The Petrogenesis of the 1.88–1.87 Ga post-kinematic granitoids of the Central Finland Granitoid Complex

by

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ACADEMIC DISSERTATION

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The evolution of the Svecofennian Orogen ranges from 1.95–1.80 Ga, with the main crust forming event occurring between 1.90–1.87 Ga. Subsequent deformation mainly occurred in southern Finland where it continued until ~1.80 Ga. A suite of post-kinematic 1.88–1.87 Ga plutons cross-cut 1.89–1.88 Ga synkinematic granitoids in the Central Finland Granitoid Complex (CFGC) in south-central Finland. This post-kinematic suite is predominantly quartz monzonites and monzogranites and have been divided into three groups based on petrographic, mineral, and chemical characteristics. Compared to the calc-alkaline synkinematic granitoids, the post-kinematic suite generally has an alkaline affinity with higher FeOtot, TiO2, K2O, Ba, Zr, and Nb and lower MgO, CaO and Sr at a given SiO2 content. The Type 1 plutons are peraluminous and Type 2 and 3 plutons are marginally metaluminous to peraluminous (A/CNK= −1.0). The Type 2 plutons, especially those in the western CFGC, approach the elevated incompatible element concentrations, tholeiitic and A-type geochemical characteristics of the 1.65–1.54 Ga rapakivi granites in southern Finland. The Type 3 plutons contain pyroxene-bearing phases (Type 3a) or pyroxene throughout (Type 3b) and have many geochemical features that are associated with magmatic charnockites. These plutons reflect high temperature relatively anhydrous magmas that began to crystallize at pressures of 5–7 kbar at temperatures in excess of 825°C and were emplaced at pressures between 2–4 kbar. The redox conditions of the plutons were relatively reduced from −0.3 to −1.5 log fO2 ΔFMQ, and record progressive oxidation and hydration during cooling. Radiogenic isotopes (Nd, Sr, Pb) of the post-kinematic plutons indicate homogeneous initial ratios: εNd (at 1875 Ma) ~0, 87Sr/86Sr ~0.703, and Stacey & Kramers-type Pb with low long-term Th/U ~2. Conventional and ion microprobe U-Pb data show that the post-kinematic magmatism took place over quite a short time period (ca. 15 Ma) during overall lithospheric convergence and the magmatism began in the northeastern CFGC at ~1.885 Ga and gradually moved to the west-southwest where the plutons are dated at ~1.870 Ga. The thickness of the crust, degree of partial melting and proportion of lower crust and mantle derived mafic magma, subsequent fractionation, water content and rate of cooling during ascent all played important roles in the petrogenesis of the post-kinematic suite. All of the post-kinematic plutons, despite mineralogical and geochemical variation, are thought to have been derived from similar parental sources and have undergone similar processes from generation to emplacement.

Key Words: granite, petrogenesis, Proterozoic, geochemistry, mineralogy, isotope geology, post-kinematic, Svecofennian orogeny, Central Finland Granitoid Complex, Finland

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PREFACE

The thesis is based on the following four papers, which are referred to in the text by their Roman numeral notation:


VI Elliott, B.A. Petrogenesis of the post-kinematic magmatism of the Central Finland Granitoid Complex II; Proto-lith characteristics and magmatic evolution. Journal of Petrology, in review.

Paper I

This mineralogical study of the post-kinematic granitoids was the first paper detailing the mineralogical and petrographic features of the post-kinematic granitoids, discriminating the three types of plutons of the 1.88–1.87 Ga suite. Mineral chemical data from feldspars, biotite, amphibole, pyroxenes, olivine and oxides were presented and intensive parameters (e.g. temperature, pressure, oxygen fugacity) were calculated from mineral equilibria. The mineral equilibria suggest a range of pressures for crystallization; generally 2–4 kbar for Al in Amphibole barometry and 5–7 kbar for those mineral assemblages that contain olivine and pyroxene or the appropriate minerals for QUIIF (Quartz-Ulvöspinel-Ilmenite-Fayalite) equilibria. Temperatures mostly reflect subsolids re-equilibration processes, recording temperatures during cooling of 450–800°C, but amphibole-plagioclase thermometry and QUIIF calculations estimate the magmatic temperatures above 800°C. Oxygen fugacity determinations indicate relatively reduced conditions for the formation of the post-kinematic granitoids (the pyroxene-bearing assemblages in particular) ranging between –0.3 and –1.5 ΔFMQ. Even though the plutons were emplaced during the orogenic event, post-dating regional compression, they have many mineralogical and petrographic features similar to the rapakivi granites of southern Finland.

B. A. Elliott’s contribution to the publication included everything, with the exception of: the microprobe analyses; the collection of many of the rapakivi-related hand specimens for petrography and associated microprobe analyses used in the study.

Paper II

This study provides a detailed description of the geochemistry of the post-kinematic granitoids and the influence of tectonic setting on the magma genesis of the 1.88–1.87 Ga suite. The Central Finland Granitoid Complex mainly consists of 1.89–1.88 Ga, highly deformed, synkinematic, I-type granodiorite and granite. The post-kinematic suite are slightly foliated to undeformed quartz monzonite to granite, and have been divided into three types based on petrographic, mineral and geochemical characteristics. The post-kinematic suite generally has an alkaline affinity, with higher FeOtot, TiO2, K2O, Ba, Zr and Nb, and lower MgO, CaO and Sr at a given SiO2 content. The Type 1 plutons are peraluminous and the Type 2 and 3 plutons are marginally metaluminous to marginally peraluminous (A/CNK~1.0). The Type 2 plutons, especially those in the western CFGC, approach the elevated incompatible element concentrations, tholeiitic and A-type geochemical characteristics of the 1.65–1.54 Ga rapakivi granites in southern Finland. The Type 3 plutons contain pyroxene-bearing phases (Type 3a) or pyroxene throughout (Type 3b) and have many geochemical features that are associated with
The generation of synkinematic granitoids in the CFGC probably involved partial melting of intermediate High-K rocks in the lower crust, incorporating a mantle-derived component from the mafic underplate (or intraplate). The magmatic episode left a dry, granulitic residue in the lower crust, which was partially melted to produce the post-kinematic magmas. The post-kinematic magmatism took place over a very short time of about ~15 Ma, while convergence was still continuing toward the south. This magmatism extended beyond the CFGC and registers a temporal shift from northeast to west-southwest, with a general change in geochemical character from C-type to A-type affinity. The post-kinematic magmas were probably emplaced during extension or transtension; the plutons with C-type affinity emplaced early in overthickened crust and those plutons with A-type characteristics slightly later when the crust was rather rigid.

B. A. Elliott’s contribution to the publication included: field work and sample collecting; petrography and modal analyses; interpretation and description of geochemical analysis results for the CFGC granitoids; discussion of the post-kinematic granitoid magma-type and temporal emplacement of the plutons across the CFGC.

**Paper III**

New U-Pb (conventional and ion probe), Nd, Pb, and Sr isotopic data for the post-kinematic plutons of the CFGC (both felsic and associated mafic intrusions) and some of the 1.89–1.88 Ga synkinematic granitoids of the CFGC are presented here. This study, combined with previously published data, helps to constrain the emplacement sequence of the post-kinematic plutons throughout the CFGC and provide some constraints on the source material that complements the petrogenetic model in Paper IV. Radiogenic isotopes (Nd, Sr, Pb) of the post-kinematic plutons indicate homogenous initial ratios: εNd (at 1875 Ma) ~0, mantle-like initial 87Sr/86Sr ratios ~0.703, and Stacey & Kramers-type Pb with low long-term Th/U ~2. Conventional and ion microprobe U-Pb data show that the post-kinematic magmatism took place over quite a short time period (ca. 15 Ma) during overall lithospheric convergence and the magmatism began in the northeastern CFGC at ~1.885 Ga and gradually moved to the west-southwest where the plutons are dated at ~1.870 Ga. The isotopic composition of the post-kinematic plutons with that of the anorogenic rapakivi granites of southern Finland are compared, allowing for the identification of several Paleoproterozoic crustal terranes (microcontinents) that were amalgamated in the Proterozoic and form an essential part of the Fennoscandian Shield.

B. A. Elliott’s contribution to the publication included: the discussion of the temporal evolution of the post-kinematic magmatism and the isotopic characteristics of the post-kinematic granitoids across the CFGC; discussion of Svecofennian terranes in southern Finland; interpretation of the results of the isotopic study in conjunction with the petrogenetic model described in Paper IV.

**Paper IV**

This study incorporates the isotopic data from Paper III and presents a geochemical model, constraining the nature of the source rock(s), the degree of partial melting, and the proportions of partial melts involved in the genesis of the post-kinematic granitoids. The 1.88–1.87 Ga post-kinematic granitoids of the CFGC provide a key geochemical link to understanding the processes involved in granite formation in Paleoproterozoic orogenic and post-orogenic terrains. Three types of post-kinematic granitoid comprise a series of plutons that migrate in age and geochemical character from northeast to south-southwest across the CFGC, shortly following the peak of the Svecofennian orogeny. The thickness of the crust and intracrustal differentiation processes played an important role in the formation of the different granitoid types. In the eastern CFGC, pyroxene-bearing (Type 3) plutons predominate and were formed from a mixture of low to moderate degree partial melts (30–50%) of intermediate to mafic mantle-derived (ferrodioritic) source rocks and partial melts (10–30%) of mafic granulite lower crust at depth. In the western CFGC, high-silica, iron-rich, fluorite-bearing (Type 2) plutons
predominate. The higher thermal gradient, thinner upper and lower crust, and significantly more shallow Moho depth resulted in higher proportions of crustal melts incorporated into the partial melts of a mafic mantle-derived source. The geochemical model, supported by isotopic data, suggests that despite the range of geochemical compositions and petrographic features, the 1.88–1.87 Ga post-kinematic granites could all have been derived from relatively similar sources, having undergone similar fractionation processes during their genesis, as has been modeled for the Jämsä and Honkajoki plutons.

INTRODUCTION

The central part of the Fennoscandian Shield in Finland is dominated by the Central Finland Granitoid Complex (CFGC). The CFGC encompasses an area of about 40,000 km² and consists mainly of granodiorite and granite, but gabbroic, ultramafic, metavolcanic and metasedimentary rocks are also found throughout the complex (Paper II). The CFGC hosts numerous 1.88–1.87 Ga post-kinematic granitoid intrusions that constrain the age at which the crust was stabilized in central Finland, and define a transition in age and geochemical evolution from northeast to west-southwest. Mineral chemical studies were carried out to constrain the conditions of formation and emplacement of the post-kinematic granitoids. Detailed mapping and sampling ensued in order to gain a better perspective of the distribution of the post-kinematic plutons throughout the CFGC. A more detailed whole-rock and isotope geochemistry was made to define the magmatic affinities and source constraints of the post-kinematic granitoids, and to compare with the synkinematic granitoids of the CFGC and anorogenic granites of southern Finland. A comparison of whole rock major- and trace-element geochemistry between bimodal, multi-phase type intrusions in the western CFGC and pyroxene-bearing intrusions located mainly in the eastern CFGC provide insights into the petrogenesis of this late stage granitic magmatism that shortly followed the orogenic culmination in an anomalously thick lithosphere. The primary goal of this thesis is to incorporate mineral chemistry, whole-rock geochemistry, and isotope geochemistry into a detailed petrogenetic model constraining the source(s) and processes that were involved in the formation of the 1.88–1.87 Ga post-kinematic plutons of the CFGC.

TECTONIC EVOLUTION OF THE CENTRAL FINLAND GRANITOID COMPLEX

The Svecofennian Orogen has been divided into three tectonic units based on lithological criteria and U-Pb zircon age data. In central and southern Finland these units form a primitive arc complex adjacent to the Archean craton, the accretionary complex of central and western Finland, and the southern Finland accretionary complex (see Figure 1; cf. Korsman et al., 1997; Nironen, 1997; Korsman et al., 1999; Rämö et al. 1999).

The accretionary arc of southern Finland contains the volcanic-sedimentary Uusimaa and Häme Belts. The Uusimaa belt is characterized by greywacke with volcanic and carbonate rock intercalations, and a belt of bimodal volcanic rocks. The mafic volcanic rocks with MORB affinities (together with carbonate rocks) were probably deposited on a Paleoproterozoic ensialic crust (Lindroos & Ehlers, 1994). The volcanic rocks of the Häme Belt are characterized by the presence of 1.89 Ga intermediate island-arc type rocks to mafic rocks with increasing within plate affinity. The southern Finland arc contains migmatites with 1.89–1.88 Ga trondhjemitic to granodioritic leucosomes formed from a greywacke host rock and 1.84–1.82 Ga granite migmatites associated with the late-orogenic magmatism (Korsman et al., 1997). Late orogenic rocks are S-type granites with ages around 1.84–1.82 Ga, and are predominantly found in a broad belt trending northeast-southwest across southern Finland. The post-orogenic rocks, dated at 1.81–1.79 Ga, have alkalic/shoshonitic affinities and range in composition from quartz monzonite to granite. They are found as small intrusions close to the northern margin of the 1.84–1.82 Ga belt of late-orogenic granites. The last major episode
Figure 1. Simplified geologic map of southern Finland showing major granitoid features and tectonic terranes south of the Archean craton. Modified after Korsman et al.
The accretionary complex of central and western Finland contains the CFGC, the Bothnia Belt to the west of the CFGC and the Tampere Belt and metasedimentary Pirkkala Belt to the south of the CFGC. The Tampere Belt is composed of well-preserved volcanic and sedimentary rocks ranging from >1.91 Ga mafic MORB-type volcanics (Kähkönen & Nironen, 1994) to younger, 1.90–1.89 Ga, fore-arc greywacke and andesitic volcanic rocks (Kähkönen et al., 1989). The Pirkkala Belt is characterized by 1.885 Ga throndhjemitic and granodioritic migmatites formed from psammitic greywacke host rocks. Small ultramafic intrusions and mafic MORB-type volcanic rocks, and change in migmatite leucosome character, have been interpreted to delineate a suture between the Pirkkala Belt of the central Finland arc and the Häme Belt of the southern Finland arc (cf. Lahtinen, 1994; Rämö et al. 1999).

Lahtinen (1994) presented a cross-sectional evolutionary model for the Svecofennian of Finland. The model involves the closure of the marine basin and collision of two arc systems 1.89 Ga ago. Nironen (1997) extended the evolutionary model to the entire Svecofennian crust (including Sweden, Estonia, and Lithuania) and presented it in a two-dimensional form (Figure 2).

The evolutionary model of Nironen (1997) entails:

(A) Initial accretion of an island arc complex (the central Finland arc) to the Archean continent took place 1.91 Ga ago;

(B) followed by subduction reversal and rotation of plate motion direction, or convergence of another (micro-) plate.

(C-D) The subsequent collision of another arc complex (the southern Finland arc) against the Central Finland arc, leading to the disappearance of two subduction zones with opposite dips, and the merging of two accretionary prisms.

According to the tectonic model of Nironen (1997), an extension of the Lahtinen (1994) model, collision of the arc complex of the central Finland arc to the Archean craton, and the subsequent collision of the southern Finland arc to the central Finland arc at 1.91–1.89 Ga caused lithospheric thickening in the CFGC area. Part of the overthickened lithospheric mantle was delaminated and compensated by hot asthenosphere. Decompression melting of the asthenosphere produced mantle magmas that rose to the base of the crust and induced melting in the lower crust. The mafic underplate and intraplate (i.e. the high velocity lower crust) induced partial melting of K-rich rocks of intermediate composition in the lower crust with additional mantle-derived material. The result was the production of the synkinematic magmatism in the CFGC, leaving an infertile granulite residue in the lower crust. Partial melting of the granulitic residue and mantle-derived material produced the 1.88–1.87 Ga post-kinematic magmatism, which was emplaced in an extensional or transpressional environment at a time when convergence was still occurring to the south in the southern Finland arc.

**THE CENTRAL FINLAND GRANITOID COMPLEX**

**Geological background**

The supracrustal rocks of the Svecofennian orogen are mainly turbiditic sediments that were metamorphosed at amphibolite facies conditions. Metavolcanic rocks, occurring in narrow 1.90–1.88 Ga age belts, are mostly intermediate in composition and have arc-type geochemical affinities. The MORB-type mafic volcanic rocks form minor units and have generally been thought to represent the lowest parts of the supracrustal sequences.
Figure 2. Tectonic model of the Svecofennian Orogen (after Nironen, 1997). Stippled pattern denotes Archean crust; the area without overprint is oceanic crust and sedimentary rocks; the grey areas are arc complexes, and the dotted areas are volcanic arcs.

Deep seismic sounding studies (Luosto et al., 1990; Korja, 1991; Luosto, 1991) have shown that the crustal thickness in the southern part of the Fennoscandian Shield varies considerably, from 40 to 65 km. The crust is thickest, at ~65 km, in eastern Finland along the contact with the Svecofennian Orogen and Karelian Domain.

The synorogenic plutonic rocks range in composition from gabbro to granite, with I-type granodiorite as the prevailing rock type (see Nurmi & Haapala, 1986). The oldest rocks of this group are the 1.93–1.92 Ga tonalitic gneisses, but crystallization ages are generally 1.89–1.88 Ga (Vaasjoki, 1996). There are a few age dates of the syn-kinematic granitoids in the CFGC, and these have also yielded ages around 1.89–1.88 Ga.

The 1.88–1.87 Ga post-kinematic granitoids of the CFGC

Besides the 1.89–1.88 Ga rocks, the CFGC comprises a distinct suite of granites that crosscut the 1.89–1.88 Ga granitoids and yield slightly younger ages around 1.88–1.87 Ga. As these granites were emplaced after major contractional movements related to collision, they are considered post-kinematic. The post-kinematic granites are found as at least 24 stocks and small (<500 km²) batholiths (see Figure 3). They are weakly to non-foliated, medium- to coarse-grained granites (many of which have multiple phases) that are, on aver-
diorite or monzogranite and plagioclase and alkali-feldspar are resorbed and largely altered to sericite. Plagioclase is often surrounded or replaced by secondary alkali feldspar. Alkali feldspar occurs as perthitic orthoclase megacrysts and medium-grained microcline.

Myrmekitic intergrowths are uncommon, but when present, pervasive. Quartz is typically interstitial and forms late stage inclusions and small composite veins.

Biotite is usually the only mafic silicate, with the exception of hornblende-biotite pluton at Lavia, and appear as (1) reddish brown, anhedral grains that commonly contain zircon grains with radioactive haloes, and (2) brown to light-brown, euhedral to subhedral grains. The reddish brown biotite may be a reaction product of amphibole, which probably preceded the euhedral biotite in the sequence of crystallization. Accessory minerals include

The Type 1 granitoids

Type 1 plutons flank the CFGC in the south, are discordant, slightly to non-foliated and consist of even- to coarse-grained, often porphyritic, biotite granodiorite or granite. Compared to the Type 2 and 3 plutons, they tend to contain more modal plagioclase, appear white/gray to pink in color, and show distinctly lower Fe/Mg than the Type 2 and 3 post-kinematic plutons (Paper I; Paper II; Lahtinen, 1996).

The Type 1 plutons are typically grano-
anhedral, interstitial fluorite, rounded zoned zircon, and euhedral apatite, and ilmenite as the sole Fe-Ti oxide.

**The Type 2 granitoids**

The Type 2 plutons are concentrated in the western and southern CFGC and are the most abundant type of pluton in the post-kinematic suite. They are discordant, usually non-foliated, even- to coarse-grained, often porphyritic, red granite. The plutons are marginally peraluminous and show high Fe/Mg that increases with increasing silica (Paper II; Lahtinen, 1996). Several of the Type 2 plutons are associated with coeval mafic plutonic rocks (Rämö, 1986; Rämö et al., 1999).

The main mafic silicate is biotite, but some plutons include one or more mafic phases that are dominated by amphibole. Biotite occurs as a primary mineral phase, and as a reaction product associated with the margins of many amphibole grains. Amphibole is anhedral, pleochroic and green-brown in color, and shows some reaction to biotite on grain margins. The mafic silicates are generally interstitial, but some euhedral biotite grains are enclosed in feldspar grains. Plagioclase is largely altered to sericite (sausservitised) and commonly replaced by alkali feldspar. Myrmekitic intergrowths are common and a composite mantle of plagioclase and quartz occasionally surrounds large orthoclase megacrysts. Quartz is interstitial and often forms roundish inclusions in feldspars. Accessory minerals include fluorite, zircon, apatite, titanite, and allanite. Zircon is euhedral to subhedral, zoned, often rhombic and enclosed in biotite and amphibole. Fluorite andapatite are ubiquitous; apatite forming small, euhedral, acicular to prismatic grains, and fluorite as anhedral interstitial grains. Epidote may also occur and is associated with alteration of allanite. Titanite often forms a reaction rim around ilmenite and is commonly enclosed in biotite or amphibole grains.

**The Type 3 granitoids**

Type 3 plutons, generally situated in the eastern part of the CFGC, are pyroxene-bearing, typically discordant and consist of even- to coarse-grained, often porphyritic, non-foliated, quartz-monzonite and granite. They are divided into two subgroups: Those with a pyroxene-bearing margin or small pyroxene-bearing bodies located near the margin (Type 3a), and those with pyroxene throughout (Type 3b; cf. Paper II). The contacts between the marginal assemblage and the center of the body are gradual and marked by a steep decrease in magnetic susceptibility. These plutons show a decrease in Ti, Fe/Mg and K/Na from the marginal assemblage toward the center of the pluton (Paper I).

The Type 3 post-kinematic plutons typically consist of a pyroxene±olivine-bearing quartz monzonite margin, which grades into biotite-hornblende monzogranite at the center. Plagioclase is unaltered and appears to represent a late cumulus phase. Grain boundaries are typically resorbed and occasionally interlocking. Alkali feldspar occurs as large perthitic orthoclase megacrysts, often zoned and in places mantled by composite quartz and plagioclase.

The marginal assemblage of these plutons contains fayalitic olivine, Fe-rich clinopyroxene and or Fe-rich orthopyroxene, amphibole and biotite; olivine, and pyroxene are equally abundant, but less than amphibole. Amphibole forms large, pleochroic green to brown-green, rarely blue-green, interstitial grains, as well as coronas around some olivine and pyroxene grains. Biotite typically forms large light brown, subhedral grains, but can also occur as a secondary reaction product of amphibole. Orthopyroxene (ferrosilite) occurs in close association with olivine and clinopyroxene. Clinopyroxene (ferroaugite) occasionally contains pigeonite exsolution lamellae. Myrmekitic intergrowths between alkali feldspar and plagioclase are common.

In the plutons that do not contain pyroxene(s) throughout, but only as a marginal assemblage, the change from the marginal assemblage to the central unit is marked by the absence of olivine and pyroxene, and a decrease in magnetic susceptibility due to the lack of magnetite formed during the reaction of olivine and pyroxene to amphibole. Amphibole is occasionally replaced by biotite, which becomes more abundant toward the center of the pluton. Accessory minerals include zircon,
apatite, and secondary titanite.

GEOCHEMISTRY

In Harker diagrams, the post-kinematic granitoids display relatively coherent trends that generally plot between the trends of synkinematic granitoids from the CFGC and the rapakivi granites of southern Finland (see Paper II). In the Al₂O₃ vs. SiO₂ diagram, the post-kinematic and synkinematic intrusions of the CFGC show rather similar decreasing trends with increasing SiO₂ (Figure 4a). The FeOtot (and TiO₂) values of the post-kinematic suite are somewhat higher, and MgO and CaO contents are lower than those of the synkinematic granitoids at a given SiO₂ content (Figure 4b, c, & e). The Type 3a plutons have lower MgO and higher FeOtot than the Type 3b plutons at similar SiO₂ contents. The Type 2 and 3 plutons have elevated FeOtot/MgO ratios compared to the Type 1 plutons and the synkinematic granitoids, although the synkinematic suite has fairly high FeOtot/MgO. The FeOtot/MgO ratios of the Type 3a plutons decrease from the margins (SiO₂ less than 64%) towards the center. In the A/CNK vs. FeO*/(FeO*+MgO) diagram, the Type 1 plutons are clearly peraluminous whereas the Type 2 and 3 plutons show trends from marginally metaluminous to marginally peraluminous (Figure 4f). In this respect, the post-kinematic plutons are more similar to typical rapakivi granites than to the syn-kinematic granitoids (cf. Haapala & Rämö, 1992).

The Type 1 post-kinematic intrusions are lower in Na₂O than the synkinematic granitoids and the rapakivi granites. In the K₂O vs. SiO₂ diagram, the syn-kinematic granitoids define a weakly ascending trend and generally plot in the high-K calc-alkaline field. The post-kinematic granitoids have even higher K₂O contents and plot partly in the shoshonitic field. The Lahnanen pluton is distinct from the other Type 3 plutons with higher SiO₂ (around 72%) and relatively low K₂O and Rb contents. Nironen & Front (1992) suggested that K₂O and Rb were enriched in residual melts that subsequently crystallized in pockets and shear zones rich in garnet and orthoclase within the Lahnanen pluton. This is probably the reason for low abundance of these elements in the pyroxene granodiorite. The Type 3b Rautalampi pluton has the lowest SiO₂ contents of all the post-kinematic plutons, and is distinctive on most Harker diagrams, plotting within the synkinematic trend. Even though the pluton has been included in the post-kinematic group, based on petrography and its relatively undeformed state, the geochemistry seems to suggest that it may be a synkinematic granitoid emplaced late and/or in an area of transpressive stress of extension.

The Ba and Zr (also Nb) values are generally higher and Sr values lower in the post-kinematic plutons than in the synkinematic granitoids at similar SiO₂ contents. The Rb/Ba ratios of the post-kinematic plutons show an increasing trend, contrary to the almost constant Ba concentrations with increasing Rb of the synkinematic rocks (Figure 5b). The synkinematic granitoids generally have higher Sr concentrations and distinctively higher Sr/Ba ratios when compared to the post-kinematic granitoids (Figure 5b). Concentrations of F are slightly higher in the Types 1 and 2 plutons than in the Type 3 plutons and the synkinematic granitoids. In particular, the high-silica varieties of the Type 2 granites in the western CFGC approach the elevated F, Rb, Nb, and Y values of the rapakivi granites (cf. Paper II).

The REE patterns of the post-kinematic granitoids are grossly similar, with mean (La/Yb)_N ratios between 11 and 12. The Type 1 and 2 plutons have negative Eu anomalies (mean Eu/Eu* = 0.49 and 0.37, respectively; Figure 6a, b). The Type 3 plutons generally have negative Eu anomalies but the marginal assemblages have rather straight normalized patterns or show slightly positive Eu anomalies (Figure 6c, d). For example, the Type 3a Jämsä pluton shows clear decrease in Eu/Eu* from the pyroxene-bearing margin to the center of the pluton.

The REE patterns of the post-kinematic plutons are similar to those of the synkinematic granitoids but the REE contents are lower in the latter. All but the one sample of the synkinematic granitoids have negative Eu anomalies (mean Eu/Eu* = 0.59). The REE
Figure 4. Harker diagrams of Al₂O₃, MgO, FeO*, K₂O, and CaO vs. SiO₂ and molecular A/​CNK vs. FeO*/ (FeO*+MgO) for post-kinematic and synkinematic granitoids from the Central Finland Granitoid Complex. Boundaries for the subdivision of subalkalic rocks of Peccerillo & Taylor (1976), Ewart (1982), Innocenti et al. (1982), Carr (1985) and Middlemost (1985) as summarized by Rickwood (1989) are shown as dashed lines in Figure 4d. Post-kinematic granitoid symbols are: Type 1 - white circles; Type 2 - grey circles; Type 3a - grey circles with thick black outlines; Type 3b - solid black circles; and synkinematic granitoids are small black dots.
patterns for rapakivi granites differ remarkably from both groups, having a strongly negative Eu anomaly (mean Eu/Eu* = 0.25) and lower (La/Yb)N ratios.

The post-kinematic and synkinematic granitoids generally plot in the same area on tectonomagmatic diagrams (Figure 7 a, b). The synkinematic granitoids fall more within the volcanic arc and syn-collisional granites field on Nb vs. Y, and in volcanic-arc granites field on Rb vs. Y+Nb. The post-kinematic granitoids tend to plot more within the within-plate granite field, but the Type 3 plutons more towards the volcanic-arc granites field in the Rb vs. Y+Nb discrimination diagram. Almost all post-kinematic and synkinematic samples plot in the area designated by Pearce (1996) as the post-collisional field (cf. Paper II). These tectonomagmatic diagrams do not really confirm the tectonic setting, but identify the transitional nature from a volcanic arc or syn-collisional type environment toward a more stable cratonic setting for which the granites were emplaced.

MINERALOGY & MINERAL CHEMISTRY

Olivine

Olivine is fayalite and only found in the quartz monzonite and monzogranite that forms the marginal assemblages of several
Figure 6. Chondrite normalized (Boynton, 1984) Rare Earth Element (REE) plots for (A) Type 1 post-kinematic granitoids; (B) Type 2 post-kinematic granitoids; (C) Type 3a post-kinematic granitoids; and (D) Type 3b post-kinematic granitoids. The synkinematic granitoids are shown as light grey REE plots in each diagram for comparison.
Type 3 plutons. The composition is relatively homogenous, ranging from Fa92 to Fa94.

**Pyroxene**
Orthopyroxene is ferrosilite and clinopyroxene is ferroaugite (Figure 8). One pyroxene or both pyroxenes may be encountered in the quartz monzonite and monzogranites of the Type 3 plutons. The ferrosilite has Fe/(Fe+Mg) ratios ranging from 0.75 to 0.86, and in ferroaugite ranging from 0.83 to 0.84. Octahedral Al$^{3+}$ (<0.03) and Ti$^{4+}$ (<0.03) are relatively constant for all the pyroxenes. The orthopyroxene grains in the Rautalampi pluton have consistently lower Fe$^{2+}$(Fe$^{2+}$+Mg) ratios (0.74–0.77), but overall pyroxene mineral chemical compositions are homogeneous.

**Amphibole**
Amphibole has only been observed in the Lavia pluton in the Type 1 plutons, and is generally absent as a major ferromagnesian silicate in the biotite dominated Type 2 plutons. Type 3 plutons that contain a pyrox-
Figure 8. Enstatite–Diopside–Hedenbergite–Ferrosilite quadrilateral diagram for the classification of pyroxenes. Grey circles with thick black outlines represent pyroxene from Type 3a post-kinematic plutons, and solid black circles indicate pyroxene from Type 3b post-kinematic plutons.

Figure 9. (A) Mg/(Mg+Fe$^{2+}$) and (B) Fe$^{3+}$/(Fe$^{3+}$+Al$^{VI}$) vs Si in formula unit diagrams for the classification amphibole (Leake, 1997). Symbols are the same as indicated in Figure 4, except no amphibole from Type 1 plutons have been analyzed to date.
enéolivine-bearing assemblage always contain substantial amounts of amphibole. Their amphibole content decreases from the margin towards the center of the plutons, when the marginal phase is present, otherwise remaining relatively constant. Amphibole range in composition from ferro-edentic hornblende to hastingsitic hornblende (or ferro-edenite and hastingsite under the Leake (1997) classification) and are relatively iron-rich with $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ ratios ranging from 0.74 to 0.89 (Figure 9).

Amphibole in the Type 3 plutons show remarkable compositional variation from margin toward the center of the pluton. Exchange reactions involving Fe, Ti, and Mg in the C-site show a distinct decrease in Fe and Ti and an increase in Mg. While the overall whole rock Fe/Mg ratio increases, the Fe/Mg ratio in amphibole decreases toward the center. Exchange reactions of Na and K, Ca show little variation. Amphibole compositions tend to increase in Na and become slightly more calcic toward the center. In general, coupled substitutions are strongly influenced by silica activity and exchange reactions involving Fe, Mg, and Ti. Amphibole compositions at the margin have higher Fe$^{2+}$, Fe$^{3+}$, Ti, Na, K, and Al$_{tot}$, and the compositions are progressively enriched in Mg, Ca, and Si toward the center.

**Biotite**

Biotite is the most common ferromagnesian silicate in the post-kinematic plutons. It is found as a primary subhedral to anhedral grains, typically interstitial, but may form subophitic-like textures with feldspars. Secon-

![Figure 10. The Mg–Al$^{VI}$+Fe$^{3+}$+Ti ternary diagram for the classification of trioctahedral micas (after Foster, 1963). Mg and Fe$^{2+}$ fields correspond to Mg- and Fe-rich micas, respectively. Symbols are the same as indicated in Figure 4.](image-url)
dary biotite is found as reaction product around amphibole, pyroxenes, and rarely olivine. The biotite is relatively iron-rich with Fe²⁺/(Fe²⁺+Mg) ranging from 0.61 to 0.79 (Type 1 plutons), 0.72 to 0.94 (Type 2 plutons), and 0.77 to 0.88 (Type 3 plutons). Biotite shows very little variation in tetrahedral Aluminum; 2.17 to 2.35 (Type 1), 1.87 to 2.21 (Type 2), and 2.11 to 2.33 (Type 3) (Al⁴⁺ atoms per 24 oxygens). On the Al⁴⁺+Fe³⁺+Ti-Fe²⁺+Mn-Mg ternary diagram, all the post-kinematic granite biotites are relatively iron rich, and the Type 1 granite biotites are discriminated by slightly higher Mg, Al, and Ti contents (Figure 10).

Fe-Ti Oxides
Ilmenite is the predominant Fe-Ti oxide in all the post-kinematic plutons. Magnetite coexisting with ilmenite is only found in the pyroxene±olivine bearing marginal assemblages of the Type 3 plutons. Hematite and more Mn-rich oxides have been observed from the Type 2 Honkajoki and Parkano plutons, indicative of higher oxygen fugacities and/or subsolidus alteration. The composition of ilmenite and magnetite is relatively homogeneous ranging from 0.94 to 0.98 X_ilm, and 0.97 to 0.99 X Mt.

Feldspars
Alkali feldspar occurs as coarse perthite megacrysts and smaller microcline grains. Plagioclase is more prevalent in the olivine- and pyroxene-bearing plutons and anorthite contents tend to vary slightly between pluton types of the post-kinematic suite. The compositional range of most alkali feldspar in the post-kinematic plutons is Or₈₂₋₉₉ (Figure 11). The composition of plagioclase in Type 1 plutons is oligoclase to andesine (An₁₈₋₄₁), the Type 2 plutons predominantly oligoclase (An₁₁₋₂₈), and rarely albite, and in the Type 3 plutons oligoclase to andesine (An₁₈₋₄₂).

Figure 11. Albite–Orthoclase–Anorthite ternary diagram for the classification of plagioclase and alkali feldspar. Symbols are the same as indicated in Figure 4.
INTENSIVE PARAMETERS

Pressure
The composition of amphibole and olivine-pyroxene equilibria were used for pressure determination. Estimated pressures of crystallization for amphibole, using the Al in amphibole geobarometer proposed by Hammerstrom & Zen (1986), are fairly consistent in the range of 2.4 to 4.3 kbar. Mineral reactions in the plutons that contain Fe-rich olivine and pyroxene-bearing assemblages are considerably more pressure sensitive (Smith, 1971, 1974; Lindsley, 1983; Bohlen & Essene, 1978; Koch-Müller et al, 1992). A projection of the pyroxene compositions, and the experimentally derived data for Fe-rich olivine-pyroxene-quartz assemblages (Smith 1971, 1974) indicate maximum pressures of 7.5 to 8.0 kbar. Similarly, calculations using the model calculations of Koch-Müller et al. estimate pressures averaging 8.9 kbar, assuming a maximum temperature of 900°C. Application of the QUIlF program to the olivine-pyroxene assemblages (Smith 1971, 1974) indicate maximum pressures of 7.5 to 8.0 kbar. There is quite a range in the calculated pressures, averaging 2.0 to 4.0 kbar (Al in amphibole) to 5.0 to 7.0 kbar (olivine-pyroxene QUIlF equilibria).

Temperature
The two-feldspar geothermometry applications (Fuhrman & Lindsley, 1988; Green & Usdansky, 1986; Stormer, 1975) yielded temperatures ranging from 380°C to 650°C, and thus failed to provide reasonable magmatic temperatures; those obtained are mostly regarded as subsolidus re-equilibration estimates. Biotite stability curves (Wones & Eugster, 1965) record maximum temperatures in the range of 700°C to 875°C for Type 3 plutons, and temperatures between 820°C and 950°C for Type 2 plutons. Average temperature estimates for amphibole, using the plagioclaspe-amphibole geothermometer proposed by Blundy & Holland (1990), gave consistent estimates between 756°C and 806°C. Their subsequent thermometer (Holland & Blundy, 1994) yielded a wider range of temperatures, 452°C to 875°C. The QUIlF assemblages (cf. Anderson et al., 1993) of the post-kinematic suite recorded a temperature range of 450°C to 800°C with lower overall temperatures for oxide-oxide calculations. Zircon saturation thermometry (Watson & Harrison, 1983) indicate a wide range of temperatures between 950° to 800° C for wt. % SiO₂ compositions around 55 and 75, respectively. The temperature estimates recorded by the biotite stability curves and amphibole appear to be magmatic, but the two-oxide and QUIlF thermometers reflect a re-equilibration cooling trend. Where all three thermometers could be utilized, the temperature estimates concur with field observations and cooling trends of individual plutons (Elliott, 1997).

Oxygen Fugacity
Oxygen fugacities calculated for biotite-ilmenite stability curves range from -1.6 to 0.65 ΔFMQ log fO₂, probably reflecting the disassociation of gases with the crystallization of hydrous mafic silicate minerals. Oxygen fugacities calculated by the QUIlF program for olivine-pyroxene bearing assemblages are relatively more reduced, ranging between -0.3 and -1.7 ΔFMQ fO₂. It has been suggested that the production of amphibole or biotite during the evolution of a magma should increase oxygen fugacity (Frost, 1990). During the evolution of the magma, an increase in the activity of H₂O will cause the consumption of magnetite, augite, and quartz, production of hornblende, and liberation of oxygen according to HMAQ equilibrium (Hornblende + Oxygen = Augite + Magnetite + Quartz + Fluid).

Most of the plutons of the post-kinematic suite contain ilmenite as the only Fe-Ti oxide and biotite as the only mafic silicate and appear to have been controlled by the KUIIB equilibrium (Biotite + Ilmenite = Feldspar + Ulvöspinel + Fluid).

The olivine-pyroxene assemblages generally co-exist with magnetite and ilmenite and were controlled by the QUIlF equilibrium (Quartz + Ulvöspinel = Ilmenite + Fayalite).

In the Type 3 plutons, relatively low oxygen fugacity condition (below FMQ) allowed iron to be incorporated into mafic silicates,
but during disassociation and the formation of a fluid phase, oxygen fugacity increased causing iron to be distributed preferentially into Fe-Ti oxides (i.e. ilmenite). Moving from the olivine- and pyroxene-bearing marginal phases to the hornblende-dominated interior of these plutons, Fe/Mg ratio and Ti abundance in the mafic silicates decrease, opposite to the behavior of other petrogenic indicators of differentiation, such as SiO₂ and Fe/Mg in the whole-rock (Paper I). This can be explained by the increasing activity of the fluid phase in the KUIIB reaction resulting in a progressively increasing oxidation state of the evolving residual magma from which the central parts of the pluton eventually crystallized.

**RADIOGENIC ISOTOPES**

A detailed description of U-Pb (conventional and ion probe), Nd, Pb, and Sr isotopic data is reported in Paper III and offers insights into the timing of granitoid emplacement and source character of the post-kinematic granitoids of the CFGC. The U-Pb dating shows a slight, yet significant, shift in age of the plutonism across the CFGC. The plutons in the northeast and east-central part of the CFGC give U-Pb ages around 1885–1880 Ma, while the plutons in the southern and western parts of the CFGC record younger ages between 1880–1870 Ma. The U-Pb geochronological data constrains the temporal evolution of the post-kinematic magmatism in the CFGC and shows a shift in geochemical composition in the post-kinematic suite with time. Initial εNd values are near chondritic (at 1875 Ma) and show no clear differences between the three types of post-kinematic plutons (Figure 12). Low overall Rb/Sr in the granitoids of the Jämsä and Honkajoki plutons are indicated by

![Figure 12. Simplified map of the Central Finland Granitoid Complex and location of the post-kinematic plutons showing the initial εNd (at 1875 Ma) values of the post-kinematic suite and some values for the synkinematic rocks (indicated by small black dots). Nd data from Appendix Paper 3, Huhma (1986), Patchett & Kouvo (1986), Makkonen (1996), Lahtinen & Huhma (1997), and Rämö & Nironen (in preparation). Pluton name and type are as indicated in Figure 3.](image-url)
PETROGENESIS OF THE 1.88–1.87 GA POST-KINEMATIC GRANITOIDS

Protolith

In the absence of direct source rock indicators (i.e. magmatic enclaves, cognate xenoliths, autoliths, etc.), determination of source rock compositions is largely based on geochemical and isotopic constraints, and trial and error partial melt modeling of probable mantle and lower crust rock types. It has been suggested that the granites of the 1.88–1.87 Ga post-kinematic suite were produced from a relatively anhydrous mafic to intermediate granulite from the lower to middle crust and from mafic mantle derived material related to mafic intra- and under-plating during the Svecofennian orogeny (Paper II). It is apparent from partial melt modeling of possible granulitic protoliths that melting of average lower crust compositions for mafic to intermediate granulite, or even felsic granulite (Rudnick & Fountain, 1995; Hölttä et al., 2000) as the sole source material, is not suitable to produce a parental melt for the Jämsä or Honkajoki suites. Fig. 13a and 13b show that significantly different partial melt parameters (>90% partial melting for compatible and <30% for incompatible rare earth elements) are required to produce melts from lower crust material with rare earth element concentrations that start to resemble those observed in Jämsä and Honkajoki. Landenberger & Collins (1996) concluded that differences in composition of C-type and A-type magmas reflect variation in the anhydrous mineral assemblages that remained in the lower crust after the previous I-type granitoid magmatism. The similar isotopic compositions across the CFGC (Paper III) suggest that the source material for the post-kinematic suite was relatively similar despite the variation in pluton character (i.e. C-type character in the east and A-type character in the west). Considering the similarity in mineralogy and bulk chemical composition of many of the post-kinematic granites and many anorogenic granitoids (cf. the Wolf River batholith, Anderson & Cullers, 1978; the Sherman batholith, Frost et al., 1999; the Pikes Peak batholith, Smith et al., 1999), a similar type of source material may be a likely candidate as the source for the Jämsä and Honkajoki plutons.

Isotope geochemistry suggests that the source material was characterized by near chondritic initial Nd isotope values, very low overall Rb/Sr (initial $^{87}$Sr/$^{86}$Sr ratios for the Jämsä pluton and the Perämaa mafic intrusion at 0.7028 and 0.7032, respectively) and moderate U/Pb ratios (see Paper III). However, it would be unrealistic to assume that a predominantly mantle derived source, generated at the base of anomalously thick crust, did not incorporate melt fraction from crustal material during melting and ascent. Basaltic underplating and intraplating plays an important role in crustal growth and differentiation, and is probably the cause for the anomalously thick crust in east-central Finland (Korja et al., 1993; Korja & Heikkinen, 1995). Underplating and intraplating of basaltic magma pro-
Figure 13. Chondrite normalized rare earth patterns of possible source rocks in the petrogenesis of the 1.88–1.87 Ga post-kinematic suite. Normalized REE patterns and partial melting trends are shown for (A and B) two compositions of lower crust xenoliths from east-central Finland, (after Hölttä et al., 2000); (C) ocean island basalt (after Sun & McDonough, 1989); and (D) ferrodiorite (after Mitchell et al., 1996) and compared with calculated averages of biotite-hornblende granite and biotite granite from the Honkajoki complex and pyroxene-bearing quartz monzonite and biotite-hornblende granite from the Jämsä pluton (normalization values after Boynton, 1984). Shaded areas represent trends for partial melting between 90% (dashed line), and 50% (A), 10% (B), and 10% (C and D) (dotted line).
vide a heat source to melt granulitic lower crust and may yield fractionates to produce mafic and ultramafic crystal cumulates plus evolved magmas that may intrude the upper crust or crystallize in the lower crust and undergo subsequent melting to produce more silicic partial melts (Rudnick, 1992).

For the post-kinematic plutons of the CFGC, therefore, geochemical constraints suggest (1) an Fe-enriched mantle derived protolith, and (2) assimilation of crustal material during melt generation of the granitic magmas. Geochemical modeling of partial melting (batch melting) and mixing between mantle and crust source rocks help to constrain rock types from which the post-kinematic suite may have evolved.

**Basalt**
Due to their iron enriched nature and relatively reduced redox state, differentiated tholeiitic basalt has been suggested as a possible protolith for reduced rapakivi granites (Frost & Frost, 1997). Geochemical characteristics similar to those observed in the post-kinematic granitoids (e.g., high Zr, FeO<sub>tot</sub>/ (FeO<sub>tot</sub>+MgO), and K<sub>2</sub>O) have been observed in high-K fayalite rhyolites derived from differentiated tholeiitic basalt (Hildreth et al., 1991), giving the possibility that a similar source might be a viable candidate also for the post-kinematic suite. The rare earth element modeling suggests that 90% partial melting of ocean island basalt is needed to produce rare earth and trace element patterns that would resemble the initial liquid composition for the Jämsä and Honkajoki plutons (Figure 13c).

**Diorite, Ferrodiorite, Ferromonzodiorite**
Ferrodioritic parental material has been proposed as a source rock for certain (reduced type) anorogenic granites and anorthosite-mangerite-charnockite-granite (AMCG) related intrusions (Frost et al., 1999; Scoates et al., 1996; Mitchell et al., 1996). Ferrodiorite is probably a more likely candidate than basalt because it has a lower melting point than basalt, and ferrobasalts and eruptive equivalents are found in many extensional settings (Frost & Frost, 1997). As Scoates et al. (1996) have shown, monzonitic rocks with >4.0% K<sub>2</sub>O<sub>tot</sub> at intermediate SiO<sub>2</sub> contents (~60%) can be formed from ferrodioritic source compositions, but only at very low degrees of partial melting (~10%). These major element melt compositions are very similar to the compositions of the pyroxene-bearing plutons in the CFGC. However, rare earth element modeling constraints suggest that the possibility of obtaining trace element concentrations similar to those observed in the Jämsä or Honkajoki plutons from a solely ferrodioritic source by less than 30% partial melting is highly unlikely (Fig. 13d). Rare earth element modeling indicates 30–50% partial melting of ferrodiorite would produce compositions similar to a probable initial liquid for the Jämsä pluton, but trace modeling and major element concentrations from experimental work require lower degrees of partial melting.

**Mafic granulite (lower crust)**
The results from the deep seismic sounding study Global Geoscience Transect SVEKA (GGT/SVEKA) across the CFGC indicate the presence of anomalously thick, fairly heterogeneous lower crust (Korsman et al., 1999). The lower crust was delaminated as a result of mafic underplating and is composed partly of eclogite and partly of granulites (Korsman et al, 1999; Hölttä et al., 2000). Xenoliths in kimberlite pipes from east-
central Finland are the only known examples of lower crust assemblages from which to model lower crust partial melt constituents. Xenolith modal compositions range from largely hornblende, plagioclase, and pyroxene to equal amounts of plagioclase, pyroxene and garnet, with minor amounts of hornblende and phyllosilicates (cf. Hölttä et al., 2000). It appears very unlikely that the mafic granulite residue could be the sole source for the post-kinematic plutons (Figure 13a and 13b). Trace element and rare earth element models would require extremely low partial melts of hornblende-rich granulite, and strongly disfavor garnet-rich compositions as the sole source material (Figure 14). The geochemical characteristics and intensive parameters suggest a relatively hot and dry source, which does not favor a hornblende-rich granulite as a source material for the post-kinematic granitoids. Under fluid absent conditions, however, reactions of hornblende and quartz to produce pyroxene, plagioclase and melt could occur (Rushmer, 1991), and would generate suitable protolith compositions to the post-kinematic granitoids.

**Crystallization**

Modeling (fractional crystallization or ‘FC’) the effects of individual mineral fractionation on trace element distribution in the Jämsä and Honkajoki plutons show which minerals could have been important in magmatic evolution. The Ba vs. Sr plot shows trends consistent with major fractionation of feldspars (Figure 15).

The Jämsä pluton shows fractionation of feldspar, predominantly alkali feldspar in minor proportions from the quartz monzonite to the biotite-hornblende granite. Further fractionation at a considerably higher proportion produces the quartz-rich granite. This is consistent with field observations as the biotite-hornblende granite covers ~70% of the total pluton area and the quartz-rich granite and

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**Figure 14.** Sr vs. Ba scatterplot diagram of rocks from the Honkajoki and Jämsä plutons, trends for partial melting of ferrodiorite and xenoliths from east-central Finland, and mixing trends between ferrodiorite partial melt and xenolith partial melts. The area designated as “Melt Source” area is the best-fit mixing ratio of partial melts between ferrodiorite and xenolith 1, as deduced from rare earth element patterns. The path of the evolution trend for Sr and Ba is illustrated as (A) the parental melt differentiates/fractionates prior to emplacement, (B) fractionates after emplacement, and (C) differentiates/segregates/fractionates during the later stages of crystallization. Jämsä samples are represented by: open circles (pyroxene-bearing margin); open circles with a horizontal line (hornblende-biotite granite); open circles with a horizontal and vertical line (quartz rich granite); and Honkajoki samples are represented by: black squares (hornblende-biotite granite) and grey squares (biotite granite). The bulk distribution coefficient is a partition coefficient calculated for a rock for a specific element from the Nernst partition coefficients of the constituent minerals and weighted according to proportions.
quartz monzonite only about 17% and 13%, respectively. The segregate sample from the quartz-rich granite phase shows fractionation in the direction of biotite and hornblende in minor proportions (<30%).

The Honkajoki pluton shows similar fractionation trends, but at more evolved compositions, where the biotite-hornblende granite is similar to the biotite-hornblende granite of Jämsä, and the main felsic phase biotite granite is similar to the quartz-rich granite phase at Jämsä. The higher proportion of the more evolved phase in the Honkajoki pluton suggests a larger, more fractionated magma source and produce a wider range in trace element concentrations.

REE modeling suggests the source materials for both pluton suites were mixed proportions of partially melted lower crust and a mantle-derived ferrodioritic/ferromonzodioritic rock. Figure 16 illustrates mixing proportions for partial melts of ferrodiorite and lower crust material. The xenolith compositions (that best represent the range of rock types in the lower crust in central Finland; see Hölttä et al., 2000) show that hornblende-plagioclase dominated rocks are more suitable source components than garnet-bearing pyroxene-dominated compositions. The mixing model also shows that a source melt of mainly ferrodiorite composition will increase in Ba and slightly decrease in Sr during early fractionation of plagioclase and clinopyroxene. After emplacement and fractionation processes, hydration and cooling begin to effect the crystallizing phases (at lower pressure) and Sr decreases with decreasing Ba. The vector created between the phases of each pluton...
Figure 16. Chondrite normalized rare earth element patterns illustrating the petrogenesis of the Jämsä pluton (normalization values after Boynton, 1984). The initial parental liquid was probably derived from (a) 80–90%: 30–50% ferrodiorite partial melt and 10–20%: 10–30% mafic lower crust partial melt. The melt (b) fractionated a relatively thin pluton margin of pyroxene-bearing quartz monzonite at 10–30%, followed by (c) a slow crystallization of the main phase biotite-hornblende granite at 50–70%, and (d) the late stage differentiated granite melt separated into glomerocrystic bands and mafic segregates at 10–30% to produce the quartz-rich granite.
suite reflects back to the initial proportion of partial melt involved in producing the initial melt composition/trace element concentrations. In Figure 14, it is shown that a mafic granulite of pyroxene dominant modal composition probably had little involvement in producing the initial melt for Honkajoki or Jämsä. The initial melt is constrained to compositions of higher Sr and Ba. Furthermore, the vector created between phases of each suite suggests that the Honkajoki initial melt formed at higher partial melt proportions in the ferrodiorite/mafic granulite mixture model than that of Jämsä. The area designated “source melt” in Figure 14 covers the range of source-melt mixtures derived from REE modeling for both pluton suites.

The initial Jämsä melt was calculated from a reintegration of the phase compositions by aerial distribution. The partial melt mixing model of 80–90% ferrodiorite at 30–50% partial melt and 10–20% mafic granulite partially melted at 10–30% creates a fairly close approximation of the initial Jämsä liquid composition (Figure 16a). The fractional crystallization of the marginal quartz monzonite (Stage 1 fractionation) at 10–30% produces a REE pattern close to the approximated melt, or the composition of the melt after the crystallization of the marginal pyroxene-bearing quartz monzonite (Figure 16b). The crystallization of the biotite-hornblende granite (~70% of the entire pluton area) fractionated from the post-Stage 1 liquid at about 70% produces a close approximation to the quartz-rich granite liquid (Figure 16c). The quartz-rich granite phase is host to numerous mafic glomerocrystic pockets or pipes that separated from the felsic liquid and can be modeled as a third and final stage of fractionation producing patterns virtually identical to the quartz-rich granite having fractionated about 10-30% of the minerals and proportions that compose the mafic segregates (Figure 16d).

The Honkajoki granites may have been derived from similar source rocks as the Jämsä pluton. In contrast to the in situ closed system fractionation model derived for the Jämsä intrusion, the Honkajoki complex resembles a more open system where the biotite-hornblende granite and biotite granite

![Figure 17. Chondrite normalized rare earth element patterns illustrating the petrogenesis of the Honkajoki pluton (normalization values after Boynton, 1984). The initial parental liquid was probably derived from (a) 60–70% : 50–70% ferrodiorite partial melt and 30–40% : ~10% lower crust partial melt. The melt (b) fractionated biotite-hornblende granite at 30–50%, and (c) the main phase biotite granite at 50–70% fractionation.](image-url)
were generated at depth and emplaced as separate intrusive phases. The initial liquid for the granite phases is modeled as a simple partial melt of ferrodiorite and mafic granulite at 60–70% ferrodiorite partially melted at 50–70% mixed with 30–40% mafic granulite partially melted at ~10% (Figure 17a). Simple fractionation of the initial melt at 30–50% (Stage 1 fractionation) produces patterns closely resembling the biotite-hornblende granite REE pattern (Figure 17b). Further fractionation at 50–70% of the post-Stage 1 liquid produces patterns similar to the biotite granite REE pattern (Figure 17c).

The 1.88-1.87 Ga post-kinematic plutons were formed over a relatively large area and have phases that differ in mineralogical and geochemical compositions. The petrogenetic model described here, in conjunction with isotopic evidence, shows that the Jämsä and Honkajoki plutons could have been derived from partial melts of similar source rocks and may have shared a similar magmatic evolution.

DISCUSSION

The structure of the crust in central Finland

A detailed geophysical profile across the CFGC shows the depths to the mantle and lower-most high velocity lower crust and is extrapolated into a three dimensional perspective in Figure 18. The depth of the lower crust in the western CFGC near Honkajoki is ~21 km, and ~23 km in the eastern CFGC near Jämsä. The depth to the Moho in the western CFGC is ~54 km in the western CFGC near Honkajoki, and ~58 km in the eastern CFGC near Jämsä. The greater depth and thicker lower crust attribute to the character and relative number of Type 3 plutons located in the eastern CFGC. These pyroxene-bearing assemblages reflect a higher pressure and more anhydrous nature of the source material generated at greater depths and are probably composed of a larger proportion of mantle derived material. In the eastern CFGC, the deeper mantle and thicker lower crust produced more partial melt of lower crust but contributed a lower proportion of crustal melt to the overall
post-kinematic granitoid magmas. In the western CFGC, the mantle is relatively more shallow and the lower crust relatively thinner, and the post-kinematic magmas incorporated a higher proportion of crustal melt at lower degrees of partial melt probably due to lower pressures and a more open system in which ascent was relatively more rapid (i.e. extensional tectonic setting). Overall, assuming that the present structure reflects that of ~1.88–1.87 Ga, the crustal structure across the CFGC is perhaps an important factor in controlling the petrogenesis of the post-kinematic granites; the depth to mantle and thickness to of the lower crust being a major influence on mineralogical compositions and geochemical character of the post-kinematic plutons.

**The effect of water activity and cooling rate on magmatic evolution**

Pyroxene-bearing plutons (previously referred to as being derived from C-type magmas in Paper II) predominate in the eastern CFGC and high silica, predominantly biotite-bearing plutons (those with A-type characteristics) are generally located in the western CFGC (cf. Paper II). The initial geochemical variation, prior to fractionation processes, is seen as a function of variation in melt percentage and mixing proportion between melts from lower crustal material and the mantle derived material in the lower crust. The variation in mineral composition is a function of water activity and rate of cooling as the magmas were emplaced at shallower levels.

Experimental studies on the effect of water content in granitic systems during ascent show that water content in the melt fraction increases dramatically during fractionation with increased cooling rate when compared to adiabatic systems or systems where the cooling rate is lower (cf. Holtz & Johannes, 1994; Johannes & Holtz, 1996). The experimental approach can be utilized to explain the observation of anhydrous assemblages (i.e. pyroxene and olivine) where heat exchange was much lower during crystallization and more hydrous assemblages (i.e. amphibole and biotite, or biotite only) formed due to the increasing water content in the melt fraction at an increased cooling rate. The emplacement of the post-kinematic magmas in the eastern CFGC shortly followed the peak of the orogeny, whereas the plutons in the western CFGC were emplaced ~10 Ma later when the crust was relatively cooler. Calculated trajectory paths for the ascent of granitic melts at different cooling rates (Holtz & Johannes, 1994) can be applied to the petrological variation observed in the post-kinematic suite. In Figure 19, we assume that two plutons originate from similar a source composition at the same temperatures, pressure and water content. Trajectory ‘A’ represents the crystallization path of one pluton at −5 J g⁻¹ kbar⁻¹ and path ‘B’ represents the same magma crystallizing at a slightly faster cooling rate, -10 J g⁻¹ kbar⁻¹. If we assume an initial crystal/melt ratio of 50%, and the initial water content (as indicated in Figure 19) of 2.0% in the melt, the model predicts increasing wt.% H₂O during the evolution of the magma. Any fractionation processes, assuming a system closed to additional magma, could increase the wt.% H₂O in the residual melt dramatically (cf. Holtz & Johannes, 1994).

Similar to water content, the ascent and cooling processes of granitic magmas can be strongly influenced by viscosity. Model calculations show that viscosity of granitic melts is strongly influenced by water content. Johannes & Holtz (1996) show that even though a magma at the same pressure is in a much cooler environment (200° C less), the viscosity is lower at higher water contents. If we apply this to the cooling during ascent model (Figure 19), where increased cooling rate increases water content in the residual melt, the viscosity can decrease, promoting fractionation. Viscosities of granitic magmas remain approximately constant (or increase slightly) during ascent under adiabatic conditions. Conversely to increased cooling, adiabatic ascent can produce decompressional melting, decreasing the wt.% H₂O in the residual melt, and increasing the viscosity of the magma. In such a case, it is quite possible that the magma can reach its rheologically critical melt percentage (typically between 25% and 40%), where it becomes too rigid to behave as a magma and discontinues ascent. Furthermore, many of the plutons in the western CFGC contain accessory fluorite. Experimental studies on the effect of F on granitic systems show
an increase in H$_2$O solubility and lowering of the liquidus temperature with increasing F content (cf. Bailey, 1978; Manning, 1981; Johannes & Holtz, 1996). This would allow magma with a higher water activity to migrate to comparable emplacement levels as granitic magmas with lower water activity and lower F content.

**Temporal shift in magmatism across the CFGC**

The geographic position of U-Pb ages for the post-kinematic granitoids show a trend of decreasing ages from northeast to west-southwest across the CFGC (see Paper III). The plutons in the northeast have ages around 1885 Ma and those in the in the west-southwest have ages between 1870–1875 Ma. The shift is accompanied by a change in character of the post-kinematic granitoid magmatism: the older plutons are generally less evolved pyroxene-bearing (charnockitic) granitoids, and the younger intrusions have many characteristics usually associated with A-type granitoids. The thickness of the continental crust across the CFGC region shows a significant change from east to west where the high velocity lower crust is ~7 km thicker in the east than in the west (Korsman et al., 1999). The initial accretion of the central Finland arc to the Archean craton produced fractures or conduits, even though the crust may have been more plastic at the time, for which the early post-kinematic granites could use to migrate through the crust. The accretion of the southern Finland arc occurred shortly after, about 10 – 30 Ma, which induced stress in the southern portion of the central Finland arc. The temporal distribution of post-kinematic plutons may not, necasarily, be associated with separate basaltic underplating/intraplating “events”, but rather the migration of tectonic stress that induces fractures or conduits for mafic magmas to induce melting, and allows granitic magmas to reach their current emplacement level.

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**Figure 19.** Pressure–Temperature diagram showing the liquidus curves for the haplogranite system and minimum melt compositions and specified water contents (after Johannes & Holtz, 1996). Pressure–Temperature paths (A) and (B) represent initially identical granitic magmas ascending at different cooling rates (-10 J g$^{-1}$ kbar$^{-1}$ and ~5 J g$^{-1}$ kbar$^{-1}$, respectively). Thermobarometry calculations for the Jämsä pluton and Honkajoki complex mineral equilibria are shown for comparison.
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