

THE RELATIONSHIP BETWEEN CHLORAPATITE AND PGE-RICH CUMULATES IN LAYERED INTRUSIONS: THE KLÄPPSJÖ GABBRO, NORTH-CENTRAL SWEDEN, AS A CASE STUDY

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ABSTRACT

The Kläppsjö Gabbro, in north-central Sweden, is a layered intrusion with two horizons of ultramafic cumulates that occur among otherwise relatively evolved gabbroic cumulates. Assays for Pt, Pd, and Au reveal enriched concentrations at discrete levels within each of the ultramafic sections. Apatite in these same samples have unusually high X^{Cl} values (as much as ~0.85). Chlorapatite is quite uncommon in such settings, but is associated with the economically significant J–M and Merensky PGE reefs of the Stillwater and Bushveld complexes, respectively. However, below the mineralized horizons in the Kläppsjö Gabbro, there is no chlorapatite, as there is in those two complexes, nor are the mineralized horizons demonstrably associated with mixing of variably evolved magmas. Thus the PGE mineralization does not appear to fit either of the two most accepted models for PGE concentration in layered intrusions. We suggest that the mineralization in the Kläppsjö Gabbro is the product of minor sulfide accumulation from basaltic liquids relatively rich in PGE and Au. This enrichment may be associated with segregation of the sulfide liquid in the plumbing system, but the high Cl contents of the apatite associated with high Pt and Au concentrations in the ultramafic rocks suggest a source enriched in PGE, Au, and Cl.

Keywords: apatite, halogens, platinum-group-elements, layered intrusions, economic geology, Kläppsjö Gabbro, Sweden.

SOMMAIRE

Le massif gabbroïque de Kläppsjö, dans la partie centre-nord de la Suède, est un complexe stratiforme contenant deux niveaux de cumulats ultramafiques parmi des cumulats gabbroïques relativement évolués. Des analyses pour le Pt, Pd, et Au révèlent un enrichissement à des niveaux spécifiques dans chacune des deux sections ultramafiques. L'apatite dans ces mêmes échantillons fait preuve de teneurs anormalement élevées en X^{Cl} (jusqu'à ~0.85). La chlorapatite est relativement rare dans de tels milieux, mais elle est associée avec les bancs minéralisés en éléments du groupe du platine (EGP) dits de J–M et de Merensky, dans les complexes de Stillwater et de Bushveld, respectivement. Toutefois, en-dessous des niveaux minéralisés de la séquence gabbroïque de Kläppsjö, il n'y a pas de chlorapatite, comme dans ces autres exemples de bancs minéralisés. Il n'y a pas non plus d'évidence que les zones minéralisées pourraient résulter d'un mélange de magmas variablement évolués. Il semble donc que la minéralisation en EGP ne peut pas s'expliquer en invoquant l'un ou l'autre des deux modèles généralement proposés pour expliquer la concentration des EGP. L'origine de la minéralisation dans le cas du gabbro de Kläppsjö Gabbro résulterait plutôt d'une accumulation d'une fraction mineure de sulfures à partir de venues de liquide basaltique relativement enrichies en EGP et en Au. Cet enrichissement pourrait être associé à une ségrégation de liquide sulfuré dans le système de conduits, mais les teneurs élevées en chlore de l'apatite associée aux anomalies en Pt et en Au des roches ultramafiques laissent présager une source enrichie en EGP, Au, et Cl.

(Traduit par la Rédaction)

Mots-clés: apatite, halogènes, éléments du groupe du platine, complexe stratiforme, géologie économique, gabbro de Kläppsjö, Suède.

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INTRODUCTION

Significant resources of platinum-group elements (PGE) are found in stratiform "reef" horizons in several layered intrusions, the most economically significant examples being the Merensky Reef of the Bushveld Complex and the J–M Reef of the Stillwater Complex. The level of concentration of the PGE in the basaltic magmas responsible for the layered intrusions hosting magmatic PGE-rich deposits is considered to be low (typically <20 ppb Pt or Pd; Brugmann *et al.* 1993, Rehkämper *et al.* 1999, Momme *et al.* 2002). Extraordinarily efficient processes of enrichment are thus required (factor of 1000) to form economically viable deposits. The association of chlorapatite below and at the level of the PGE horizons in the Stillwater and Bushveld complexes suggests that Cl-rich volatiles may be responsible for ore concentration. In this contribution, we examine the origin of Pt and Au enrichments in the Kläppsjö Gabbro, in north-central Sweden, that are associated with chlorapatite. Unlike the reef horizons in the Stillwater and Bushveld complexes, apatite compositions below the mineralized horizons in the Kläppsjö Gabbro are Cl-poor; the new data provide an opportunity to further evaluate the relationship between chlorapatite and PGE mineralization.

MODELS FOR PGE ENRICHMENTS
IN LAYERED INTRUSIONS

Hydromagmatic models for PGE concentration in layered intrusions rely upon a Cl-rich volatile phases, exsolved from crystallizing interstitial liquid in cumulates below the reefs, to scavenge S and PGE and transport them to the reef level (*e.g.*, Ballhaus & Stumpfl 1986, Boudreau & McCallum 1992). In these models, the parental magma is sulfide-saturated, so that PGE-enriched sulfides are available in the pile of crystals to react with the upward-moving fluids. The abrupt change in concentration of the PGE at the level of the reef may be related to a physical or chemical trap, with analogies to the reducing front that concentrates soluble U in rollfront uranium deposits (Harshman 1972). As an alternative, upward-moving fluids encountering the top of the pile of crystals, then dissolving into the overlying liquid, might cause the dissolved S and PGE to precipitate (Boudreau & Meurer 1999, Meurer *et al.* 1999, Lechler *et al.* 2002).

Models invoking an orthomagmatic origin, in contrast, require that a sulfide-undersaturated magma be crystallizing in the chamber prior to the reef formation. Such a magma would mix with a new magma of a different composition, causing the system to become sulfide-saturated, thus forming a reef. For example, a boninitic magma is considered to be parental to most of the cumulates below the J–M Reef of the Stillwater Complex. However, at the level of the reef and above, injections of a tholeiitic magma are invoked to explain

changes in isotopic data and mineral paragenesis (Wooden *et al.* 1991, Lambert *et al.* 1994). The mixing of the resident boninitic magma with the first injections of this tholeiitic magma could have induced sulfide saturation and produced immiscible droplets of sulfide liquid that scavenged PGE from a large volume of magma (Campbell *et al.* 1983, Naldrett 1989). Because the PGE strongly favor sulfide liquids over silicate liquids (on the order of 10,000:1; Barnes & Maier 1999), a small amount of sulfide can effectively concentrate the PGE and, upon settling to the floor, form a PGE reef. Proponents of orthomagmatic models might argue that the association of chlorapatite with the PGE-rich horizons is coincidental, and at most explains minor redistribution of the already concentrated ore.

In this contribution, we test the viability of the hydromagmatic model to explain the high concentrations of PGE in the ultramafic cumulates associated with the Kläppsjö gabbro, in north-central Sweden. Unlike the Stillwater and Bushveld complexes, which have lower ultramafic sections and become progressively more evolved upward, the ultramafic cumulates of the Kläppsjö Gabbro that host PGE mineralization occur at two higher levels in the stratigraphy, and are juxtaposed with much more evolved cumulates. We examine the halogen contents of interstitial apatite throughout the Kläppsjö gabbro to determine if there is a progressive enrichment and abrupt decline in their Cl content as documented in the Bushveld (Boudreau & Kruger 1990) and Stillwater (Boudreau & McCallum 1989) complexes. The viability of the orthomagmatic model is also considered, using variations in compositions of cumulus minerals to assess the importance of magma mixing at the PGE-enriched horizons. Lastly, we consider the possibility that the high PGE content of the ultramafic cumulates is directly related to a high concentration of PGE in the primitive magmas prior to emplacement (Keays & Lightfoot 2002).

THE GEOLOGICAL SETTING OF THE KLÄPPSJÖ GABBRO

The Kläppsjö Gabbro is an early orogenic Svecofennian (~1870 Ma) pluton, located in the Baltic Shield of central Sweden (Lat. 63°41', Long. 17°12'). The ~2.0–1.75 Ga Svecofennian country rock is comprised primarily of marine sedimentary units of the Bothnian basin between the Skellefte and Bergslagen volcanic belts (Gaál & Gorbachev 1987; Fig. 1). These turbidites were intruded by felsic to mafic magmas, producing igneous bodies traditionally classified as early, late, and post-orogenic and anorogenic, relative to the Svecofennian orogeny. Sedimentary units and early orogenic plutons were locally metamorphosed during a low-pressure amphibolite-facies event before ~1.82 Ga, when the late-orogenic Härnö granites were intruded (Claesson & Lundqvist 1995). Minor metamorphism of the Kläppsjö Gabbro resulted in some localized serpentinization of olivine and may have produced the

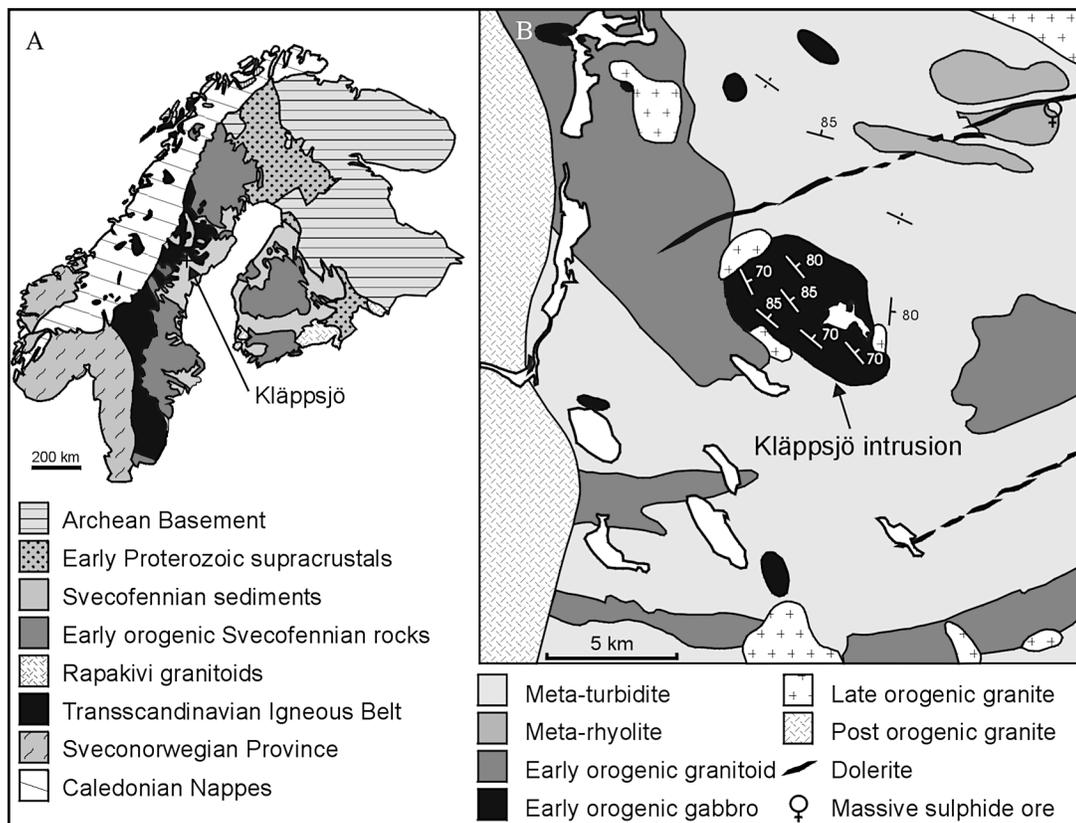


FIG. 1. A. Geological outline of the Fennoscandian Shield, modified after Gaál & Gorbatshev (1987). The cross marks the location of the Kläppsjö gabbro. B. The geology of the Kläppsjö area, modified after Lundqvist *et al.* (1990) and Filén (2001).

corona texture seen between plagioclase and olivine in some samples (*e.g.*, Claeson 1998). The samples included in this study are relatively fresh and were not substantially affected by the metamorphic event(s).

The Kläppsjö Gabbro is exposed for ~6 km along strike, and ~3.5 km perpendicular to strike (Fig. 1). The subvertical to steeply northeast-dipping igneous layering is subparallel to the layering in the surrounding sediments, indicating that the gabbro intruded into the greywackes, and developed an original near-horizontal attitude of the igneous layering. The intrusion consists of ultramafic, leucogabbroic, and ferrogabbroic megauits, tens to hundreds of meters thick, forming a ~3 km thick layered sequence (Filén 2001). The cumulus minerals in the ultramafic rocks, olivine and minor chromite, are commonly enclosed in ortho- and clinopyroxene oikocrysts. The gabbroic rocks contain olivine, plagioclase, and clinopyroxene as cumulus (granular) phases, and the more evolved (ferrogabbroic) units also contain abundant ilmenite and cumulus (euhedral) apatite. Accessory minerals in all rocks include orthopyroxene (ab-

sent in the ferrogabbros), hornblende, biotite, and apatite (cumulus in the ferrogabbros). Minor amounts of sulfides occur in most samples; this fraction is dominated by pyrrhotite, chalcopyrite and pentlandite, but other trace phases include pyrite, sphalerite, sulfarsenides and arsenides. Sulfarsenides and arsenides are more abundant in the ultramafic rocks than in the surrounding gabbroic units. Occurrences of sulfide-rich (up to 21%) boulders and outcrops (0.63–0.85% Ni, 0.37–1.03% Cu) from the southernmost (lower marginal) part indicate zones rich in sulfides, but the exposure is poor. The PGE content of these samples is low (F.A. Hellström, in prep.).

Apatite occurs in all cumulates of the Kläppsjö Gabbro, but is a cumulus (liquidus) mineral only in the most evolved ferrogabbros. The habit of the apatite crystals varies considerably depending on the modal proportions of the cumulus minerals. An unusual feature of the apatite in the ultramafic cumulates is that many crystals occur as very large interstitial grains, some with maximum dimensions of 0.5 to >1 mm (Fig. 2). Despite the

presence of these large grains, apatite in these cumulates is scarce; the bulk-rock P contents are typically less than 0.1%. Large interstitial grains of apatite have not been reported in ultramafic cumulates from either the Stillwater or Bushveld complexes and, in our experience, are extremely uncommon in cumulates in general

(*e.g.*, Meurer & Boudreau 1996, Willmore *et al.* 2000, Meurer & Natland 2001). In the mafic cumulates, apatite occurs as small grains interstitial to the cumulus minerals, with habits that range from anhedral to euhedral. The apatite in the ferrogabbros is most commonly associated with other minerals typical of evolved

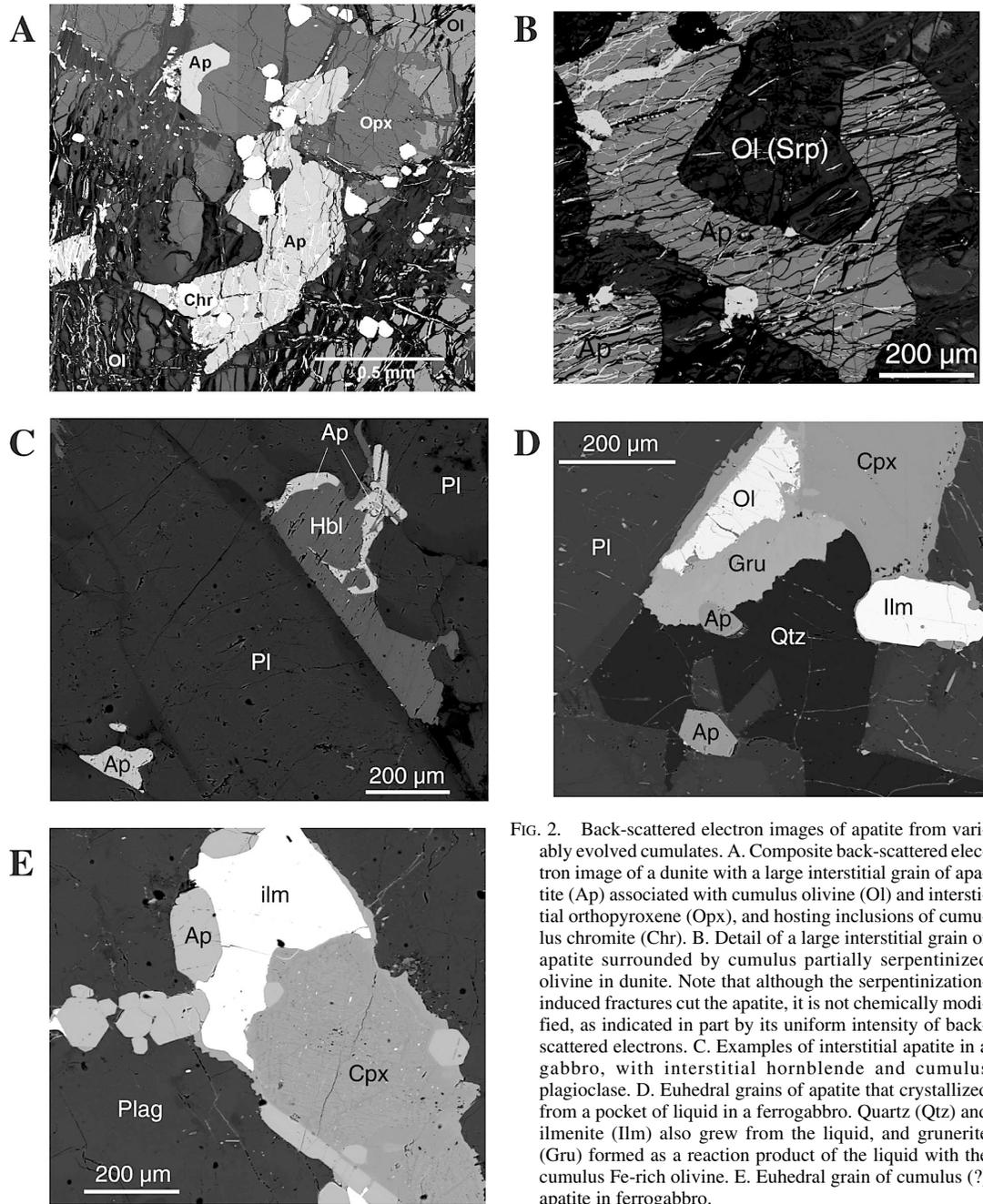


FIG. 2. Back-scattered electron images of apatite from variably evolved cumulates. A. Composite back-scattered electron image of a dunite with a large interstitial grain of apatite (Ap) associated with cumulus olivine (Ol) and interstitial orthopyroxene (Opx), and hosting inclusions of cumulus chromite (Chr). B. Detail of a large interstitial grain of apatite surrounded by cumulus partially serpentinized olivine in dunite. Note that although the serpentinization-induced fractures cut the apatite, it is not chemically modified, as indicated in part by its uniform intensity of back-scattered electrons. C. Examples of interstitial apatite in a gabbro, with interstitial hornblende and cumulus plagioclase. D. Euhedral grains of apatite that crystallized from a pocket of liquid in a ferrogabbro. Quartz (Qtz) and ilmenite (Ilm) also grew from the liquid, and grunerite (Gru) formed as a reaction product of the liquid with the cumulus Fe-rich olivine. E. Euhedral grain of cumulus (?) apatite in ferrogabbro.

rocks, such as quartz and ilmenite, and found disseminated throughout the samples. It typically has a euhedral, prismatic habit (Fig. 2).

Stratigraphic variations in the Fo content of the olivine, the Mg# of the clinopyroxene [both as molar $MgO / (MgO + FeO^*)$], and the An content of the plagioclase [molar $CaO / (CaO + K_2O + Na_2O)$] reveal no systematic evolution with stratigraphic height (Fig. 3). On the other hand, these parameters do vary abruptly below and above the ultramafic horizons, especially the An content. The jumps in compositions to more primitive values invariably coincide with shifts from gabbroic to ultramafic assemblages (F.A. Hellström, in prep.). These changes are interpreted to reflect the injection of a more primitive liquid into a solidifying mass of magma.

SAMPLING AND ANALYTICAL METHODS

Samples for this study were taken primarily from two drill cores through the two ultramafic horizons of the Kläppsjö suite. These samples were augmented with surface samples to provide more complete stratigraphic coverage. Apatite in nearly all but the most evolved of the samples is scarce; the grains commonly are quite small (*i.e.*, less than 100 μm), and not readily identified using a petrographic microscope. Therefore, all apatite grains were identified by systematically traversing the entire sample while imaging it in back-scattered elec-

tron mode and directing the output of a wavelength-dispersion spectrometer set to $PK\alpha$ to be superimposed on the screen. Ten grains of apatite were analyzed in samples with abundant apatite; otherwise, all grains larger than $\sim 15 \mu m$ in minimum dimension were analyzed.

Apatite compositions were determined at Duke University and at the University of Houston, using a Cameca Camebax electron-microprobe and a JEOL JXA-8600 superprobe, respectively (Table 1). Standard analytical conditions for both instruments were: acceleration voltage 15 kV, cup current 15 nA, beam diameter 10 μm , and counting times 10–40 s. The peaks for Cl, F, and P were counted first to minimize loss of these elements due to sample degradation by the beam. On both instruments, F was measured using a multilaminate, synthetic, “light-element” crystal. Mineral standards were used, including chlorapatite and fluorapatite checked against NaCl and CaF_2 at Duke, and fluorapatite at UH. Replicate analyses of apatite from four samples at both laboratories revealed no differences within error. The proportion of OH was calculated by site difference ($Cl + F + OH = 1$ “atom” per formula unit). Data were corrected using either a Cameca Phi Rho Z (PAP) correction (Duke) or JEOL ZAF correction (UH).

Quantitative determinations of the halogen content of apatite can be complicated by diffusion of the halogens parallel to the crystallographic *c* axis during the

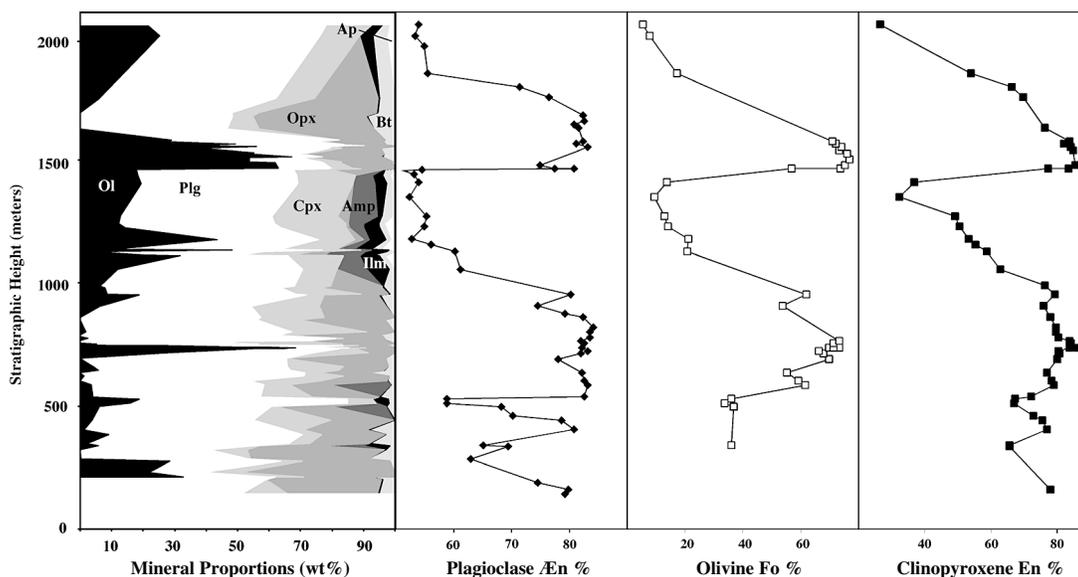


FIG. 3. Stratigraphic variations in the Kläppsjö gabbro; data from F.A. Hellström (in prep.). The first column shows the variation in the primary mineralogy, calculated using a multiple linear regression of the mineral compositions against the bulk-rock composition. The other three columns show variations in average mineral compositions. Mineral symbols are: Ol: olivine, Pl: plagioclase, Cpx: clinopyroxene, Opx: orthopyroxene, Amp: magmatic amphibole, Il: ilmenite, Bt: biotite, and Ap: apatite.

electron-microprobe analysis. Methods have been proposed to mitigate this effect (Stormer *et al.* 1993). Our analytical method incorporates the most important of these strategies, as discussed elsewhere (Meurer & Boudreau 1996, Meurer & Natland 2001). Estimated relative errors for F and Cl determinations are 8.0 and 4.5%, respectively (*cf.* Willmore *et al.* 2000). Care was taken to avoid analysis of altered apatite, as low-temperature alteration can substantially cause a decrease in the Cl and an increase in the OH content (Boudreau & McCallum 1990).

More than 500 PGE assays on samples of the Kläppsjö suite were collected as part of a PGE–Au ex-

ploration program in Sweden by the Swedish Geological Company, carried out between 1984 and 1990 (Filén 2001). These assays were conducted primarily on samples from the two drill cores, which penetrated the two sections of ultramafic cumulates, although a small number of samples were also collected from shorter (20 cm) drill holes on outcrops (Fig. 3). We rely upon these data for our understanding of the PGE distribution in the intrusion. To augment these data, a suite of samples from throughout the intrusion have been analyzed for their major- and trace-element concentrations (F.A. Hellström, *in prep.*). The complete dataset will be discussed elsewhere, but below we describe the stratigraphic variations in Cu and S.

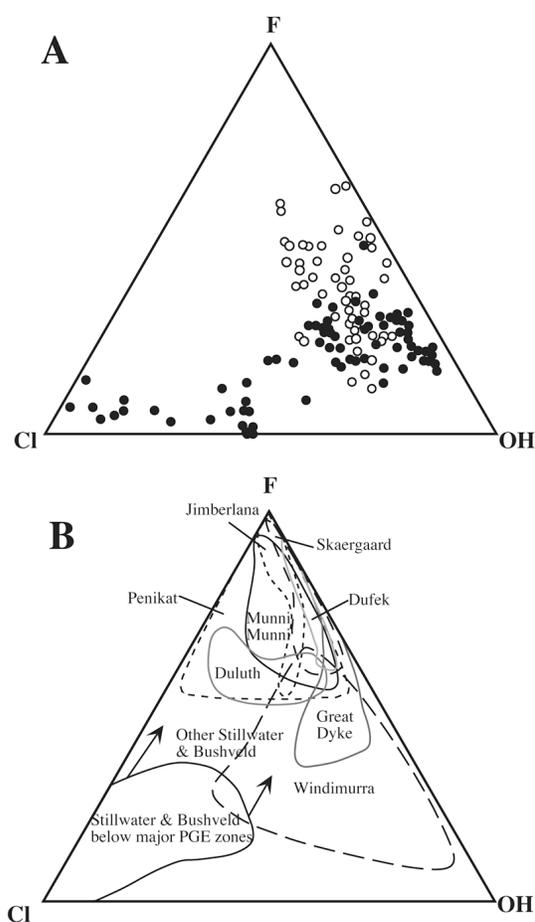


FIG. 4. A. Variation in the occupancy of the anion site in apatite from the Kläppsjö gabbro. Solid circles are compositions from ultramafic cumulates, and open symbols are compositions from gabbroic cumulates. B. Anion-site variability in apatite from other layered intrusions, modified from Boudreau (1995). The arrows extending from the field of apatite compositions that occur below the major PGE reefs in the Bushveld and Stillwater complexes indicate the evolutionary trend of the apatite above the reef horizons.

ANALYTICAL RESULTS

Apatite compositions in the Kläppsjö cumulates define two groups (Fig. 4a). One contains a mixture of chlorapatite and hydroxylapatite, with ≤ 0.3 (mole fraction fluorapatite in apatite). Chlorapatite is found exclusively in the ultramafic cumulates, and it has higher average Na contents (Table 1). Apatite-group minerals from mafic cumulates are OH–F-dominant, with maximum $X_{\text{Ap}}^{\text{Cl}}$ below 0.25 (Fig. 4a). Very little zonation is found in the apatite; although a few samples have significant variations between grains, most show relatively limited between-grain variability, less than 0.3 for $X_{\text{Ap}}^{\text{Cl}}$, X_{Ap}^{F} , and $X_{\text{Ap}}^{\text{OH}}$. Similar variability in apatite from the Stillwater Complex has been ascribed to within-sample fractionation and degassing (Meurer & Boudreau 1996).

Comparison of the compositions of the apatite encountered at Kläppsjö with those of other layered intrusions reveals hydroxylapatite ($X_{\text{Ap}}^{\text{OH}}$ typically from 0.6 to 0.8) to be far more common in the Kläppsjö Gabbro than in most other layered intrusions, which are typically dominated by fluorapatite (X_{Ap}^{F} between 0.6 and 1.0). The bulk of the apatite compositions in the Kläppsjö Gabbro are most similar to apatite from the Windimurra intrusion (Fig. 4b). The chlorapatite from the Kläppsjö Gabbro ($X_{\text{Ap}}^{\text{Cl}}$ between 0.55 and 0.95) is comparable only to the chlorapatite from the Bushveld and Stillwater complexes, found at and below the level of their major PGE reefs (Fig. 4b).

High concentrations of the PGE and Au are associated with ultramafic portions of the intrusion. Samples from an ultramafic unit 10–20 m thick in the southern part show high values of platinum, with five samples between 1.1 and 9.2 ppm Pt (Fig. 5) and one sample as high as 21.0 ppm Pt (not included in Fig. 5). Analyses of samples from the 110-m-thick ultramafic unit in the central part of the intrusion also show some modestly elevated Pt and Pd values; a 2-m section in the lower part of this unit (~1468 m) contains ~0.2 ppm Pt and 0.06–0.09 ppm Pd. An 8.3-m section in the central part of this ultramafic unit (1531–1537 m) has significant concentrations of Au, 0.11–1.17 ppm, with an average of 0.49 and 0.88 ppm for the last three meters (Fig. 5).

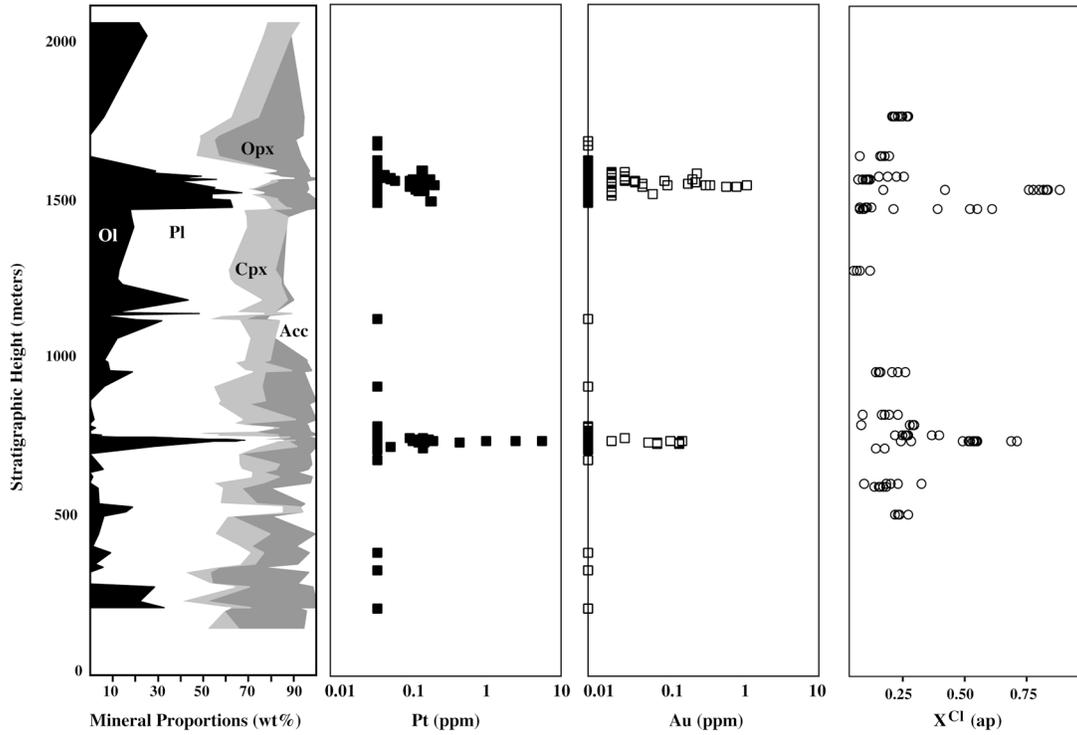


FIG. 5. A simplified plot of modal variation in the stratigraphic section is shown, with variations of the bulk-rock Pt and Au, and X_{Ap}^{Cl} . Mineral symbols are as in Figure 2, except for Acc, which represents all accessory phases. Detection limits for Pt are 0.04 ppm, and for Au, 0.01 ppm. A single analysis from the lower ultramafic unit with ~21 ppm Pt was omitted from the figure so that the scales for the Pt and Au would be the same (see text for details).

TABLE 1. REPRESENTATIVE COMPOSITIONS OF APATITE CRYSTALS ORDERED ACCORDING TO INCREASING STRATIGRAPHIC HEIGHT, KLÄPPSJÖ GABBRO, NORTH-CENTRAL SWEDEN

Height	P ₂ O ₅	CaO	Na ₂ O	SiO ₂	FeO	Ce ₂ O ₃	La ₂ O ₃	F	Cl	OH	O=F,Cl	Total	X_{Ap}^{Cl}	X_{Ap}^F	X_{Ap}^{OH}
505	41.96	55.27	0.05	b.d.l.	0.26	0.05	0.00	0.50	1.80	1.55	-1.31	100.12	0.26	0.13	0.61
592	41.79	56.48	0.01	b.d.l.	0.00	0.08	0.13	1.60	0.92	1.15	-1.87	100.28	0.13	0.42	0.45
603	41.20	55.55	0.03	0.19	0.25	0.10	0.04	1.08	1.26	1.34	-1.56	99.46	0.18	0.29	0.54
713	41.14	55.62	0.01	0.08	0.04	0.08	0.29	0.83	0.79	1.66	-1.12	99.42	0.11	0.22	0.67
736	41.65	55.68	0.06	0.03	0.15	b.d.l.	b.d.l.	1.14	4.95	0.66	-2.49	100.82	0.70	0.04	0.26
737	41.08	54.81	b.d.l.	0.37	1.68	b.d.l.	b.d.l.	0.68	1.84	1.38	-1.48	100.34	0.26	0.18	0.55
753	41.86	55.46	0.01	0.00	0.09	0.19	0.01	1.25	1.62	1.11	-1.89	99.70	0.23	0.33	0.44
789	41.35	55.52	b.d.l.	0.03	0.26	b.d.l.	b.d.l.	1.03	1.81	1.17	-1.79	99.46	0.26	0.27	0.47
820	41.61	55.81	0.02	0.32	0.35	b.d.l.	b.d.l.	1.12	1.22	1.34	-1.58	100.20	0.17	0.29	0.53
955	41.88	55.18	b.d.l.	0.38	0.25	0.08	0.14	0.94	0.89	1.58	-1.27	100.06	0.13	0.25	0.62
1272	42.09	55.75	0.01	0.23	0.32	0.08	0.02	1.88	0.24	1.20	-1.79	100.02	0.03	0.50	0.47
1466	41.76	54.58	0.06	0.00	0.33	0.07	0.05	0.22	3.60	1.06	-1.93	99.81	0.52	0.06	0.42
1471	41.02	55.45	0.02	0.31	0.21	0.09	0.12	1.15	0.32	1.61	-1.18	99.12	0.05	0.31	0.65
1524	41.21	55.26	0.08	0.08	0.04	0.10	0.15	0.16	5.95	0.26	-3.00	100.29	0.85	0.04	0.10
1556	42.79	55.29	0.06	0.13	0.18	0.05	0.09	0.95	0.55	1.73	-1.12	100.70	0.08	0.25	0.67
1565	41.41	56.10	0.03	0.01	0.31	0.21	0.12	1.03	1.16	1.42	-1.47	100.32	0.16	0.27	0.57
1628	40.49	55.79	0.02	0.12	0.12	0.07	0.05	1.20	1.21	1.26	-1.65	98.69	0.17	0.32	0.51
1753	42.30	55.51	0.02	0.04	0.19	0.16	0.09	1.81	1.57	0.76	-2.37	100.08	0.22	0.48	0.29

O = F,Cl: oxygen equivalence of fluorine and chlorine, OH calculated by difference in the anion site (see text). Compositions are reported in wt.%, and height, in meters.

Sulfur concentrations are consistently high in the lower ultramafic section, but only modestly elevated in the upper ultramafic section. However, Cu shows distinctive peaks in both ultramafic sections, in contrast to essentially invariant background concentrations in the mafic cumulates (Fig. 6).

DISCUSSION: CL-RICH APATITE AND PGE ENRICHMENT

The difficulty with documenting the role of volatiles in magmatic processes in mafic systems, as is required to evaluate the hydromagmatic model, is that the main liquidus minerals (olivine, plagioclase, and pyroxene) are all anhydrous, and therefore do not directly record the volatile history. An apatite-group mineral occurs as a ubiquitous interstitial phase in nearly all ultramafic and mafic cumulates. As substitution into the OH-site is ideal at magmatic temperatures (Tacker & Stormer 1989), apatite provides an excellent means of tracking the volatile evolution (*e.g.*, Boudreau & McCallum 1989, Meurer & Boudreau 1996). This attribute stands in contrast to Fe–Mg amphiboles and biotite, in which

the F–Cl incorporation is strongly controlled by crystal chemistry (Volfinger *et al.* 1985). Analysis of the halogen contents of an apatite has even been proposed as an exploration tool for PGE enriched horizons in layered intrusions (Boudreau 1993). Both the J–M and Merensky reefs are associated with interstitial chlorapatite (Boudreau & McCallum 1992, Willmore *et al.* 2000).

If PGE were scavenged from underlying cumulates and concentrated in the ultramafic horizons in the Kläppsjö suite, then a trend of increasing Cl in the apatite below these horizons is expected (Meurer *et al.* 1999, Boudreau & Meurer 1999). However, no such trends are found, with chlorapatite ($X_{\text{Ap}}^{\text{Cl}} > 0.55$) being restricted to the ultramafic cumulates (Fig. 5). Nor are any systematic trends in the bulk-rock concentrations of Cu or S observed (Fig. 6), as might be expected if these elements were redistributed by exsolved volatiles (*e.g.*, Willmore *et al.* 2000). Thus we conclude that no large-scale remobilization of PGE occurred as a consequence of degassing of magmatic volatiles. This inference does not preclude small-scale degassing as a means of local enrichment. Volatile-migration fronts docu-

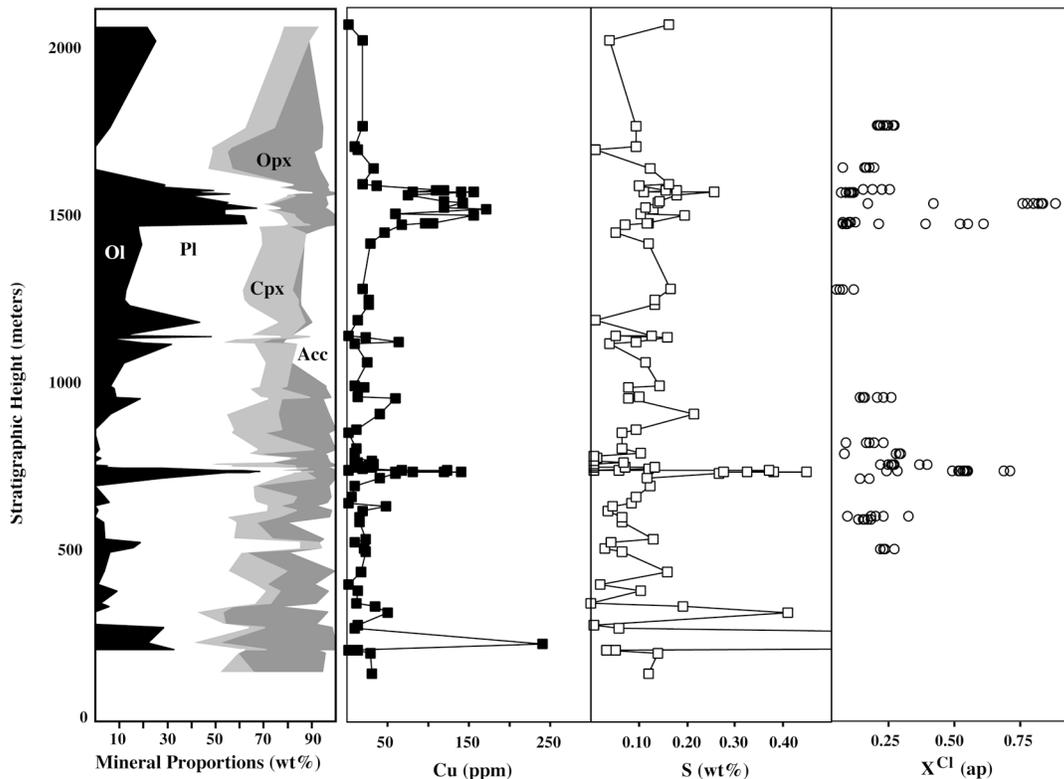


FIG. 6. A simplified plot of modal variation in the stratigraphic section is shown, with variations of the bulk-rock sulfur and Cu, and $X_{\text{Ap}}^{\text{Cl}}$. Mineral symbols are as in Figure 2, except for Acc, which represents all accessory phases.

mented in the Middle Banded Series of the Stillwater Complex developed and broke down on the scale of 200–300 m, and produced sharp enrichments in Cu and Au, but at subeconomic levels (Meurer *et al.* 1999). This situation stands in contrast to the fluid-migration fronts below the J–M reef, which likely developed over as much as two kilometers. A much higher density of sampling would be required to assess the importance of small-scale processes.

Could the PGE have been concentrated by sulfide saturation, triggered by a magma-mixing event, *i.e.*, the orthomagmatic model? The Fo and An contents increase (albeit irregularly) below the ultramafic cumulates at the 750 m level, and decrease above this level, which is consistent with mixing (Fig. 3). The gradual increase in the Fo and the jagged increase in the An content both suggest that batches of more primitive liquid were injected over a period of time prior to the emplacement of the main batch that formed the ultramafic cumulates. An increase in both Fo and An above the ultramafic cumulates further suggests that small amounts of primitive liquid continued to be supplied after the main pulse. Both Fo and An increase abruptly at the base of the ultramafic cumulates at the 1500 m level, suggesting that an injection of dense primitive liquid ponded on the chamber floor with very limited mixing, or intruded into a partially or completely solidified pile of crystals. The data are too sparse to evaluate rigorously the importance of mixing above this level, but the mineral compositions do return to their pre-ultramafic-horizon values over a short interval (Fig. 3). We also note that the precious-metal enrichments in both ultramafic units occur near the middle of the section and so are not obviously associated with either the upper or lower boundaries, where mixing could occur. In both the J–M and Merensky reefs, evidence of magma mixing at the reef level is considered to support the orthomagmatic model. In the Kläppsjö gabbro, the mineralization is not clearly associated with magma mixing. Nor does this model explain the association of the high concentrations of precious metals with chlorapatite.

As an alternative model, we consider the possibility that the magma that intruded to form the mineralized horizons was already enriched in PGE, Au, and Cl relative to typical basalts. A model proposed for the genesis of massive sulfide deposits (*e.g.*, Noril'sk, Voisey's Bay) has been adapted to explain PGE reefs (Keays & Lightfoot 2002) and may be appropriate for the Kläppsjö Gabbro. The model requires early saturation in sulfides and their accumulation in a magmatic plumbing system. The dense sulfides accumulating in the feeders scavenge PGE as magma moves through. Eventually, a large pulse of sulfide-undersaturated magma dissolves the sulfides. This model has been used to explain the enrichments seen in the Merensky Reef, where initial concentrations of 106 ppb Pd and 266 ppb Pt in the liquid are suggested (Keays & Lightfoot 2002). This model might explain

the high concentrations of PGE, but does not explain their association with chlorapatite.

The coupling of chlorapatite with high PGE and Au concentrations introduces the possibility that these chemical features may be characteristics of the source region. Boudreau and coworkers have suggested that the parental magmas of both the Bushveld and Stillwater complexes were derived from subduction-related melting of the mantle (Boudreau *et al.* 1997, Willmore *et al.* 2000, 2002). The early-orogenic setting of the Kläppsjö Gabbro is consistent with the generation of Cl-rich mantle melts, with the Cl supplied from a down-going slab. We suggest that a volatile-migration process similar to that proposed to explain the PGE enrichments in the Merensky and J–M reefs could also have operated in the source region of the Kläppsjö Gabbro. In an arc setting, a Cl-rich volatile phase, derived from a down-going slab, might react with the cooler portion of the asthenospheric mantle just above and scavenge metals as they migrated upward prior to inducing partial melting (*e.g.*, Grove *et al.* 2002). The fluids could then contribute the scavenged PGE and sulfur to these melts. The currently accepted model for the tectonic setting of the Kläppsjö Gabbro is that of an early orogenic pluton. If correct, this interpretation would require a mantle metasomatic process that does not involve active subduction.

CONCLUSIONS

The Kläppsjö Gabbro hosts two known horizons that show enrichments in PGE and Au, and are associated with chlorapatite. Unlike the well-developed J–M and Merensky reefs, there is no evidence that the chlorapatite or the metal concentrations are the products of large-scale degassing of interstitial liquid and chromatic transport. Variations in mineral composition and the positions of the metal-enriched horizons indicate that sulfide saturation induced by magma mixing is equally unlikely. The data can be explained by injection of a magma that was enriched in PGE, Au, and Cl relative to typical basalt. This magma ponded on the floor of the intrusion, and sulfide accumulation led to the irregular distribution of metal concentrations.

Significant additional sampling and chemical data will be required to test this model. However, the observation that in the Kläppsjö Gabbro, Pt- and Au-enriched samples are found with chlorapatite is robust and significant. Ultramafic cumulates both above and below the enriched cumulates lack the chlorapatite, but are otherwise similar. These data reinforce the general relationship of chlorapatite with mineralization in layered intrusions, but suggest that large-scale degassing is not the only explanation for this association.

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