Attributes of Skaergaard-Type PGE Reefs

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Stratiform, platinum group element (PGE) deposits have long been known to occur in ultramafic-mafic intrusive complexes such as Bushveld and Stillwater (Naldrett, 1989b). Commonly known as PGE reefs, such deposits are typically found near the transition from ultramafic to mafic cumulates where they occur as 1-3 meter thick intervals enriched in PGEs (1-20 ppm) and trace to moderate amounts of sulfide (0.5-5 wt %). However, relatively recent discoveries have demonstrated that potentially economic stratiform PGE mineralization may also occur in tholeiitic mafic layered intrusions. Au- and PGE-bearing layers have been found most notably in the Middle Zone of the Skaergaard Intrusion (Bird et al., 1991; Andersen et al., 1998), but also in related Palaeogene intrusions of East Greenland (Arnason et al., 1997; Arnason and Bird, 2000); in the Jurassic Freetown Layered Complex of Sierra Leone (Bowles, 2000); in thick Mesozoic tholeiitic diabase sheets of the eastern United States; in the 990 Ma Rincón del Tigre complex (Prendergast, 2000); in several intrusions associated with the 1.1Ga Midcontinent Rift of North America (Miller, 1999, this volume; Miller et al., 2002); in the Paleoproterozoic Lake Owen intrusion of Wyoming (Loucks and Glasscock, 1989); and in the 1.27 Ga Muskox Intrusion (Barnes and Francis, 1995). These and other discoveries reinforce previous suggestions that reef-type PGE deposits hosted by tholeiitic intrusions make up a new class of mineral deposits, which is best represented by the Platinova reefs of the Skaergaard Intrusion (Nielsen and Brooks, 1995; Prendergast, 2000). In this presentation, we summarize the distinctive attributes of this type of deposit, which we refer to as Skaergaard-type PGE reefs and discuss how their metallogenesis may differ from classic PGE reefs.

Tholeiitic mafic layered intrusions refer to a class of intrusions formed from aluminous, olivine tholeiitic parent magmas that are commonly associated with active rift settings, especially in plume-affected areas. Troctolite, anorthosite, olivine gabbro and oxide-rich olivine gabbro are common rock types in such intrusions whereas peridotite, pyroxenite, and dunite are usually quantitatively minor. When well-differentiated, such intrusions display a simplified cumulus stratigraphy following the scheme: Ol or Pl only-> Ol + Pl -> Pl + Cpx + FeOx ± Ol -> Pl + Cpx + FeOx + Ol + Ap. They have a strong cryptic layering towards iron-enrichment indicative of Fenner-type differentiation. They differ from classic PGE reef-bearing intrusions by lacking a significant ultramafic component (early olivine-only crystallization is minor to absent in most tholeiitic intrusions) and by being poor in orthopyroxene (inverted pigeonite is rarely a cumulus phase).

Skaergaard-type PGE reefs in well-differentiated tholeiitic intrusions are similar to classic reefs hosted by ultramafic-mafic complexes such as Bushveld and Stillwater complexes, in that they occur as sulfide-poor, PGE-rich intervals that are meters in thickness and are conformable with igneous layering. However, Skaergaard-type PGE reefs differ from classic reefs in many significant ways as summarized in Table 1. Also like many classic reef deposits, Skaergaard-type PGE reefs appear to have formed by predominantly orthomagmatic processes related the saturation, exsolution, and settling of magmatic sulfide melt from silicate magma and the accumulation of sulfide in stratiform cumulate layers. And like classic reefs, some believe that postcumulus hydromagmatic processes may be predominately responsible for the formation of Skaergaard-type reefs as well (Boudreau and Meuer, 1999).

One very significant difference in their metallogenesis, however, appears to be the manner by which sulfide becomes saturated in the magma system. Although magma mixing appears to be an important triggering mechanism for sulfide saturation (or oversaturation) in classic PGE reef systems (Naldrett, 1989b), the nearly constant solubility of sulfur during differentiation of tholeiitic magmas implies that magma recharge may not be capable of producing sulfide saturation in these systems.

To demonstrate this characteristic of sulfide solubility in a differentiating tholeiitic, the sulfide solubility curve and the liquid line of descent for FeO, S and temperature were modelled for the Sonju Lake intrusion (SLI) of northeastern Minnesota (Figure 1A). The SLI is a 1-km-thick, unidirectionally differentiated, sheet-like intrusion that formed as a closed magmatic system during Midcontinent Rift magmatism (Miller and Ripley, 1996). The variation in FeO and temperature during crystallization differentiation of the SLI have been calculated by applying the fractional crystallization model of Nielsen (1990) to an estimated parent magma composition with 14.7% FeO (Miller and Ripley, 1996). The FeO model curve is similar to a FeO liquid line of descent curve (Fig. 1A) that has been calculated from mass balance of whole rock compositions through the SLI. Based on the experimental studies of Haughton et al. (1974), a 14-20% range of FeO contents at a temperature of 1200°C corresponds to sulfide solubility increasing from 0.11 to 0.19%. Over this range of increased FeO, temperature decrease has an opposite effect on sulfide solubility. The effect of temperature is not completely known in detail, but a number of experimental studies conducted between 1400 and 1000 °C reported by Naldrett (1989a) suggest a decrease in sulfide solubility by a factor of 3 to 8.5 per 100°C drop in temperature (or a 0.04 –0.09 wt. % decrease in sulfide solubility per 100°C), with a greater effect at lower overall temperatures. The estimated variations in sulfide solubility due to the changes in model FeO and temperature during fractional crystallization of the SLI are shown in Figure 1B. The resultant flat solubility curve (Fig. 1B) demonstrates the offsetting effects of increasing FeO and decreasing temperature throughout most of the SLI's crystallization history.

***TABLE 1**: Comparision of Attributes of Skaergaard-type and Classic PGE Reefs.*

	Skaergaard-type PGE Reefs	**Classic PGE Reefs**
Tectonic Setting	Plume-influenced continental rifts, occur as subvolcanic intrusions	Unclear, occur as large, isolated intrusions within Precambrian cratons
Age	Mesoproterozoic and younger	Neoarchean to Paleoproterozoic
Parent Magma	Aluminous, olivine tholeiite (E-MORB)	High-Cr/Mg/Si boninite/komatiite (U-type) with aluminous tholeiite (A-type)
Host Rock	Gabbroic to ferrogabbroic cumulates (Pl+Cpx±Ox±Ol); some associated with layering.	Pyroxenitic to noritic cumulates; locally associated with chromitite layers, early anorthositic cumulates, and pegmatite.
Sulfide Composition of Mineralized Intervals[1]	Cu/Ni >100 (closed systems) Cu/Ni >1 (open systems)	Cu/Ni = 0.3-5.0 (open systems)
Precious Metal Ratios of Mineralized Intervals[1]	Pt/Pd = 7 – 0.1 Pt+Pd/Au = 1 - 10	Pt/Pd = 2.5 - 0.2 Pt+Pd/Au > 10
Stratigraphic Distribution of Peak Concentrations[1] (⇒ below, ⇔ coincident with, / or)	Pt ⇒/⇔ Pd ⇒⇒ Au Pt + Pd ⇒ Cu (±Ni)⇔ Au	Pd ⇒/⇔ Pt ⇒/⇔ Au Pt + Pd ⇒/⇔ Ni ⇔ Cu ⇔ Au
Examples[2]	Closed systems - Skaergaard, Sonju Lake Intrusion, New Haven diabase Open systems- Layered Series at Duluth, Kap Edvard Holm Complex, Lake Owen Intrusion, Freetown Complex, Muskox Intrusion, Rincón del Tigre Complex	Bushveld Complex, Stillwater Complex, Great Dyke, Munni Munni Complex, Jimberlana Intrusion, Penikat, Portimo and other Fenno-scandian intrusions, Rum Intrusion, Muskox Intrusion, Rincón del Tigre Complex

[1] *Based on data from this study; Arnason and Bird, 2000; Prendergast, 2000; Andersen et al., 1998; Lee, 1996; Barnes and Francis, 1995; Naldrett, 1989b.*

[2] *PGE reefs in the Muskox and Rincón del Tigre intrusions have attributes in common with both reef types.*

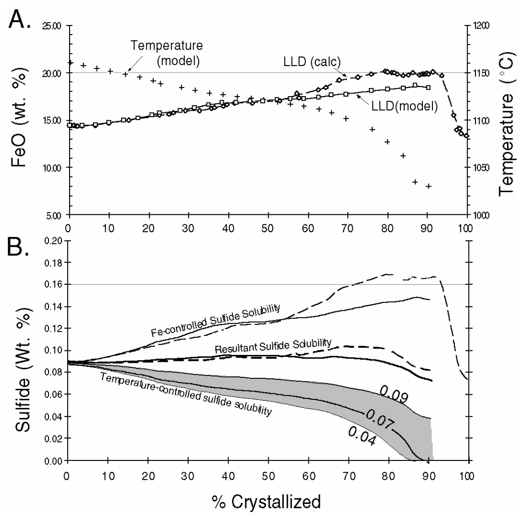

Figure 1. *Model curves for FeO, temperature, and sulfide solubility variation during crystallization differentiation of the Sonju Lake intrusion. A) Variation in FeO and temperature based on fractional crystallization model of Nielsen (1990) and variation in FeO based on mass balance calculation (Miller and Ripley, 1996). B) Variation in sulfide solubility due to effects of temperature (factor range of 0.04–0.09 wt% sulfide/100°C after Naldrett, 1989a) and FeO concentration (based on experimental data from Haughton et al., 1964). Resultant solubility curves are based on a median temperature factor of 0.07 wt% sulfide/100°C.*

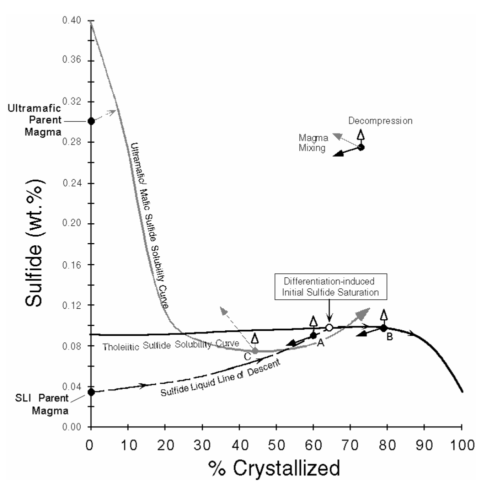

Figure 2. *Resultant sulfide solubility curve for Sonju Lake intrusion compared to solubility curve estimated for ultramafic/mafic magma systems (Naldrett, 1989b). Liquid line of descent for sulfide in the SLI magma calculated by Rayleigh distillation and based on sulfide saturation at 65% crystallized. Vector arrows show effects of magma mixing and decompression for three different situations. Point A shows effects on tholeiitic SLI magma just prior to sulfide saturation. Point B shows effects on sulfide-saturated SLI magma. Point C shows effects on evolved ultramafic magma system.*

Chemostratigraphic studies show that the Sonju Lake intrusion reached sulfide saturation at 65% crystallized (Miller, 1999; this volume). Treating sulfide as an incompatible component up to the point of saturation, the liquid line of descent of sulfide during fractional crystallization can be calculated by simple Rayleigh distillation. Assuming a sulfide concentration of 1.1 wt.% at saturation, the calculated liquid line of descent curve implies an initial sulfide concentration of the parent magma of 0.35 wt.% (Fig. 2). It is clear that magmatic recharge of this parental composition will not result in saturation or oversaturation of sufide. Also plotted in Figure 2 is the sulfide solubility curve estimated for ultramafic/mafic magma systems by Naldrett (1989b), which shows how magma mixing can result in sulfide oversaturation is such systems. Although stratiform PGE mineralization in the Kap Edvard Holm intrusion appears to be related to magma mixing (Arnason and Bird, 2000), it is not clear how this has occurred from an uncontaminated tholeiitic parent magma.

Rather than magma recharge, magmatic processes of crystallization differentiation, decompression due to magma venting, and changes in phase equilibrium appear to be important in the formation of most Skaergaard-type reef occurrences. The Sonju Lake intrusion looks to be the most clear cut example of sulfide saturation triggered by straightforward crystallization differentiation, though a detail examination of the reef is underway to confirm this interpretation. Andersen et al. (1998) have similarly interpreted the Pd and Au mineralization of the Skaergaard to have formed by fractional crystallization driving the magma to sulfide saturation. However, the cyclical nature of PGE mineralization and modal layering in the host gabbro may suggest a more dynamic triggering mechanism. Miller (this volume) has interpreted the PGE mineralization and the related macrocyclic layering in the Layered Series at Duluth as resulting from periodic decompression due to magma venting from a shallow (<5km) depth. Perhaps the Platinova reefs of the Skaergaard formed in a similar manner. Sulfide saturation triggered by changes in phase equilibrium, especially the onset of Fe-oxide crystallization, is evident in the Rincón del Tigre complex (Prendergast, 2000).

In conclusion, the suggestion by Nielsen and Brooks (1995) that the stratiform PGE and Au mineralization discovered over a decade ago in the Skaergaard intrusion may constitute an important new type of mineral deposit now seems prophetic in light of similar discoveries in other igneous provinces. Although an economically viable deposit has yet to be found, the search for Skaergaard-type PGE reefs has only just begun. Like their classic reef cousins, exploration for this subtle style of mineralization requires systematic sampling and a thorough understanding of the crystallization history of the host intrusion.

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