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**TECTONO-GEOCHEMICAL CONTROLS ON  
PGE-SULPHIDE AND CHROMITE  
MINERALISATION IN FENNOSCANDIAN  
MAFIC ROCKS**

**STEPHEN A. PREVEC**

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by

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**October, 2003**

# TECTONO-GEOCHEMICAL CONTROLS ON PGE-SULPHIDE AND CHROMITE MINERALISATION IN FENNOSCANDIAN MAFIC ROCKS

## ABSTRACT

The *c.* 2500-2440 Ma Karelian intrusions of the Fennoscandian Shield comprise probably the most lithologically comprehensive suite of Palaeoproterozoic sequences in the world, and represent a significant target for economic mineralisation of the platinum group elements, along with nickel, chrome and copper. While there has been extensive study of many of the intrusions within this suite in the context of PGE mineralisation during the past twenty years or so, in addition to a considerable quantity of high precision geochronology, the approach has been one largely dictated by drilling data on prospective targets derived from earlier work linked to chrome or nickel prospects. A coherent tectonic model, which would support the derivation of structural-chemical controls on different types of mineralisation, would allow for a more systematic approach towards evaluating this magmatic suite. Existing models, developed on the basis of age dates, Sm-Nd isotopic, major, and trace element data, range from a rifting environment relating either to subduction or back-arc tectonics or to hotspot- or plume-induced doming. While the physical manifestations of the various models may not differ much in terms of the mechanical response of the crust, the genetic implications in terms of magmatic compositional evolution, and therefore of magmatic sulphide-related mineralisation, are significant.

On the basis of existing lithological and geochemical classifications of Karelian magmas, several variations have been proposed on structural-chemical models relating to rift proximity and magmatic source and within-crust evolution, which can be used to constrain (1) plume versus arc tectonic models; and (2) local structural controls on mineralisation style relating to tectonic setting, thereby providing constraints on mineralisation potential. Specifically, assuming that magmatism was closely associated with the subsidence phase of rifting (perhaps suggestive of passive rifting due to crustal extension, rather than by doming and uplift), models relating preservation of variably evolved intrusions to rift-proximity have been suggested. The variations are interpreted in terms of changes in the source composition with time, and with either variations in degree of preservation depending on rift position, or the physical nature of the rift in terms of magmatic traps.

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**CONTENTS**

	<b>Page</b>
<b>INTRODUCTION</b>	<b>1</b>
<b>Tectonic Setting</b>	<b>1</b>
<b>Mineralisation</b>	<b>3</b>
<b>Classification of Intrusions: Chemistry and Metallogeny</b>	<b>3</b>
<b>DISCUSSION: TOWARDS A TECTONIC MODEL</b>	<b>5</b>
<b>Magmatic Distribution</b>	<b>5</b>
<b>A Rift-Aulacogen Model</b>	<b>5</b>
<b>Rift-proximal vs Distal Control Models</b>	<b>8</b>
<b>Geochemical Constraints</b>	<b>10</b>
<b>Alternative Models</b>	<b>10</b>
<b>SUMMARY AND CONCLUSIONS</b>	<b>12</b>
<b>ACKNOWLEDGEMENTS</b>	<b>12</b>
<b>REFERENCES</b>	<b>12</b>

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# TECTONO-GEOCHEMICAL CONTROLS ON PGE-SULPHIDE AND CHROMITE MINERALISATION IN FENNOSCANDIAN MAFIC ROCKS

## INTRODUCTION

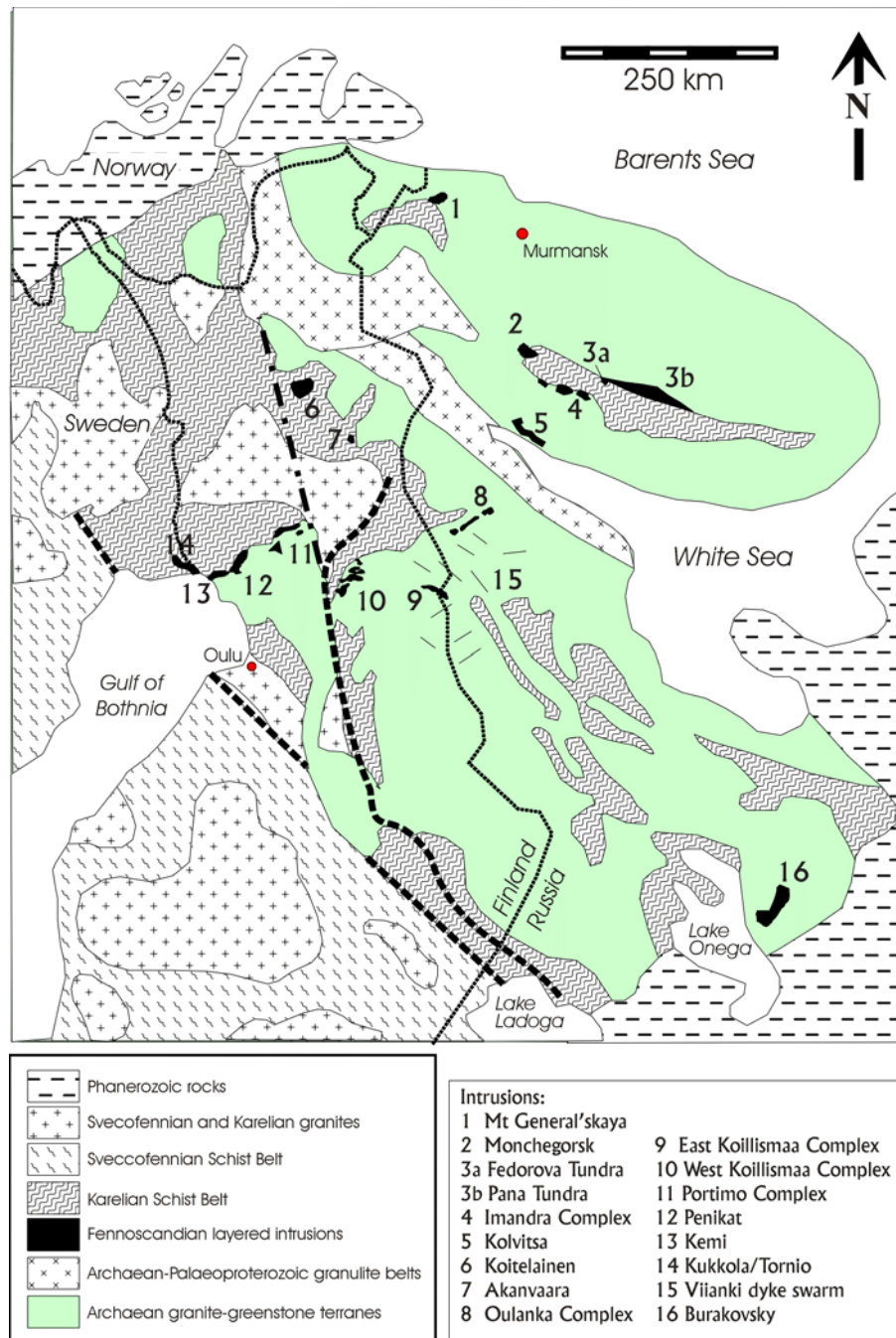
The Palaeoproterozoic represents a period of significant mafic magmatism worldwide (e.g., Heaman, 1997; Alapieti and Lahtinen, 2002), and is particularly well-represented in the Fennoscandian Shield (Finland, Sweden and Russia) and in the Canadian Shield (specifically part in Ontario, Canada). These two shields both host large volumes of mafic magmatism in the form of volcanic extrusives, intrusives, and dykes, many aspects of which have been summarised and compared in the two settings by Vogel *et al.* (1998). Both of these settings are fundamentally craton-marginal environments interpreted in the context of rift-related magmatism and deposition. The mafic intrusions are spatially associated with exposures of (now metamorphosed) clastic sedimentary sequences (the Karelian Supergroup, in Finland), overlying Archaean granite-greenstone terranes, as depicted in Figure 1, below. The Karelian mafic intrusive suite is of particular interest due to its relatively high occurrences of ultramafic rocks, chromite, and platiniferous sulphides, and their apparent distribution will be used as the basis for examining tectonic controls.

### Tectonic Setting

While the intrusions themselves have been the subject of reasonably detailed mapping over the past twenty years, complemented by high-precision geochronology (e.g., Amelin *et al.*, 1995), the tectonic setting which controls the emplacement of the suite remains a matter of debate. Amelin *et al.* (1995) favoured a starting plume-initiated rift as the setting, whilst Vogel *et al.* (1998) observed that no geochemical signature consistent with Palaeoproterozoic plume activity (whatever that might be) is recorded, but enigmatic destructive plate margin signatures (HFSE anomalies) are present. It is perhaps of interest that the contemporaneous Great Dyke in Zimbabwe displays osmium isotopic signatures consistent with a plume, non-lithospheric source (J. Kramers, pers. comm. 2003, and in press in *Journal of Geology*), suggesting an approach which might be relevant in discriminating a plume source. Laajoki (1986) identified four discrete components to the deposition of the Karelian sediments, of which the first is associated with Palaeoproterozoic (or Neoarchaeon) rifting, the middle two with progressively deepening basins, and the last with possible ensialic back-arc affiliations.

The Palaeoproterozoic setting in Karelia appears to encompass a prolonged (at least 70 Ma) series of events involving rifting (either active or passive), relating to either collisional tectonics (subduction, back-arc basins, etc.) or plumes (doming, extension, aulacogens and fore-rift basins). So while the broad compositional characteristics of this environment may be well-established, the mechanisms are clearly not.

Alapieti and Lahtinen (2002) summarised the post-emplacement tectonic history, which comprises the deposition of the Palaeoproterozoic Jatulian and Kalevian sedimentary



**Figure 1:** Simplified geological setting for Fennoscandian Karelian intrusions, after Vogel et al. (1998). The central fault location, based on Laajoki (1986) has been arbitrarily extrapolated to the north (using a different line symbol) as a possible explanation for the offset in the apparent alignment of intrusions.

Formation at 2200-2100 and 2000-1900 Ma, respectively. This was followed by the Svecofennian (also known as the Svecokarelian) Orogeny at c. 1900-1800 Ma, a major metamorphic and deformational event. Translation of the Karelian intrusions into multiple blocks along vertical faults occurred during their early post-consolidation history, and were later rotated into their current positions during the later Svecokarelian Orogeny as a

consequence of shift from extensional to compressional tectonic regimes around the craton (e.g., Weihed, 2001).

## Mineralisation

The mineral exploration history of the Karelian intrusives has developed from the discovery of chrome deposits (at Kemi) in the 1950s to nickel-copper exploration from the 1960s onwards, and presently to PGE exploration since the mid-1980s (as summarised by Alapieti and Lahtinen, 2002), intensifying in the 1990s. PGE mineralisation can be divided into six categories based on host mineral associations and stratigraphic location in their intrusions (see Table 1).

**Table 1: PGE mineralisation styles in Karelian intrusions (after Alapieti and Lahtinen, 1986, 2002)**

<i>Style</i>	<i>Mineralisation</i>	<i>Setting</i>	<i>Examples</i>
1	disseminated and massive base metal and PGE sulphide deposits	marginal facies of intrusions (but apparently not basal breccias), associated with silicic contamination	Konttijärvi-Ahmavaara, Suhanko Block of Portimo; western Koillismaa
2	PGE as cpy and PGM	Offset mineralisation (footwall-hosted shoots)	Kilvenjärvi Block, Narkaus (Portimo)
3	base metal and PGE sulphide-bearing reefs	reefs within the layered series (Merensky-type)	AP, PV Reefs in Penikat; SK, RK Reefs in Portimo; West Pana Tundra; western Koillismaa; Burakovo
4	sulphide-poor PGE reefs	reefs within the layered series, often with disseminated chromite or with chlorite schists	SJ Reef, Penikat
5	disseminated base-metal sulphide-PGE deposits	with microgabbro-norites within the layered series	western Koillismaa; Oulanka
6	PGE enrichments	associated with “upper chromitites”	Koitelainen; Akavaara; western Koillismaa (?)

The upshot of this is that a very wide range of Cu-Ni-PGE metal and sulphide deposit types is represented within this suite of intrusions, such that no single genetic model can be usefully applied (often even within a single intrusion or intrusive complex). However, the intention of this summary is to try to relate the ore-genetic environments with characteristic traits of the magmatic sources, potential contaminants, and the physical environment(s) of emplacement.

## Classification of Intrusions: Chemistry and Metallogeny

Alapieti and Lahtinen (2002) observed that the Karelian intrusions can be broadly divided into lithological categories, consisting of :

- (1) ultramafic-mafic complexes (Bushveld and Stillwater-type) with thick ultramafic lower sections overlain by anorthositic and gabbroic rocks),
- (2) mafic intrusions (with thin or absent ultramafic lower sections and gabbro-anorthosite above); and
- (3) intermediate ‘megacyclic’ intrusions, comprising repeated, progressively differentiated cycles, each analogous to ultramafic-mafic or mafic types above (which, incidentally, are also characteristic of the Bushveld Complex, although not categorised as such by Alapieti and Lahtinen, 2002).)

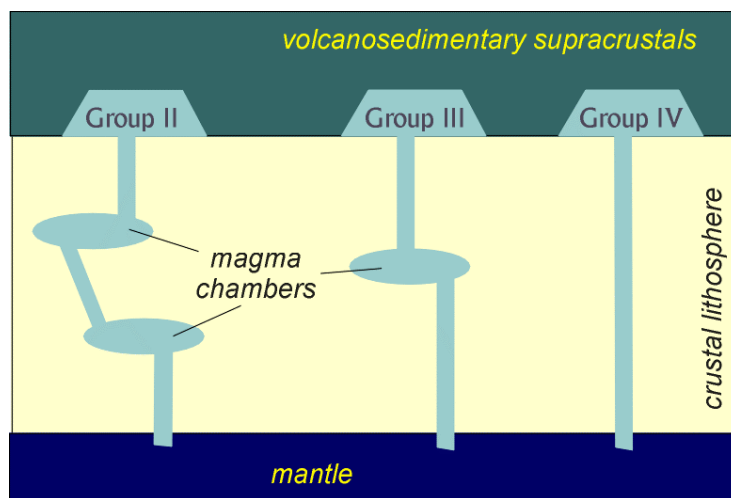
Vogel *et al.* (1998) defined three categories of Fennoscandian mafic intrusions (in addition to one - Group I - for their Canadian-Huronian correlative equivalents) on the basis principally of age, chrome content and incompatible element ratios and abundances. In brief, these three categories can be summarised as follows:

Group II : *c.* 2500 Ma in age, relatively leucocratic and unmineralised;

Group III : *c.* 2450 Ma, chromite-absent, with occasional PGE mineralisation;

Group IV: *c.* 2450 Ma, chromite-bearing, with significant volumes of ultramafic rocks, significant chromium and PGE mineralisation.

There are some unsupported complexities relating to their categorisation criteria, such that individual intrusive complexes (specifically the Penikat and Portimo complexes) have megacycles belonging to different groups.



**Figure 2:** Model suggested by Vogel *et al.* (1998) for derivation of distinct geochemical groups, as described in the text. Group II has been equated with Group I in this case for simplification, not inconsistent with the comparative observations of their paper.

increasing residual garnet in source, and  
decreasing fractionation in magma chambers during ascent  
+ increasing incompatible element abundances;  
+ increasing HFSE / LREE ratios  
+ increasing volumes of ultramafic rocks  
+ increasing Cr concentrations

Nonetheless, they derived a model relating the source characteristics of the Fennoscandian groupings with that of the Huronian suite via a combination of depletion of the source by:

- (1) variations in the amount of garnet residue left by mantle melting; and
- (2) variations in differentiation of the parental liquid resulting from differential amounts of fractional crystallisation and crustal assimilation within and by the crust (respectively) during ascension, as represented by mid- or upper-crustal magma chamber stages.

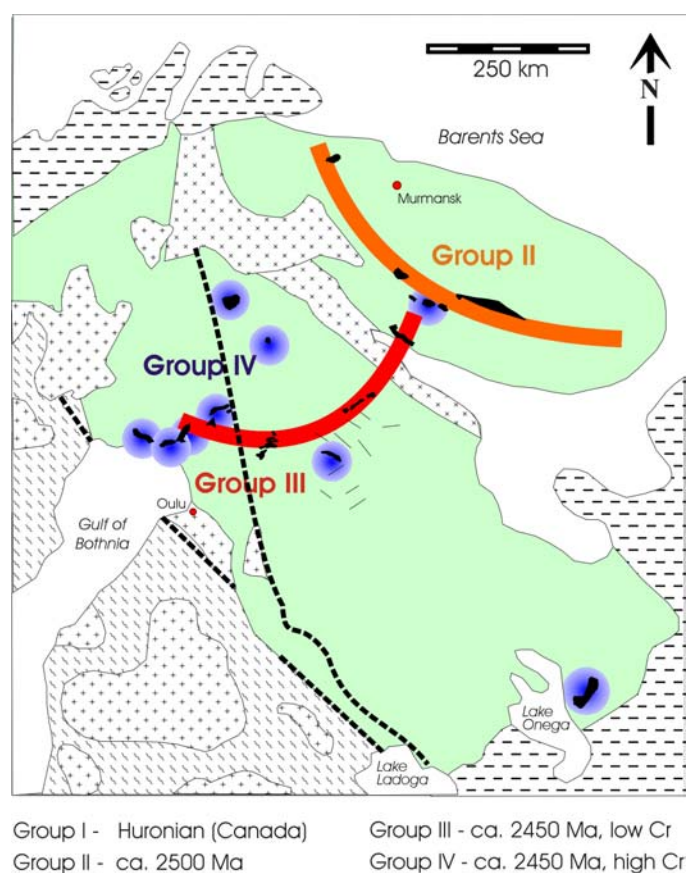
The result is variable amounts of fractionation, reflected by LREE/HREE and HFSE/REE ratios and abundances of these components. This model is depicted cartoon-style above (Fig. 2). Vogel *et al.* (1998) suggested depletion of asthenospheric mantle by partial melting, and subsequent enrichment by mantle metasomatism.



## DISCUSSION: TOWARDS A TECTONIC MODEL

### Magmatic Distribution

In contrast to the Huronian magmatic suite in Canada, both the Sariolan and the Karelian (Jatulian and Kalevian) volcanosedimentary formations are distinctly younger (100 and > 200 million years, respectively) than the layered intrusions, such that it is difficult to reliably prepare paleogeographical positions of these intrusions relative to their apparent setting, or to correlate magmatism with sedimentation. However, assuming that their positions relative to one another have not been fundamentally altered, a number of apparent trends can be identified by applying the geochemical groupings to the geographical distributions of the intrusions, as shown in Figure 3. Group II intrusions define a northwest-southeast-trending curvilinear array in the northeast, while Group III lie along a southwest-northeast trend.



**Figure 3 :** *Geographical Distribution of Fennoscandian intrusions according to geochemical and age groupings of Vogel et al. (1998). The Karelian Supercycles have been omitted from the diagram for clarity.*

The Group IV intrusions appear as dispersed, largely distal phenomena relative to the other two trends. The Viianki dykes are omitted from the geochemical classifications on the basis of their characterisation as potential parental liquids to the Fennoscandian intrusions (e.g, Iljina, 1994). They are hence considered separately here as well.

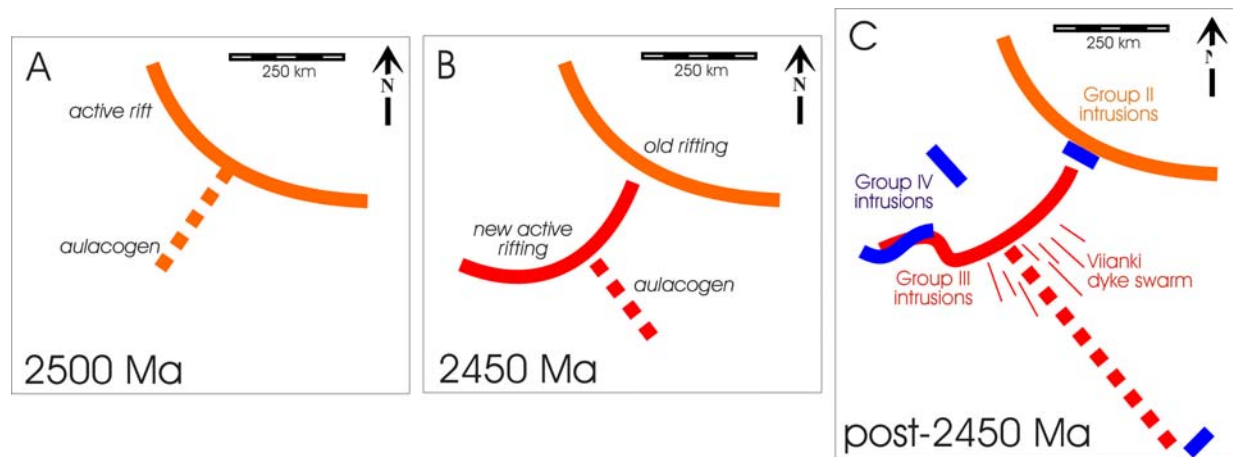
### A Rift-Aulacogen Model

Figure 3 can be defined in terms of the following characterisations:

- (1) a c. 2500 Ma old linear belt, represented by Group II intrusions;
- (2) a c. 2450 Ma old linear belt; and
- (3) a suite of 2450 Ma intrusions which do not fall on a single linear array, but may represent either intrusions distal to the Group II and III arrays, or perhaps two separate linear arrays of

their own (not shown in Fig. 3).

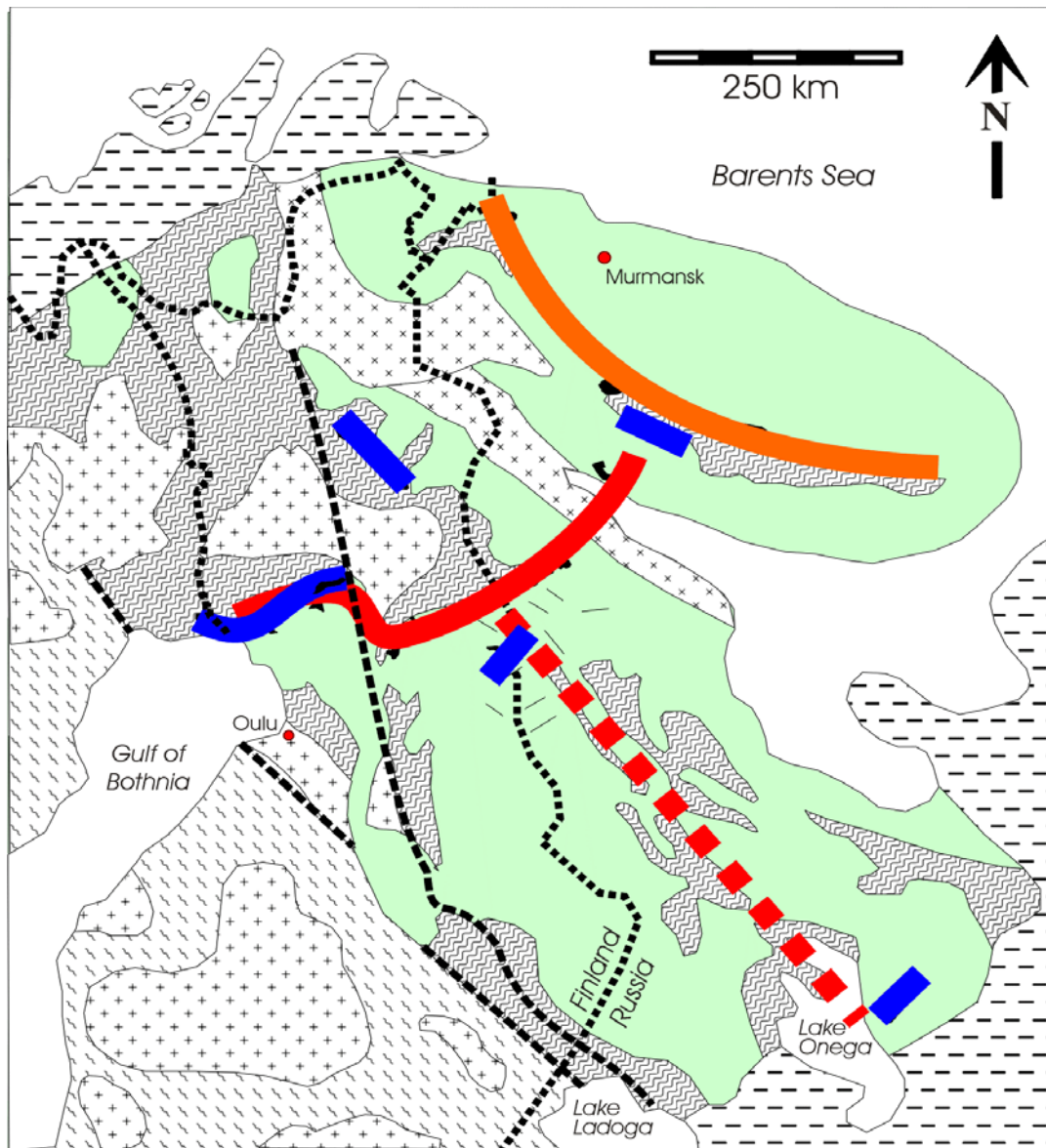
The Viianki dykes lie to the southeast of the Group III array. Using the radial dyke model of Fahrig *et al.* (1987), and recognising that the distribution of this dyke swarm, as presented, is by no means radial in any obvious way, it could be postulated that these dykes represent the aftermath of a failed arm or aulacogen related to doming or rifting at *c.* 2400 Ma. These would then be analogous to the Hearst-Matachewan swarm in northern Ontario. In this case, an evolutionary sequence as depicted in Figure 4 might be envisioned.



**Figure 4:** Schematic model of magmatic evolution of the Fennoscandian intrusions by rift- and aulacogen-related tectonics.

The Group IV intrusions may be modelled as having occurred as illustrated in Figure 4C, such that they were emplaced distally to the rift-related extensions which host the Group III intrusions. Alternatively, they may reflect a distinct array of their own, of which perhaps at least two possible arrangements might be envisioned based on their distribution as shown in Figure 3.

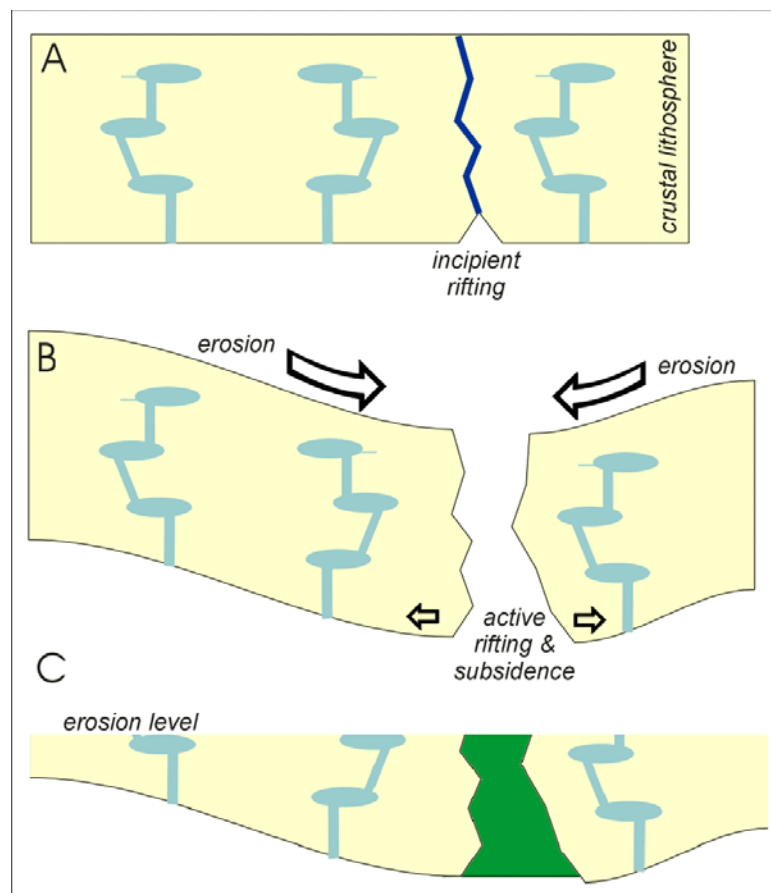
The absence of any systematic age distributions among the Group III and IV intrusions makes distinct magmatic episodicity more difficult to envisage. Therefore, a model wherein the Group III and IV intrusions are distinguished on the basis of emplacement mechanics, rather than by time, is proposed. The geochronology does not support a model involving progressive modification of the source region (by either depletion or metasomatic enrichment) between Groups III and IV (while this model remains viable for distinguishing the Group II intrusions from the younger suites). Figure 5 shows the tectonic model of two stages of rifting and aulacogens applied to the exposed distribution of Palaeoproterozoic mafic magmatism.



**Figure 5:** Application of a rift-aulacogen geometry to the distribution of Fennoscandian intrusions (in effect combining Figures 1, 3 and 4).

## Rift-proximal vs Distal Control Models

The model depicted in Figure 2 may be extended to infer that in spite of similar source characteristics, the evolution of intracrustal magma chambers has resulted in the accumulation of metalliferous sulphides at depths which are presently inaccessible through current erosion levels; in effect, that the lowermost (deepest) magma chamber beneath Group II intrusions is petrologically equivalent to the exposed Group IV intrusions. This could then be interpreted in (at least) two ways. Figure 6 shows one model.



**Figure 6:** *Incipient rift zone with dyke-sill mafic magmatic systems in place (A).*

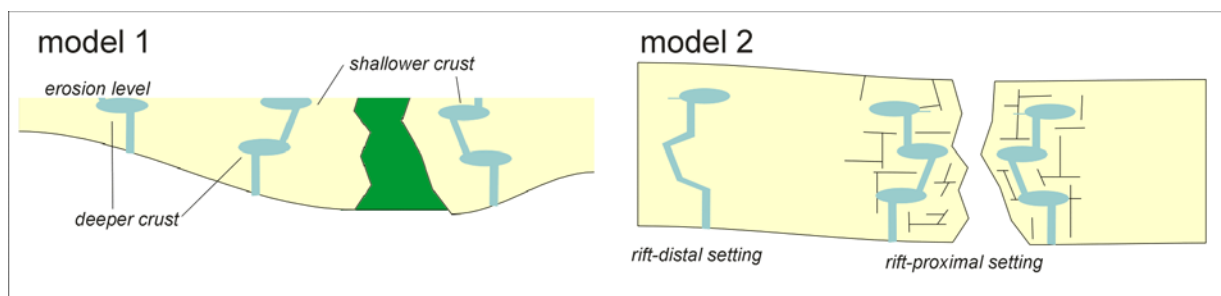
*B shows initiation of rifting, with associated basin formation and related erosion of rift shoulders. For simplicity no crustal thinning effects have been included.*

*C depicts the same picture after erosion. The vertical scale is arbitrary and is assumed to reflect upper crustal depths.*

In this model, the existing distribution of intrusions reflects different erosional levels. The existence of kilometre-thick sequences of rift-related basin sediments clearly indicates that significant topographic relief existed, so this erosional effect must certainly have occurred, the issue being to what extent. The rift-proximal intrusions would be expected to be depleted in their “heavy” components, such as sulphur, metals, and ultramafic minerals, and be more closely interlayered with rift-related volcanic rocks and basin sediments. According to this model, Group IV intrusions have been emplaced at greater depths, on average, than Group II and III intrusions. This model assumes that magmatism is roughly contemporaneous with the initiation of rift-sediment deposition, as is the case in the Huronian Supergroup in Canada. If, alternatively, magmatism is associated with doming and uplift, and was significantly post-dated by subsidence and sedimentation, this model would have to be reversed, such that the most erosion would occur adjacent to the rift, in the area of maximum uplift and thinning, so the least-evolved magmas would occur closest to the rifting. It should also be noted that the discrepancies in erosional level need not be dictated exclusively by post-emplacement subsidence effects and could reflect topographic effects (i.e., uplift, subsidence) relating to later tectonism.

The model is testable, in theory, by deriving pressure (and temperature) constraints on the emplacement depths utilising mineral compositions from metamorphosed country rocks associated with (but outside any contact metamorphic zones) the intrusions, or from two-pyroxene exsolution compositions in unaltered intrusions. However, this is highly dependent on the effects of post-Palaeoproterozoic events (tectonics, metamorphism, uplift, alteration), and would require relatively subtle distinctions in emplacement depths, as the magma staging chambers are also likely to be middle to upper crustal.

This model assumes that emplacement mechanics operate within the same in rift-proximal and rift-distal environments. Alternatively, it may be postulated that the rift-proximal environment is more susceptible to the entrapment of magmas than is the rift-distal environment. The propagating rift, whether a product of passive crustal extension in response to subcrustal upward pressures (i.e., hydraulic fracturing) or of active extension which induces asthenospheric depressurization and melting, still reflects mechanical failure of a brittle upper crust. This failure is typically manifested by both rift-parallel and rift-tangential faults, particularly the former type nearer the rift (e.g., Prevec, 2002). On the basis of the distribution of dykes associated with rift zones (e.g., Wager and Deer, 1938; Armstrong *et al.*, 1984; Fahrig, 1987) it may be assumed that these effects are significantly enhanced in the zone immediately adjacent to the rift. Magmas emplaced during rifting might then be expected to develop more complex sill-dyke geometries in the rift-proximal zone than in the rift shoulders or more distal hinterland. On this basis the Group IV intrusions would be less likely to develop staging chambers simply on the basis of a less receptive crustal architecture during their ascent. This model would allow for no differences in emplacement depth between the intrusive groups. The two models are summarised below in Figure 7.



**Figure 7:** Model 1 shows the final stage of the rift subsidence-erosion model (see Fig. 5), while model 2 schematically illustrates the effects of rift proximity and crustal architecture, as discussed in the text.

Another expected difference between the two models would be the effects of crustal contamination during ascent, including the effects of staging chamber assimilation-fractional crystallisation (A-F-C). It would be expected that Group IV intrusions should show significantly fewer manifestations of contamination by deeper crust than would Group II intrusions. If the initial staging chambers were hosted by actual granulite facies lower crust, the geochemical and lead isotopic signatures would be distinctive and should be absent from Group IV intrusions using model 2 (Fig. 7). However, if the contamination effects are largely restricted to middle and upper crust, then geochemical and isotopic signatures of the contaminant would be indistinguishable, in general (unless information regarding the specific nature of the crust in particular environments was used to deduce compositionally distinct contaminant reservoirs). However, model 1 (Fig. 7) might be expected to induce larger quantities of A-F-C (through multiple stages, more prolonged ascent, etc.), which should be



reflected by incompatible trace element and time-corrected radiogenic isotopic ratio data.

## Geochemical Constraints

Existing radiogenic isotopic signatures for Karelian mafic intrusions reflect relatively consistent distributions for Nd isotopic ratios in particular, with  $\gamma_{\text{Nd}}$  values between about -1 and -2.3 (Balashov *et al.* (1993), Amelin and Semenov (1996), Andersen *et al.* (1998)), which is slightly more depleted than (but overlapping with) the Huronian equivalents in Canada, as observed by Vogel *et al.* (1998). Balashov *et al.* (1993) interpreted their data from the Monchegorsk, Fedorovy-Pansky (intrusions 3a and 3b in Fig. 1), Olanga (Oulanka Complex in Fig. 1), and Imandra intrusive complexes in terms of derivation from a heterogeneous mantle source. They also obtained an anomalously young age (*c.* 2400 Ma) for the latter complex (the age quoted by Vogel *et al.*, 1998 for that unit is, however, consistent with the Sm-Nd isochron age of Balashov *et al.*, 1993). Andersen *et al.* (1998) interpreted the isotopic and geochemical signatures of the Mount General'skaya intrusion in terms of an enriched mantle source, consistent with the suggestions of Vogel *et al.* (1998). Alternatively, a more complex mixing analysis is provided by Amelin and Semenov (1996), who evaluated Sr and Nd isotopic data for the Burakova and Olanga (again) intrusions in terms of 5-30% contamination by migmatitic leucosomes from Mesoarchaeon crustal tonalite. Ultimately, the signatures provided by “conventional” isotopic decay schemes (Sm-Nd and Rb-Sr) indicate a systematic crustal enrichment of a mantle-derived magma. They cannot, however, unambiguously distinguish between source enrichment (i.e., as a result of prior, late-Archaeon subduction processes, for example) and pervasive syn-emplacement contamination. Other decay schemes, which are more sensitive to crust-mantle mixing, such as Re-Os, and to upper versus lower crustal contamination, such as U-Pb (Pb-Pb), are recommended, although Rb-Sr and Sm-Nd are very useful in identifying the magnitude and location of within-chamber contamination effects, and its relevance to ore mineralisation in these settings (e.g., Kruger, 1994; Zhong *et al.*, 2003).

## Alternative Models

The main alternative to the doming and rifting model(s) depicted above is provided by arc-related subduction processes, which also produce linear magmatic belts. While the Huronian magmatic belt in Canada is markedly poor in felsic magmatic rocks of any kind, the Karelian suite is somewhat better endowed. In addition, the suggestion of boninitic bulk parent compositions have been noted in association with several of the Karelian complexes, specifically the lower portions of the Penikat and Narkaus intrusions, as noted by Alapieti *et al.* (1990). Alkaline lavas, such as boninites and shoshonites, have been found to be linked with shallow asthenospheric mantle melting associated with incipient subduction (e.g., Stern and Bloomer, 1992). A broad correlation could be made between these boninitic Karelian suites and other significant chrome and platinum-bearing layered mafic intrusions with boninitic affinities, the most notable of which being the Bushveld Complex in South Africa.

Although a boninitic parent magma composition has been suggested for the Bushveld (e.g., Sharpe, 1981), the link with a subduction-related tectonic setting has remained elusive. Hatton (1987) and De Wit and Kruger (1990) have both suggested relevant models, but this concept has not subsequently been developed and Hatton himself has since been promoting a variant of a plume model for the Bushveld. It is also possible that the boninitic “feeder” dykes identified are actually syn- or post-plutonic magmatic conduits which represent liquids influenced by syn-emplacement contamination, rather than pre-plutonic feeders (e.g., pers.

comm. to the author by Mike Knoper, 2003), as has also been suggested for the Hearst-Matachewan dykes in Canada (pers. comm. to the author by Henry Halls, 1996), associated with the Huronian equivalents. Hence, while the association of boninitic compositions with chrome- and platinum-rich mafic layered intrusions may be significant, the connection with tectonic environment remains unclear.

Of greater interest is the presence of komatiitic compositions associated with some of the Karelian complexes (e.g., Puchtel *et al.*, 1997). This association is much more suggestive of a greenstone-type genetic association, most commonly affiliated with Archaean, high heat-flow, 'thin-skinned' subduction tectonics. This may favour an Archaean-style tectonic model in preference to a Proterozoic rift environment for Karelia. The compositional and lithostructural controls on arc-proximal and arc-distal magmatism (and therefore metallogenic potential) are well-established (e.g., McNutt *et al.*, 1979), although are largely relevant only to felsic magmatism, such that the primary magmatic effects in arcs are dominated by felsic to intermediate volcanism and plutonism and related fluid hydraulic processes. Extensive mafic magmatism independent of doming or hotspots is more likely related to either (1) back-arc extensional processes; or (2) inboard processes relating to shallow subduction, as has recently been proposed for other mantle-derived magmatic suites. Detailed mapping, geochronological and isotopic studies over the past twenty years or so (summarised in Prevec, 2003) suggests that anorthosite complexes are frequently closely associated with previously unrecognised crustal sutures and terrane boundaries. Gower and Krogh (2002) have suggested a relationship between anorthosite massifs in Labrador, eastern Canada, and the activity of 'flat subduction', produced by subduction of a thickened oceanic crust, perhaps by the occurrence of oceanic plateaux, to produce orogenic magmatic activity up to several hundred kilometres inboard (Gutscher *et al.*, 2000) of the actual subduction front. This could account for linear magmatic belts, which are not obviously related to proximal subduction tectonics, even in terranes less-deformed than the Fennoscandian.

In either subduction model, arc-distal processes are involved, which makes them particularly enigmatic when examined at a distance of over two billion years. However, alternative models have also been proposed for Archaean greenstone belts which do not involve subduction, such as calderas or 'megacauldrons' (e.g., Jensen, 1985) and more relevantly, hotspot-induced plumes (e.g., Abbott, 1996). Nonetheless, the existence of volcano-sedimentary units (the Vetreny Belt), which include komatiitic basalts and which are contemporaneous with the Karelian intrusive suite, does seem to indicate a genetic process distinct from the (passive?) rifting analogues on other continents.

## SUMMARY AND CONCLUSIONS

The Palaeoproterozoic Fennoscandian magmatic suite contains a diverse selection of PGE-sulphide mineralisation styles, along with apparently inter-related geochemical characteristics, which have been identified with a common source subject to modification over time (about 50 Myr). The tectonic setting for this suite is not agreed upon, although the arcuate geometry of the magmatic belts and apparent association with sedimentary packages has led to suggestions of either rifted cratonic or collisional settings. A continental rift is an attractive model in light of these associations and the particular vagaries of timing and geometry evident from the distribution of the intrusions. Analogy with contemporaneous Canadian rocks supports this model. Conversely, alternative models to rifts, such as those involving boninites or komatiites are very weakly developed, poorly supported by existing evidence, and difficult to meaningfully evaluate or constrain.

Assuming a rifting model has allowed for speculation as to mechanical controls over magmatic emplacement geometries, which would influence rate of ascent and degree of magma evolution during ascent. Two possible models have been suggested which relate degree of magma evolution, and hence of magmatic sulphide retention, to rift-proximity. These models and their significance are potentially testable through detailed evaluation of mineralogical properties relating to emplacement depths (such as mineral palaeobarometry and thermometry), and distinctive chemical characteristics representative of the magmatic source (such as select isotopic signatures). The relevance of these controls to mineralisation potential on the detailed scale must be evaluated by detailed investigation of the relationship between magmatic evolution and mineralisation styles. Apart from modest efforts at Penikat (Halkoaho, 1993), which demonstrated some breadth, but still focussed largely on the mineralised zones, these relationships remains largely unconstrained.

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