Pd as a typical PGE and Cu as a typical base metal, Boudreau and Meurer (1999) used a numerical model to illustrate how metal separations can develop in a vapor-refining zone as fluid evolved during solidification of a cumulus pile leaches sulfide and redeposits it higher in the crystal pile. The solidification/degassing ore-element transport was coupled with a compaction model for the crystal pile used by Meurer and Boudreau (1996). Solidification resulting from conductive cooling through the base of the compacting column leads to an increasing volatile concentration in the intercumulus liquid until it reaches fluid saturation. Separation and upward migration of this fluid leads to an upward-migrating zone of increasing bulk water contents as water degassed from underlying cumulates enriches overlying, fluid-undersaturated interstitial liquids. Sulfide is resorbed from the degassing regions and is reprecipitated in these vapor-undersaturated interstitial liquids, producing a zone of relatively high modal sulfide that also migrates upward with time. Owing to its strong preference for sulfide, Pd is not significantly mobile until all sulfide is resorbed. The result is a zone of increasing PGE-enrichment that follows the sulfide resorption front as solidification and degassing continues. In detail, the highest Pd concentrations are stratigraphically below the peak in S and base metals. The high Pd/S ratio mimic values conventionally interpreted as the result of high (silicate liquid)/(sulfide liquid) mass ratios ("R" values). However, in this case, the high Pd/S ratio is the result of a chromatographic/ reaction front enrichment and not a magmatic sulfide saturation event.

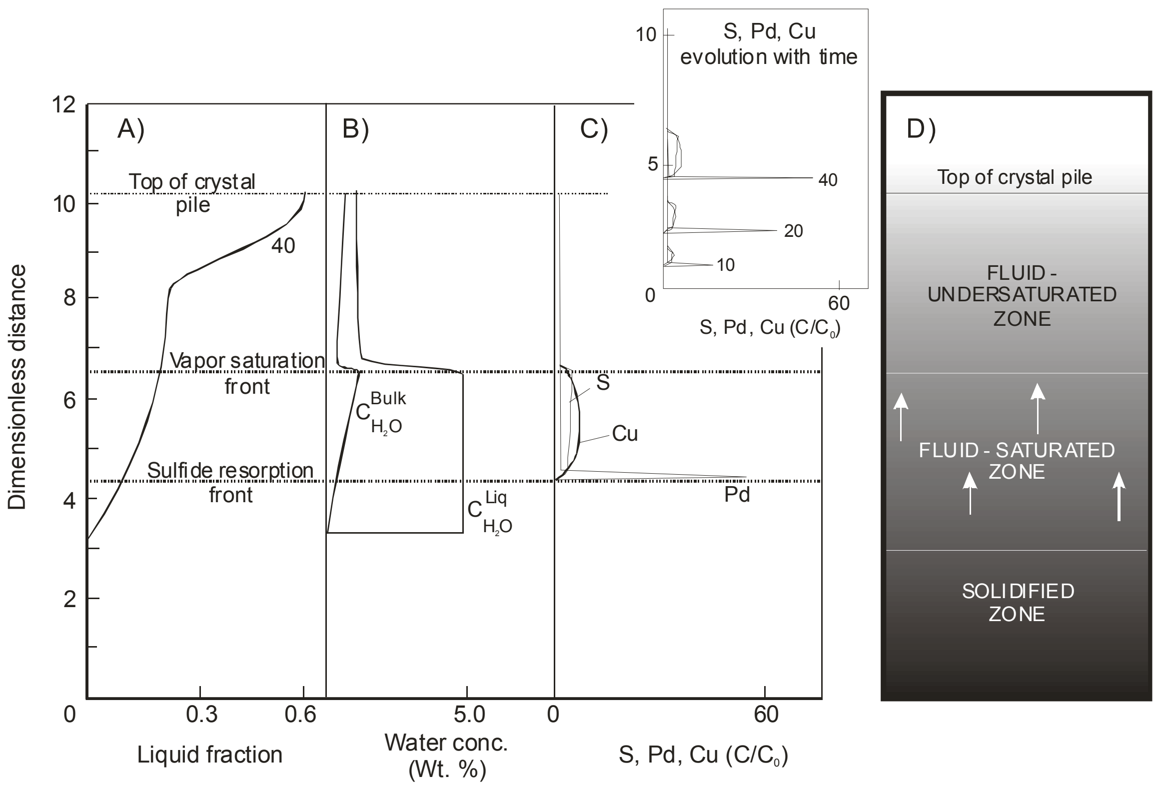

Figure 3. *Effect of fluid separation and migration during solidification of a compacting crystal pile on the distribution of water, S, Cu and Pd after 40 dimensionless time steps. A) Plot of liquid fraction; the top of the crystal pile is just over 10 dimensional units, and the cumulate section between 0 and 3.3 dimensionless units has completely crystallized. B) Plot of bulk water content ,* $C^{Bulk}_{H_2O}$ *and water concentration of the interstitial liquid,* $C^{liq}_{H_2O}$. *The region between 3.3 and 6.5 dimensionless units is the fluid saturated zone. C) Plot of bulk concentrations of S, Cu and Pd relative to their initial concentration. Note the peak in Pd enrichment occurs at the sulfide-dissolution front. Inset shows development of ore element profiles at 10, 20 and 40 dimensionless time steps, respectively. D) Cartoon of the physical situation in the crystal pile. From Boudreau and Meurer (1999).*

Development of Traps for Metal Concentrations

One consequence of crystallizing more interstitial liquid in the upper portions of the ultramafic sections is that it creates a discrete compositional layering. The crystallization of interstitial liquid produces more evolved overgrowths and interstitial minerals that increase the bulk-rock Fe content. The higher Fe content may induce sulfide precipitation as fluids exsolved from magnesian cumulates below react with the more Fe-rich silicates via reactions of the type:

$$\underset{\textit{Fluid}}{H_2S} + \underset{\textit{silicate}}{FeO} = \underset{\textit{po}}{Fe_{1-x}S} + \underset{\textit{fluid}}{H_2O}$$

Because of this stratigraphic variability, more than one metal/sulfide zone may develop as the infiltrating fluid reequilibrate with different bulk compositions.

The presence of several discrete porosity waves just below the ultramafic-mafic boundary also creates the potential for multiple mineralized horizons. When the upward migrating fluid encounters a porosity wave that is undersaturated, it will redissolve into that liquid until it is saturated and then continue to move upward. Depending upon the porosity and permeability of the overlying cumulates, sulfur and metals may become trapped in a porosity wave that crystallizes more slowly than the overlying cumulates.

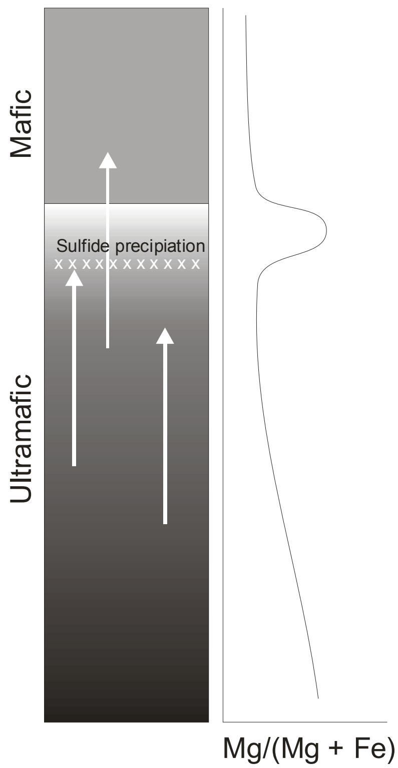

Figure 4. *Cartoon illustrating upward migrating fluids precipitating PGE-sulfide at Fe0-enriched zone at the top of a fast compacting ultramafic section.*

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