MANTLE- AND CRUST-DERIVED MAGMATISM IN THE SOUTHERN FENNOSCANDIAN SHIELD AT c. 1.8 Ga; EVIDENCE FROM GEOCHEMISTRY, ISOTOPES AND GEOCHRONOLOGY

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The geochemistry and isotopic composition of c. 1.80 Ga mafic intrusive rocks were studied in two main areas: i) the Transscandinavian Igneous Belt (TIB) in southern Sweden (incl. some samples from the c. 1.87 Ga Hedesunda complex), and ii) minor, essentially post-kinematic complexes in southern Finland and Russian Karelia. In the latter case, related granitoid rocks were incorporated in the study.

The TIB rocks show large variations in evolutionary levels and range in composition from ultramafic to quartz dioritic, with 38 to 60 wt% SiO_2 and Mg# from 85 to 46. Even though masked by various cumulus components the rocks are dominantly calc-alkaline, enriched in LILE and LREE, but relatively depleted in HFSE and HREE, and display continental arc signatures. A slight shift to less strongly enriched, more oceanic-arc type compositions, is discerned in the southernmost TIB and the Hedesunda rocks. $\varepsilon_{Nd}(t)$ for the mafic TIB rocks range between +0.7 and +2.1, with two exceptions at ±0 and +2.7, while the $^{87}Sr/^{86}Sr(t)$ fall in the range 0.7020-0.7029, with two exceptions at 0.7033 and 0.7038. Together with previous data, these results define a 'mildly depleted mantle' composition of c. +1.0 to +2.0 and 0.7020-0.7030 for the TIB. The mafic rocks in southern Finland and Russian Karelia range from ultramafic to monzodioritic, with SiO_2 32-60 wt% and Mg# from 78 to 31, but with considerably higher alkali contents compared with the TIB rocks. The compositions are shoshonitic with $K_2O+Na_2O > 4$ wt%, $K_2O/Na_2O > 0.5$, $Al_2O_3 >9$ wt%, and strongly elevated LILE and LREE contents, but with relative depletions in HFSE and HREE (high Ce/Yb ratios). $\varepsilon_{Nd}(t)$ range between +0.1 and +0.8 and $^{87}Sr/^{86}Sr(t)$ 0.7027-0.7031 in southern Finland, with one exception at +1.4 and 0.7019, i.e. slightly lower $\varepsilon_{Nd}(t)$ compared with the TIB. The sources of the mafic magmatism can be interpreted in terms of a depleted mantle, variously overprinted by fluids and melts from subducted slabs. In the west (TIB), H_2O-dominated fluids percolated and prepared shallower (lower Ce/Yb; spinel lherzolite field) mantle sections by less strong enrichment, while increasingly more carbonate- and sediment-influenced, deeper (higher Ce/Yb; garnet lherzolite field) mantle supplied magmas to the c. 1.8 Ga magmatism when advancing eastward. The subduction-related mantle wedge enrichment occurred not long before the magmatism as shown by the T_{DM} <2.1 Ga for both areas, i.e. during the preceding Svecofennian arc development.

One group of granitoids associated with the c. 1.8 Ga intrusions in southern Finland is marginally peraluminous, transitional between I (volcanic-arc) and S (syn-collisional) types, and derive from mixed igneous and sedimentary, but juvenile Svecofennian sources, as supported by near-chondritic ε_{Nd}(1.8 Ga), but higher $^{87}Sr/^{86}Sr$(1.8 Ga) ratios (0.7048-0.7062). The other group is transitional between I and A (within-plate) types in character and have dominantly igneous protoliths. Geochemistry and isotopes in these complexes suggest that the compositional variation between c. 50 and 70 wt% SiO_2 may be explained by hybridization between the strongly enriched mantle-derived magmas and anatectic granitic magmas from the juvenile Svecofennian crust. The 1811±6 Ma Petravaara intrusion contains a significant portion of Archaean, mostly igneous protolith material [ε_{Nd}(1.8 Ga) = -2.8 and $\varepsilon_{Hf}(t)$ for zircons between +2.8 and -11.9].

The c. 1.8 Ga TIB magmatism in the west was emplaced during convergence in continental margin arcs, with coeval subduction towards the north and east. Contemporaneously in the east, the post-kinematic intrusions were emplaced within the crust immediately following regional metamorphism and anatexis at c. 1.85-1.81 Ga that was related to the collision with the Volgo-Sarmatian continent from the SE. This complicated palaeotectonic situation created a tectonic regime where lithospheric mantle sources were tapped to generate the strongly enriched shoshonitic magmas, whose ascent probably was facilitated by deep-reaching post-collisional, transpressional/transtensional shear zones. The emplacement of the magmas induced melting in the crust that caused the associated granitoid magmatism.

Keywords: Fennoscandian Shield; Svecofennian; Transscandinavian Igneous Belt; continental arc; shoshonitic; post-collision; Sm-Nd, Rb-Sr, U-Pb and Lu-Hf isotopes

Rutanen, Henrikki 2010. Mantel- och skorpederiverad magmatism i södra Fennoskandiska skölden för ca 1,8 miljarder år sedan; upplysningar från geokemi, isotoper och geokronologi. Doktorsavhandling, Åbo Akademi. 45 sidor + 4 artiklar.

Geokemi och isotopsammansättningarna hos ca 1,80 Ga gamla mafiska intrusioner studerades i två huvudområden: i) Transskandinaviska magmatiska bältet (TMB) i södra Sverige, inklusive några prov från det ca 1,87 Ga gamla Hedesunda-komplexet, och ii) mindre, närmast postkinematiska komplex i södra Finland och ryska Karelen. I det senare fallet var även tillhörande granitoider inkluderade i studierna.

TMB-bergarterna skiljer sig avsevärt i utvecklingsgrad och omfattar sammansättningsmässigt bergarter från ultramafiter till kvartsdioriter, med 38-60 wt% SiO_2 och Mg# 85-46. Trots kumuleringseffekter kan bergarternas huvudsakligen kalkalkalina karaktär urskiljas; de är anrikade på LILE och LREE, men relativt utarmade på HFSE och HREE, vilket är kännetecknande för kontinentala öbågar. För sydligaste TMB och Hedesunda kan en lägre anrikning skönjas, vilket antyder en något mera oceanisk öbågekaraktär. $\varepsilon_{Nd}(t)$ för de mafiska TMB-bergarterna varierar mellan +0,7 och +2,1, förutom två värden vid ±0 och +2,7, medan $^{87}Sr/^{86}Sr(t)$ faller mellan 0,7020 och 0,7029, med två undantag vid 0,7033 och 0,7038. Tillsammans med tidigare data antyder dessa resultat för TMB en 'milt utarmad' mantelsammansättning med $\varepsilon_{Nd}(t)$ mellan ca +1,0 och +2,0, samt $^{87}Sr/^{86}Sr(t)$ mellan 0,7020 och 0,7030. De mafiska bergarterna i södra Finland och ryska Karelen varierar från ultramafiska till monzodioritiska, med SiO_2 32-60 wt% och Mg# 78-31, men med avsevärt högre alkalihalter jämfört med TMB. Sammansättningarna är shoshonitiska, med K_2O+Na_2O > 4 wt%, K_2O/Na_2O > 0,5, Al_2O_3 >9 wt%, samt starkt förhöjda LILE- och LREE-halter, men med relativ utarmning av HFSE och HREE (höga Ce/Yb). Södra Finland har, med $\varepsilon_{Nd}(t)$ varierande mellan +0,1 och +0,8, en aningen lägre $\varepsilon_{Nd}(t)$ än TMB, medan $^{87}Sr/^{86}Sr(t)$ är 0,7027-0,7031, med ett undantag vid +1,4 och 0,7019. Källan för all den studerade mafiska magmatismen kan beskrivas som en utarmad mantel som i varierande grad påverkats av fluider och smältor ur subducerande litosfärplattor. Lägre Ce/Yb antyder infiltrering och påverkning av H_2O-dominerande fluider i spinell-lherzolitfältet i övre manteln för TMB. Den mafiska ca 1,8 Ga gamla magmatismen österut, med stigande Ce/Yb, avspeglar en ökande påverkan av sedimentderiverade karbonatfluider och smältor inom allt djupare mantelområden i granat-lherzolitfältet. Denna subduktionsrelaterade mantelanrikning skedde inte långt före magmatismen, utan under den föregående öbågeutvecklingen i den Svekofenniska domänen, vilket antyds av T_{DM} <2,1 Ga i vartdera studieområdet.

En grupp granitoider, associerade med de ca 1,8 Ga gamla intrusionerna i södra Finland, är svagt peraluminösa, samt visar både I (vulkanisk öbåge) och S (synkollisional) typ-granitoidkaraktär. Denna grupp har ett blandat magmatiskt och sedimentärt, men juvenilt, Svekofenniskt ursprung, vilket kan antas p.g.a. nära kondritiska ε_{Nd}(1,8 Ga)-värden, men högre $^{87}Sr/^{86}Sr$(1,8 Ga)-värden vid 0,7048-0,7062. Den andra gruppen ligger geokemiskt mellan I och A (intraplatt) typ-granitoider, och har magmatiska protoliter. Geokemin och isotoperna hos dessa intrusioner indikerar att sammansättningsvariationen mellan ca 50 och 70 wt% SiO_2 kan förklaras med hybridisering mellan de kraftigt anrikade, mantelderiverade magmorna, och anatektiska granitmagmor från den juvenila Svekofenniska skorpan. 1811±6 Ma gamla Petravaara-intrusionens magma inkorporerade en betydande andel arkeiskt material ur en huvudsakligen magmatisk protolit [ε_{Nd}(1,8 Ga) = -2,8 och $\varepsilon_{Hf}(t)$ för zirkoner mellan +2,8 och -11,9].

Den ca 1,8 Ga gamla TMB-magmatismen i väster skedde vid konvergens i kontinentalrandbågar, med kontinuerlig subduktion mot norr och öster. Samtidigt i öster intruderade de postkinematiska intrusionerna i skorpan omedelbart efter den ca 1,85-1,81 Ga gamla regionalmetamorfosen, som var kopplad till kollisionen med den Volgo-Sarmatiska kontinenten från sydost. Denna invecklade paleotektoniska konfiguration orsakade en tektonisk regim där litosfäriska mantelkällor levererade de starkt anrikade shoshonitiska magmorna, vilkas uppstigning troligen möjliggjordes av djupgående postkollisionala, transpressionala/ transtensionala skjuvzoner. Intrusionerna orsakade uppsmältning av den omgivande skorpan, vilket framkallade den associerade granitoidmagmatismen.

LIST OF PAPERS

The present thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. Olav Eklund, Dmitry Konopelko, Henrikki Rutanen, Sören Fröjdö and Alexey D. Shebanov (1998) 1.8 Ga Svecofennian post-collisional shoshonitic magmatism in the Fennoscandian shield. Lithos 45, 87-108.

II. Ulf B. Andersson, Henrikki Rutanen, Åke Johansson, Joakim Mansfeld and Andrius Rimša (2007) Characterization of the Paleoproterozoic mantle beneath the Fennoscandian shield: geochemistry and isotope geology (Nd, Sr) of ~1.8 Ga mafic plutonic rocks from the Transscandinavian Igneous Belt in southeast Sweden. International Geology Review 49, 587-625.

III. Henrikki Rutanen and Ulf B. Andersson (2009) Mafic plutonic rocks in a continental arc setting: geochemistry of 1.87-1.78 Ga rocks from south-central Sweden and models of their palaeotectonic setting. Geological Journal 44, 241-279.

IV. Henrikki Rutanen, Ulf B. Andersson, Markku Väisänen, Åke Johansson, Sören Fröjdö, Yann Lahaye and Olav Eklund (manuscript) 1.8 Ga magmatism in southern Finland: strongly enriched mantle and juvenile crustal sources in a post-collisional setting.

Henrikki Rutanen is chiefly responsible for Papers II-IV. He did sampling, laboratory works, figures, tables and some of the least-squares fractionation estimations for Paper I as a research assistant for the research group “Magmatic probes through the Svecofennian shield”, led by Prof. Olav Eklund at Turku University.

CONTENTS

INTRODUCTION

The present work deals with c. 1.8 Ga magmatism across the Fennoscandian Shield that was emplaced following the accretion of microcontinents and juvenile arc crust of the northwestern East European Craton (e.g. Nironen 1997, Lahtinen *et al.* 2005, Bogdanova *et al.* 2006). The arc-accretion magmatism had by 1.8 Ga evolved into continental arc magmatism of the Transscandinavian Igneous Belt (TIB) in the west (Papers II and III). Simultaneously, in southern Finland and Russian Karelia in the east, accretion was followed by continental collision that by 1.8 Ga had shifted to a post-collisional setting (Papers I and IV).

Accretion within plate tectonics is described as tectonic juxtaposition (not necessarily subduction-involved) of two or more terranes, or terranes to a craton margin (e.g. Nokleberg *et al.* 1997, Rodianov *et al.* 2004). These tectonic units can more precisely include continental fragments (passive or active continental margins) and oceanic or continental arc-terranes, or continental-margin arc superterranes (including terranes of different origin such as island-arc, passive continental margin, oceanic terranes, etc.). According to Korja *et al.* (2006), in general all continental orogens have formed in accretionary modes at convergent margins, where lateral growth of the continental plates mainly takes place, and only some of the orogenies then evolve into collisional ones, where reworking of the crust occurs due to subduction and collision of the already amalgamated terranes. The Svecofennian Domain of the Fennoscandian Shield has long been considered a typical example of an accreted orogen (Gaál & Gorbatschev 1987, Windley 1995).

Suites of related plutonic magmatism may intrude into several of the tectonically accreted units, or blocks, and link them together by stitching belts, plutons or dyke swarms (Nokleberg *et al.* 1994, Parfenov *et al.* 1999, Rodianov *et al.* 2004). Such *post-accretional* magmatism occurs after the main accretion in the late history of two or more of the involved blocks. The post-accretional plutonic magmatism can be related to reactivation of strike-slip shear zones in transpressional or pure shear regimes (e.g. Thomas *et al.* 2004, Cruden *et al.* 2006), to brittle extensional structures (Allen & Tadesse 2003) or rifting (Dilek 1989); all operating in arc, intra-plate or microcontinent settings in assemblages of just accreted blocks. The resultant rocks may thus form both in within plate (plume) environments and at lithological transform boundaries (Rodianov *et al.* 2004), along which the igneous units and fragments of terranes can experience extensive (even hundreds of kilometres) post-accretional movements (Nokleberg *et al.* 1994). As a whole, the post-accretional rocks comprise undeformed, or in later processes deformed, mostly mantle-linked juvenile (with restricted crustal involvement), often calc-alkaline, mafic to felsic sheeted dykes and tabular plutons, with or without internal compositional variation/zoning (Lucas *et al.* 1996, Whalen *et al.* 1999). One type of post-accretional magmatism may occur along the margin of a newly assembled collage of accreted juvenile arcs and microcontinents, where continued subduction and convergence establishes a continental arc setting. This is a situation that may apply to the western and south-western margin of the Svecofennian Domain at c. 1.8 Ga during the formation of TIB (Papers II and III).

In many cases the accretion and amalgamation of variable crustal slivers is followed by a major *collision* between two converging crustal blocks, the Alpine-Himalayan Belt being the prime example (summarised e.g. in Windley 1995). During continental collision crustal thickening and heating of the lower units lead to melting and the formation of *syn-collisional*, mostly crustally derived granitic magmatism (e.g. Wilson 1989, von Blanckenburg & Davies 1995).

Continuing lithospheric plate convergence after a major collision episode, result in intracontinental thrust and wrench deformation and/or lateral escape of discrete terrains, accompanied by *post-collisional* magmatism (Bonin *et al.* 1998). Post-collisional magmatism derives initially from sources still influenced by crustal materials subducted below the orogenic subcontinental lithospheric mantle (Bonin *et al.* 1998, Liégeois 1998, Liégeois *et al.* 1998, Bonin 2004). The resultant rocks are dominantly mafic-intermediate, high-K calc-alkaline to shoshonitic, but also strongly peraluminous and alkaline-peralkaline granitoids are volumetrically significant (Liégeois 1998, Bonin 2004).

In a subduction regime, the break-off and sinking of a lithospheric slab produces a widening gap above it, into which there is a convective in-flow of high temperature, low-density mantle material and associated rise of the isotherms that promote melting and cause post-collisional activity (Zeck *et al.* 1998). Similarly, tectonic extension can provoke partial melting by decompression (e.g. Liégeois *et al.* 1998). The produced melts underplate the continental crust and cause further melting, with post-collisional rock suites as the final result (e.g. Waight *et al.* 1998). According to Whalen *et al.* (2006) decompressional partial melting cannot operate in continent-continent collision zones after e.g. a slab break-off because asthenospheric material is prevented to rise through the thickened lithosphere to levels with enough low pressures. The hot asthenospheric mantle can instead provoke partial melting on the above lying metasomatised lithospheric mantle wedge (Turner *et al.* 1993, 1996), producing early post-collisional potassic magmas, introducing depleted asthenospheric melts later in an intra-plate setting (Mahéo *et al.* 2002). van de Zedde & Wortel (2001) suggested that during slab break-off conditions the anatexis of mantle wedge and asthenospheric material is only a transient process lasting some millions of years, while, because of the much lower solidus temperature, anatexis of the overlying crustal material can proceed for substantially longer time periods.

Heat sources traditionally invoked for post-collisional magmatism are orogen scale delamination (Nelson 1992), or convective thinning, or erosion, of the lithosphere (Houseman *et al.* 1981). Both of the models allow the rise of hot mantle material, and thus also of the regional isotherms, which were earlier depressed during the main orogenic thickening (Liégeois *et al.* 1998, Bonin 2004). In both models, dense lithospheric root-removal would result in markedly isostatic elevation, accompanied by a rapid temperature rise due to the emplacement of hot asthenosphere close to the Moho. The associated magmatism would be characterised by early asthenospheric mantle melts, followed by increasingly crustally contaminated calc-alkaline melts, succeeded by crustal partial melts. The mafic melts reflect lithospheric mantle sources affected by heating from below, and melting at successively shallower levels (cf. Turner *et al.* 1999, Wang *et al.* 2004). Both the convective thinning and the delamination models predict random and unlinear zones of magmatism (Whalen *et al.* 2006), in contrast to e.g. the slab break-off and shear zone-controlled magmatism. Of the traditional models, Bonin (2004) prefer delamination for the rather short-lived post-collisional processes. In contrast, Kukkonen & Lauri (2009) proposed recently that radiogenic heat production of the overthickened crust had an important impact on the prolonged magmatism in the SE Svecofennian Domain.

Post-collisional source regions commonly contain large juvenile components, either of mantle, or newly formed crust of igneous or sedimentary character (e.g. Bonin 2004). They are represented by depleted mantle sections, enriched during the preceding subduction period, now forming the subcontinental lithospheric/asthenospheric mantle. This mantle is affected by dehydration melting under a cooling regime and producing decreasing volumes of progressively more K- and LILE (large ionic lithophile element)-rich magmas (e.g. Wilson 1989, Bonin *et al.* 1998, Conceição & Green 2004). In these, normally water-saturated, post-collisional environments crystallisation and differentiation of Mg-rich amphibole and biotite are facilitated. In the vicinity of intracrustal mafic magma chambers anatexis may occur, e.g. by incongruent melting of hydrous minerals such as biotite, generating peraluminous S-type granitoids. The associated crustal melting is often accompanied by magma-mingling and -mixing processes between the crustal- and mantle-derived magmas, and the common formation of mafic microgranular enclaves (Bonin *et al.* 1998, Liégeois *et al.* 1998).

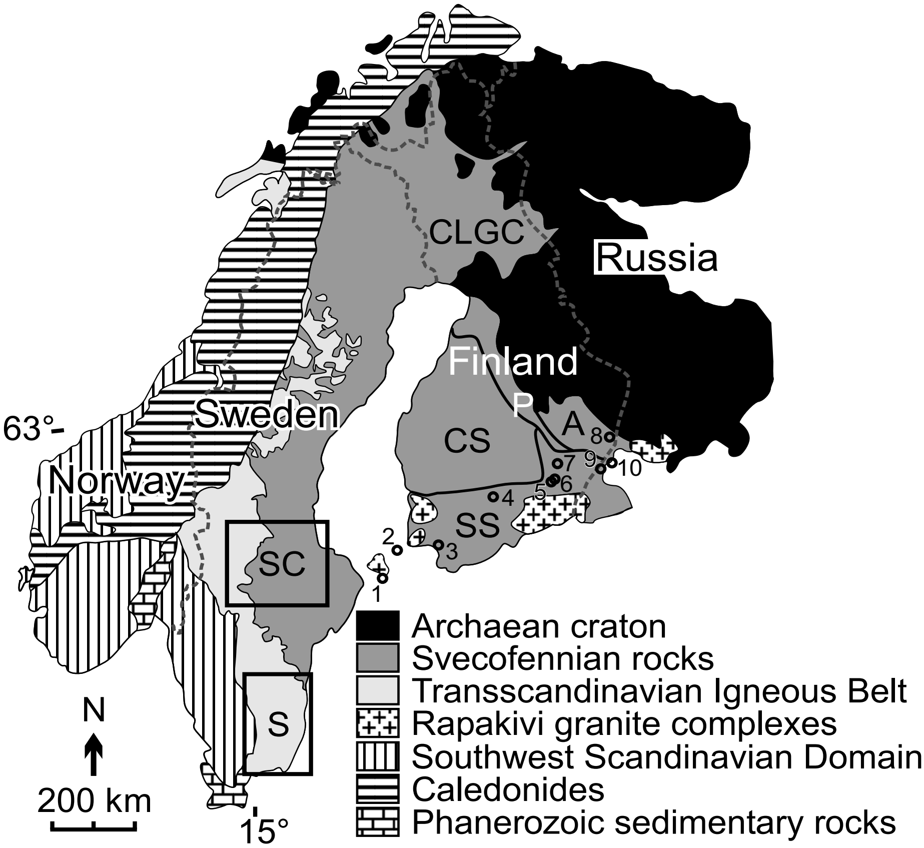

Fig. 1. Geological overview of the Fennoscandian Shield (modified after Högdahl & Sjöström 2001). The study areas in Sweden: SC = south-central Sweden (cf. Fig. 1 in Paper III), S = southeastern Sweden (cf. Fig. 1 in Paper II). The Palaeoproterozoic units discussed in the present work (e.g. after Korsman *et al.* 1997, Väisänen 2002, Väisänen *et al.* 2002): SS = Southern Svecofennian Arc Complex (abbreviated 'SSAC' in the main text; more detailed in Fig. 1 in Papers I and IV), A = Archaean Karelian Domain covered by Palaeoproterozoic supracrustals, P = Primitive Arc Complex of central Finland (PAC), CS = Central Svecofennian Arc Complex (CSAC), CLGC = Central Lapland Granitoid Complex. The positions of the post-collisional intrusions more thoroughly studied in Papers I and IV are numbered: 1 = Lemland, 2 = Åva, 3 = Turku area, 4 = Renko, 5 = Parkkila, 6 = Luonteri, 7 = Pirilä, 8 = Petravaara, 9 = Elisenvaara, 10 = Kalto. The positions of the rest of the post-collisional intrusions in southern Finland and Russian Karelia can best be seen on Fig. 1 in Paper IV.

Some of the post-collisional intrusions of the present study have, especially in early works, been grouped as *post-orogenic*. Actual post-orogenic epochs are totally intracontinental according to Bonin *et al.* (1998), Liégeois (1998), and Bonin (2004). The bimodal post-orogenic suites are exposed as volcanic plateaux, dyke swarms, caldera volcanoes and subvolcanic ring complexes, aligned along large transcurrent fault zones created during collision and reactivated afterwards. The suites contain scarce basic rocks, almost no intermediate rocks, and predominant granitoids. Bonin *et al.* (1998) defined two main groups: a) the alkali-calcic to alkalic granitoid associations, characterised by biotite-plagioclase fractionation and moderate LILE-HFSE (high field strength element)-enrichment, and b) the alkali-granitoid association, characterised by amphibole-alkali feldspar fractionation. This definition corresponds better with the 1.65-1.50 Ga suite of rapakivi granite complexes of the Fennoscandian Shield, traditionally referred to as anorogenic (cf. e.g. Eklund 1993, Ahl *et al.* 1997, Andersson 1997a, Andersson *et al.* 2002, Rämö & Haapala 2005; Fig. 1). An enriched magma source is also characteristic for the post-orogenic magmatism according to Bonin *et al.* (1998) and Bonin (2004). However, the differences observed between the post-collisional Mg-K and high-K calc-alkaline suites and the post-orogenic alkaline suites correspond to source variation, and only to a minor extent to differentiation processes (Liégeois *et al.* 1998, Bonin 2004).

The more strictly *anorogenic* rocks have no obvious relationships to an orogen, and they are characteristically more alkaline than rocks related to orogenic belts with high HFSE and REE (rare earth element) (e.g. Bonin 1990, Pitcher 1993), but also less alkaline, even tholeiitic, mafic anorogenic rocks occur (e.g. Best & Christiansen 2001). Examples of strictly anorogenic rocks in the Fennoscandian Shield are Phanerozoic alkaline/carbonatitic complexes, such as e.g. Fen, Alnö, Sokli, Iivaara, Lovozero and Khibina, as well as kimberlites in Finland and NW Russia (e.g. Andersen & Taylor 1988, Lundqvist *et al.* 1990, Trønnes & Brandon 1992, Downes *et al.* 2005, O'Brien *et al.* 2005).

SCOPE OF STUDY

The present work has concentrated on two areas of c. 1.8 Ga old rocks in the Fennoscandian Shield (Fig. 1); 1) the southern part of the TIB (Patchett *et al.* 1987) in Sweden in the west (Papers II and III), and 2) intrusions with rocks assigned to the 'group 3' granites by Sederholm (1932, 1934) in southern Finland and Russian Karelia in the east (Papers I and IV). These units have traditionally been interpreted as post-orogenic, because they mostly show no signs of deformation (Lundquist 1979, Simonen 1980, Nyström 1982, and e.g. Andersson *et al.* 2004a). This is, however, strictly not true due to the presence of penetrative synkinematic structures in some older TIB rocks (e.g. Wikström 1991). Additionally, the western part of the TIB has undergone an extensive post-1.7 Ga, penetrative polydeformational history (e.g. Lindh & Gorbatschev 1984, Wahlgren *et al.* 1994, Gorbatschev & Bogdanova 2006). The non-genetic label *post-kinematic* is assigned to the studied 'group 3' intrusions in southern Finland in Paper IV, to emphasize that they have intruded essentially after the end of the Svecofennian *penetrative* deformation, though signs of magmatic, syntectonic foliation is present in a few of the intrusions in the west (Väisänen *et al.* 2000). The aim of the work was to decipher the origin and evolution of the magmas and to deduce a plate-tectonic environment for the studied plutonic rocks, based on whole-rock and isotope geochemistry.

FENNOSCANDIAN FRAMEWORK

The Fennoscandian Shield (Fig. 1) in northern Europe comprises the exposed NW part of the Palaeo-Mesoproterozoic East European Craton stretching from northernmost Europe to the Black Sea and from the Carpathians in the west to the Urals in the east (cf. Fig. 5 below; e.g. Bogdanova *et al.* 2006 and refs therein). Fennoscandia is covered in its NW by the Phanerozoic Caledonides, and in the SE by platform sediments of mainly the same eon, like almost entirely both the other craton segments, Volgo-Uralia in the east and Sarmatia in the southeast. At 2.1-2.0 Ga the latter two were amalgamated with each other (e.g. Bogdanova 2005), and at c. 1.84 Ga the combined Volgo-Sarmatia collided with the Fennoscandian crustal segment, building the eventual East European Craton (Lahtinen *et al.* 2005).

The Fennoscandian Shield itself was initiated when >2.5 Ga old Archaean rocks formed a cratonic nucleus in the present NE Finland and NW Russia (Fig. 1). 2.45-2.0 Ga ago the craton was subjected to rifting in its interior and along the margins (e.g. Park *et al.* 1984, Gaál & Gorbatschev 1987, Huhma *et al.* 1990, Peltonen *et al.* 1996). Partly overlapping with this period of divergence, at 2.1-1.93 Ga, juvenile crust was generated southwest of the craton in several distinct arc systems with intervening basins. Only some remnants of these rocks have been identified in outcrop (e.g. Skiöld *et al.* 1993, Wasström 1993, 1996, Lundqvist *et al.* 1998, Vaasjoki *et al.* 2003, Skiöld & Rutland 2006), but they are abundantly documented in detrital zircon populations (Huhma *et al.* 1991, Claesson *et al.* 1993, Lahtinen *et al.* 2002, 2010, Andersson *et al.* 2004a, 2006b, Rutland *et al.* 2004, Sultan *et al.* 2005, Bergman *et al.* 2008). This earliest phase of crust formation in the Svecofennian Domain resulted in several juvenile microcontinents (Lahtinen *et* *al.* 2005), some of which contain unexposed Archaean basement (Andersson *et al.* 2002). During the main period of the Svecofennian orogeny, at 1.91-1.86 Ga, the earliest Svecofennian crust was reworked and the major part of the juvenile Svecofennia was created and accreted to the Archaean nucleus, forming what now is the Svecofennian Domain (e.g. Gaál & Gorbatschev 1987, Baker *et al.* 1988, Gaál 1990, Nironen 1997, Korja & Heikkinen 2008, and refs therein). In the present central and southern Finland the Primitive Arc Complex (PAC; Korsman *et al.* 1997, Väisänen 2002; Fig. 1) accreted at first, at 1.91-1.90 Ga, to the Archaean craton (e.g. Korsman *et al.* 1999). At c. 1.89-1.88 Ga the Central Svecofennian Arc Complex (CSAC; Korsman *et al.* 1997, Väisänen *et al.* 2002) collided from the southwest/west with the PAC (Lahtinen 1994) and immediately following, at c. 1.87 Ga, this newly welded package experienced a collision from the south by the Southern Svecofennian Arc Complex (SSAC; e.g. Korsman *et al.* 1997, Väisänen *et al.* 2002, Ehlers *et al.* 2004). The southern Svecofennian province in south-central Sweden, i.e. the Bergslagen area, forms the western extension of the SSAC with lithologic, age-related, tectonic and shear zone orientation similarities (e.g. Lahtinen *et al.* 2005, Paper III). The magmatism in the Fennoscandian crustal segment that occurred south of the actual Shield, in areas presently covered by Phanerozoic sediments (c. 100 m - >10 km thick), i.e. the Baltic states, western Russia, NE half of Poland and NW Belarus, was mainly also of island arc type. This part consists of several amalgamated, mostly SSW-NNE trending, 2.0-1.82 Ga arcs that have predominantly been metamorphosed to amphibolite and granulite facies prior to or during the north- or NW-directed convergence (e.g. Bogdanova *et al.* 2006, Paper III).

After a debated (e.g. by Cagnard *et al.* 2007) intervening period of extension at 1.86-1.84 Ga (Lahtinen *et al.* 2002, Korja *et al.* 2006) convergence resulted in the accretion and collision from the south(east) by the possibly simultaneously rotating Volgo-Sarmatian crustal segment (Pesonen *et al.* 2003, Bogdanova 2005, Bogdanova *et al.* 2008) at 1.84-1.79 Ga (e.g. Lahtinen 1994, Lahtinen *et al.* 2005, Väisänen & Skyttä 2007). This was accompanied by episodes of high-T and low-P metamorphism, crustal remelting in the Svecofennian Domain, and late-orogenic Svecofennian magmatic activity. Migmatites and mostly relatively small granitic intrusions, mainly of S-type, but also less abundantly I-type granitoids were produced, and the activity lasted until c. 1.75 Ga in Sweden (e.g. Huhma 1986, Andersson 1991, Suominen 1991, van Duin 1992, Ehlers *et al.* 1993, Claesson & Lundqvist 1995, Romer & Öhlander 1995, Öhlander & Romer 1996, Andersson & Öhlander 2004, Kurhila *et al.* 2005). Simultaneously in the west, continued east to NE directed subduction along the Fennoscandian continental margin marked the inception of the magmatism in the TIB (e.g. Högdahl *et al.* 2004).

Post-accretional magmatism commenced in the earliest phases of the TIB at the southern border zone of the Bergslagen area in southern Sweden around 1.85 Ga (TIB-0; Ahl *et al.* 2001). During the voluminous TIB-1 magmatic episode, at 1.81-1.75 Ga, the magmatism developed into an extensive reworking of the newly formed Svecofennian crust along its western continental margin (Fig. 1; e.g. Andersson *et al.* 2004b, Papers II and III). Simultaneously (1815-1760 Ma), small post-collisional intrusions, often shoshonitic in character, penetrated the crust further inward the continent in southern Finland and Russian Karelia (cf. Väisänen *et al.* 2000, Andersson *et al.* 2006a, Papers I and IV). Thus, the magmatism at 1.82-1.75 Ga developed during the waning stages of NW-SE-oriented oblique continent-continent collision in the east, and NNE- and E-directed continental margin subduction in the west (Papers II, III, and IV). During this time c. N-S shortening and NW-SE dextral transpression is typical in the south-central Svecofennian Domain (e.g. Sjöström & Bergman 1998, Högdahl & Sjöström 2001, Väisänen & Skyttä 2007).

Westwards, in Sweden and Norway, Fennoscandia continued to grow in the interval 1.7-1.55 Ga (Gothian orogeny; e.g. Gaál & Gorbatschev 1987). Major orogenic activity in the Shield ended with the Sveconorwegian orogeny (1.2-0.9 Ga; e.g. Lindh 1987, Åhäll & Gower 1997, Bingen *et al.* 2005). Within the Svecofennian Domain the crust was partly re-organised also during the extension-related anorogenic rapakivi granite and related magmatism at 1.65-1.47 Ga (Fig. 1; e.g. Rämö & Haapala 1995, Andersson 1997a, 2001) and the alkali-rich granitoid plutonism in southernmost Fennoscandia at c. 1.45 Ga (Fig. 1 in Paper II; e.g. Åberg 1988, Čečys *et al.* 2002, Brander & Söderlund 2009).

THE INCLUDED STUDIES

The papers of this thesis are essentially concerned with the origins of the c. 1.82-1.75 Ga magmatism in the southern Fennoscandian Shield, with the main emphasis on mafic plutonism and its mantle source/s. Papers II and III addresses the sources and settings mainly of 1.80-1.78 Ga mafic plutonic TIB rocks in SE Sweden and south-central Sweden, respectively. Paper I discusses the character and origin of c. 1.8 Ga shoshonitic post-collisional magmatism in southern Finland and Russian Karelia, while Paper IV deals further with the c. 1.8 Ga post-collisional mafic and felsic rocks in southern Finland.

Southern Småland-Värmland Belt and Tving suite of Blekinge (Paper II)

Geochemistry and Sr-Nd isotope geochemistry of 1.81-1.75 Ga (TIB-1), undeformed, mafic intrusions were studied throughout the southernmost part of TIB in southeastern Sweden (southern Småland-Värmland Belt, SVB, and Tving suite of Blekinge, TSB; Fig. 1 in Paper II). The aims were to characterise the mantle sources from which the mafic TIB-1 magmas were extracted, the extent of crustal interaction, and to derive clues for interpretation of the plate tectonic environment.

94 samples were collected from 50 intrusions, and after field and microscopic studies 42 samples were analysed for geochemistry. 15 of these were selected for Sr and Nd isotopic analysis, based on geographical and geochemical diversity. None of the investigated intrusions have been dated, but because contact relations to the surrounding granitoids often show magma mingling-mixing relations, and there are frequent occurrences of mafic enclaves and synplutonic mafic dykes within the granitoids of this area, the mafic intrusions are considered coeval with the granitoids, with ages of c. 1.80 Ga.

Compositions vary from peridotitic to monzogabbroic. The SiO_2 contents of the intrusions vary between 39 and 54 wt%, and Mg# (magnesium number) between 81 and 45, indicating considerable variation in evolutionary level. Ultrabasic rocks may be cumulate-enriched; some rocks are enriched in plagioclase, while some of the most evolved rocks tend to be enriched in Fe, Ti and P. The signatures are predominantly calc-alkaline, LILE-LREE (light rare earth element)-enriched and HFSE-depleted, of continental arc type in the north, grading to slightly less enriched, oceanic affinities southwards. The ε_{Nd}(1.80 Ga) values range from +2.0 to +0.7 and $^{87}Sr/^{86}Sr$(1.80 Ga) from 0.7022 to 0.7029 (with one outlier at -0.03 and 0.7033), without correlation to fractionation (e.g. Mg#) or crustal contamination, indicating sources that are ”mildly depleted”. The most depleted ratios occur in the south, trending with the geochemistry toward more enriched compositions northward. As none of the samples had more depleted compositions, and published ε_{Nd}(1.80 Ga) values above +2 are rare for mafic rocks in the southern TIB (ε_{Nd} for depleted mantle, DM, at 1.80 Ga = +3.9; after DePaolo 1981), such isotopically ”mildly depleted” mantle sources seem to be characteristic for the whole area. The spread towards slightly more enriched isotopic compositions, irrespective of chemical evolution, may be due to variations in the mantle source itself or slight local crustal contamination. It is important to note, however, that one reason for the limited isotopic range may be the rather juvenile nature of the associated crust; ε_{Nd}(t) values below -1.7 are unknown for the southern TIB. Hence, no Archaean components appear to be present in this part of the Fennoscandian Shield.

In conclusion, the mafic plutonic TIB-1 rocks in southern Sweden are characterised by LILE-LREE-enriched signatures with subduction-type, mainly calc-alkaline geochemistries, and were generated from isotopically ”mildly depleted” mantle sources in a continental arc environment. These sources are inferred to represent depleted mantle wedge material that was subjected to enrichment not long before (model age for depleted mantle, T_{DM}, c. 2.0 Ga), i.e., during subduction associated with the preceding arc accretion (2.1-1.82 Ga), and/or during the TIB-1 magmatism itself, by hydrous fluids with a sediment and/or melt input increasing northward. The TIB-1 magmatism occurred [above a south(west)wards-retreating subduction zone] along the continental margin of the juvenile Svecofennian continent at 1.81-1.75 Ga.

Southern Dala Province, northern Småland-Värmland Belt and middle-Svecofennian Hedesunda complex (Paper III)

Geochemistry and isotope geochemistry of c. 1.79-1.78 Ga, undeformed mafic intrusions of TIB-1 in the Fennoscandian Shield have been studied throughout its central part in south-central Sweden (southern Dala Province and northern Småland-Värmland Belt, SVB). In addition, the c. 150 kilometres eastward situated mafic end-members of the 1.87 Ga Svecofennian Hedesunda intrusive complex were examined (Fig. 1 in Paper III). The aims were to characterise the mantle sources from which the mafic magmas were extracted, determine the extent of crustal interaction, and to derive clues for interpretation of the plate tectonic environment.

36 samples were collected from 24 intrusions, and after field and microscopic studies 17 samples were analysed for geochemistry. 10 of these were selected for Sr and Nd isotopic analysis, based on geographical and geochemical diversity. None of the investigated intrusions have been dated, but because contact relations to the surrounding granitoids often show magma mingling-mixing relations, and there are frequent occurrences of mafic enclaves and synplutonic mafic dykes within the granitoids of this area, the mafic intrusions are considered coeval with the granitoids, with ages of c. 1.79 Ga for the Järna suite and the Säfsnäs area, 1.78 Ga for the Filipstad area, and 1.87 Ga for the Hedesunda complex.

Rock types vary mostly from gabbros and norites to quartz diorites. One monzodiorite with a SiO_2 contents just below 60 wt% was analysed. For the rest of the intrusions the SiO_2 contents vary between 43 and 55 wt%, and the Mg# between 76 and 49, indicating some variation in evolutionary level. Some rocks are cumulus-enriched, e.g. in plagioclase, clinopyroxene, Fe-Ti oxides and apatite. The signatures are from calc-alkaline to shoshonitic, LILE-LREE-enriched and HFSE-depleted, of continental arc type, with subordinate oceanic tendencies for the Hedesunda rocks. The $\varepsilon_{Nd}(t)$ values are mostly between +1.0 and +2.1, and $^{87}Sr/^{86}Sr(t)$ values range mainly between 0.7020 and 0.7028. One outlier has $\varepsilon_{Nd}(t)$ of +2.7, while another has $^{87}Sr/^{86}Sr(t)$ of 0.7038. There is no systematic correlation between chemical parameters and isotope ratios. As all samples, except one, have $\varepsilon_{Nd}(t)$ values $\leq$+2.1, and published $\varepsilon_{Nd}(t)$ values above +2 are rare for mafic rocks in the south-central TIB (ε_{Nd} for DM at 1.80 Ga = +3.9; after DePaolo 1981), an isotopically ”mildly depleted” mantle source [$\varepsilon_{Nd}(t)$ c. +1 to +2] seems to be characteristic for mafic plutonic TIB rocks in south-central Sweden, as well as for the 1.87 Ga Hedesunda complex. A trend of isotopic overlap with the c. 1.7 Ga basic Dala lavas of TIB, which show slightly elevated $^{87}Sr/^{86}Sr(t)$ values, is discerned for the Järna rocks. One reason for the limited isotopic range may be the rather juvenile nature of the associated crust; negative $\varepsilon_{Nd}(t)$ values are unknown for felsic rocks in the south-central TIB. Hence, no Archaean components have been detected in TIB rocks of this area.

In conclusion, the mafic TIB-1 and middle Svecofennian Hedesunda rocks in south-central Sweden are characterised by LILE-LREE-enriched and HFSE-depleted, subduction-type, from calc-alkaline to shoshonitic geochemistries. They were generated from isotopically ”mildly depleted” mantle sources in a primarily continental arc environment. The sources are inferred to represent depleted mantle wedge material that was subjected to variable fluid-induced enrichment not long before (T_{DM} c. 2.0 Ga), i.e. during the preceding Svecofennian subduction and arc accretion (2.1-1.87 Ga), and/or during the TIB magmatism (1.85-1.78 Ga) itself. The TIB-1 magmatism took place in connection with the southern end of a subduction zone, dipping eastwards below the N-S running western continental margin of the juvenile Svecofennian continent at 1.79-1.78 Ga. The c. 1.87 Ga mafic Hedesunda rocks show a slightly less enriched (‘oceanic’) composition and appear to have been emplaced in a continental back-arc environment during N-S convergence at 1.87 Ga. The emplacement of the Hedesunda complex may have been facilitated by the E-W oriented major shear zones present in the area.

1.8 Ga post-collisional intrusions in southern Finland and Russian Karelia (Papers I and IV)

Approximately twenty relatively small (1-15 km across) c. 1815-1760 Ma Svecofennian post-collisional, undeformed, uni-, bi- or polymodal intrusions occur in a 600 km long belt within the c. 1.90-1.86 Ga SSAC and the southwestern Archaean Karelian Domain covered by c. 2.06-1.97 Ga supracrustal rocks, from the Åland Islands in SW Finland to the region northwest of Lake Ladoga in Russian Karelia (Fig. 1 in Papers I and IV).

Both Paper I and IV report on these intrusions. Paper I gave for the first time an overview of the whole 1.8 Ga post-collisional magmatism in southern Finland and Russian Karelia. Emphasis was put on the Lemland and Åva intrusions in SW Finland, the Luonteri intrusion in SE Finland, as well as the two Elisenvaara intrusions and the Kalto lamprophyre dyke swarm in Russian Karelia. The discussion centers around geochemistry, mineralogy, volatiles, differentiation and source character. Paper IV complements this research by studying the post-collisional intrusions at Turku, Renko, Parkkila, Luonteri, Pirilä, and Petravaara, scattered throughout the southern mainland of Finland. The purpose was to apply whole-rock geochemistry and more comprehensive isotope geochemistry studies to be able to identify various crustal and mantle source components, the extent of their respective contribution to these diverse magma types, and to derive clues for interpretation of the tectonic setting in which the magmas were produced.

Paper I

The Svecofennian 1.8 Ga post-collisional rocks in southern Finland and Russian Karelia range from ultramafic, calc-alkaline, apatite-rich potassium lamprophyres to peraluminous HiBaSr granites, and form a shoshonitic series with $K_2O+Na_2O > 5$ wt%, $K_2O/Na_2O > 0.5$ and $Al_2O_3 > 9$ wt% over a wide spectrum of SiO_2 (32-78 wt%). Although strongly enriched in all rocks, the LILEs Ba and Sr and the LREEs generally define a decreasing trend with increasing SiO_2. Depletion is noted for HFSEs Ti, Nb and Ta. Available isotopic data show overlapping values for lamprophyres and granites within separate intrusions and a co-genetic origin is thus not precluded.

Initial magmas (Mg# > 65) in the recognised shoshonitic association are considered to be generated in an enriched lithospheric mantle during post-collisional uplift some 30 Ma after the regional Svecofennian metamorphic peak. However, prior to the melting episode, the lithospheric mantle was affected by carbonatite metasomatism; more extensively in the Russian Karelia than in the west. The melts generated in the more carbonate-rich mantle were extremely enriched in P_2O_5 (c. 4 wt%) and F (c. 12000 ppm), in LILEs, with Ba on c. 9000 ppm and Sr on c. 7000 ppm, as well as in LREEs, with La on c. 600 ppm and Ce on c. 1000 ppm.

The parental magma was fractionated by 55-60 wt% of biotite+clinopyroxene+ apatite+magnetite+titanite, according to calculations on Elisenvaara rocks, whereupon intermediate varieties were produced. After further fractionation, 60-80 wt%, of K-feldspar+amphibole+plagioclase±(minor magnetite, titanite and apatite), leucosyenites and quartz-monzonites were formed. In the west, where the source was less affected by carbonatite metasomatism, calc-alkaline lamprophyres (vogesites, minettes and spessartites) and equivalent plutonic rocks (monzonites) were formed. By removal of about 50 wt% of the magma as biotite, amphibole, plagioclase, magnetite, apatite and titanite it is possible to produce the magma of peraluminous HiBaSr granites, according to calculations for Lemland rocks. The impact of crustal assimilation was considered to be low.

As a result, at c. 1.8 Ga the post-collisional shoshonitic magmatism brought juvenile material, particularly enriched in alkalis, LILE, LREE and F, into the Svecofennian crust. Although areally restricted (Figs. 1 and 5), the regional distribution of the post-collisional intrusions may indicate that larger volumes of 1.8 Ga juvenile material resides in unexposed parts of the crust.

Paper IV

Voluminous magmas were emplaced at c. 1.8 Ga in the Fennoscandian Shield, within the >1500 km long TIB in the west and the Central Lapland Granitoid Complex in the north, as well as smaller intrusions within the southern Svecofennian Domain (Fig. 1). In southern Finland and Russian Karelia a number of minor, essentially post-kinematic plutons of variable composition have intruded the 1.95-1.82 Ga Svecofennian crust. Paper IV concentrated on six of these: the 1815-1794 Ma old (Simonen 1982, Korsman *et al.* 1984, Vaasjoki & Sakko 1988, Vaasjoki 1995, Väisänen *et al.* 2000) Turku, Renko, Parkkila, Luonteri, Pirilä and Petravaara intrusions (Fig. 1). The U-Pb zircon SIMS age was determined for Petravaara to 1811 ± 6 Ma (MSWD = 1.4).

Basic-intermediate rocks of the Luonteri and Parkkila intrusions are alkali-calcic, shoshonitic, monzonitoid rocks, while those from the Turku and Renko intrusions show a trend from alkalic/shoshonitic to (high-K) calc-alkaline. The granitoid rocks tend to be calc-alkaline, metaluminous to marginally peraluminous of volcanic-arc type in Luonteri and Petravaara, while those at Turku, Renko, and Pirilä tend to be more alkali-rich, peraluminous, and transitional into the syn-collisional field. The latter group is geochemically similar to the late Svecofennian (1.85-1.81 Ga) migmatite-related granites in the same area.

The basic-intermediate rocks are strongly LILE- and LREE-enriched, depleted in HREE (heavy rare earth element), and with significant negative Nb-Ta-anomalies. They almost exclusively fall within volcanic-arc basalt fields of basalt discrimination diagrams, away from MORB (mid-ocean ridge basalt) and OIB (ocean island basalt) (with a few Turku rocks trending towards OIB composition), at compositions considerably more enriched than both crust and andesitic arcs. Their compositions are essentially unrelated to contamination in the crust, by being geochemically separate from all types of compositions in the Svecofennian upper crust.

The isotopic data for the basic-intermediate rocks fall within the narrow ranges of $\varepsilon_{Nd}(t)$ 0 to +1 and $^{87}Sr/^{86}Sr(t)$ 0.7027 to 0.7033, except the Renko monzodiorite that is slightly more depleted (+1.4 and 0.7019, respectively), i.e. mildly depleted to undepleted (T_{DM} <2.1 Ga) and overlapping with data from other c. 1.8 Ga post-kinematic rocks in southern Finland (Patchett & Kouvo 1986, Lahtinen & Huhma 1997, Nironen & Rämö 2005, Rämö *et al.* 2005, Andersson *et al.* 2006a, Torppa & Karhu 2007, Woodard *et al.* 2008, Woodard & Huhma, in review). The south Finland data overlap the least depleted compositions of the coeval mafic TIB rocks, but are generally more enriched than the 'mildly depleted mantle' identified for TIB [$\varepsilon_{Nd}(t)$ +1 to +2 and $^{87}Sr/^{86}Sr(t)$ 0.7022 to 0.7028; e.g. Papers II and III]. The peraluminous Turku and Renko granites, associated with the monzodiorites, yielded elevated $^{87}Sr/^{86}Sr(t)$ values (0.7048 and 0.7062), at similar $\varepsilon_{Nd}(t)$ (-0.1 and +0.6), thus isotopically overlapping with early Svecofennian metaigneous crust. The Pirilä granite has disturbed Rb-Sr system with an unrealistically low $^{87}Sr/^{86}Sr(t)$. In contrast, the Petravaara granite in the east shows a distinctly lower $\varepsilon_{Nd}(t)$ of -2.8, at a relatively low $^{87}Sr/^{86}Sr(t)$ of 0.7033, indicating the involvement of an Archaean, probably lower crustal source component. Initial Hf isotopic data, recovered from the SIMS-dated zircons, spread in between ‘mildly depleted’ and Archaean compositions, supporting a mixed mantle and crustal origin with a significant Archaean component.

The low, MORB-like HREE contents and positive $\varepsilon_{Nd}(t)$ values, combined with strongly elevated LILE and LREE abundances of the basic intermediate rocks, suggest depleted mantle sources subsequently subjected to pervasive metasomatic enrichment. The metasomatic agents were dominated by carbonates and sediment-derived melts, rather than H_2O-dominated fluids as was the case for TIB in the west. The trace element data suggest that the Turku and Renko magmas were slightly more influenced by carbonate metasomatism, compared with those at Luonteri and Parkkila that show a stronger sedimentary influence. The mantle enrichment process took place mainly during the

Svecofennian subduction-related orogeny, not earlier than 2.1 Ga as indicated by the T_{DM} ages.

The geochemistry and relatively high $\varepsilon_{Nd}(t)$, combined with elevated $^{87}Sr/^{86}Sr(t)$, of the peraluminous Turku and Renko granites are consistent with a derivation from juvenile, Rb-rich, early Svecofennian metasedimentary and/or metaigneous rocks as by-products of the post-tectonic shoshonitic magmatism. The calc-alkaline granitic rocks at Luonteri and the Pirilä granite derive from the metaigneous crust, while Luonteri rocks at SiO_2 contents <70 wt% carry a component of mixing with the enriched mafic magmas. Mixing between crustal and mantle magmas is also proposed for rocks in the range 50-70 wt% SiO_2 in the Turku complex. Apart from the Petravaara intrusion in the east, no pre-Svecofennian crustal components have been identified in these intrusions.

Summary of Papers I and IV

In Papers I and IV studied minor, essentially post-kinematic, 1815-1760 Ma plutons, were emplaced within the crust of the SSAC and the southwestern Karelian Domain immediately following regional metamorphism and anatexis at c. 1.85-1.81 Ga. The regional metamorphism has been related to a collision with the Volgo-Sarmatian continent in the SE at that time, and these intrusions may thus be labelled post-collisional in relation to that orogeny. This is corroborated by their shoshonitic composition, typical for post-collisional settings. The emplacement of the intrusions may have been facilitated by crustal scale shear zones that were active during the post-collisional shift from compression to extension. Slab break-off and mantle upwelling after collision is a viable process to generate melting in the enriched sub-Svecofennian mantle at 1.8 Ga, and may account for a 'hint' of OIB chemistry in the Turku complex. Simultaneously, NNE- and E-directed subduction was active along the continental margin in the west (see below in Fig. 5), tapping less enriched mantle sources and creating the TIB. However, at present, the implication of this complicated tectonic configuration for the post-collisional magmatism in southern Finland and Russian Karelia is not totally resolved.

SUMMARY OF CONCLUSIONS

Circa 1.8 Ga old rocks in the southern Fennoscandian Shield include the extensive TIB in south-central and southeastern Sweden with numerous mafic plutonic bodies, as well as mostly bimodal, relatively small (a few kilometres wide), essentially post-kinematic intrusions or dykes in the SSAC and the southwestern Karelian Domain in southern Finland and Russian Karelia. The geochemistry and origin of these rock types have been the focus of interest in this thesis.

Geochemistry of mafic 1.8 Ga TIB magmatism

The TIB r~~ocks studied range from ultramafic to~~ leucodioritic, and are calc-alkaline, high-K calc-alkaline to marginally shoshonitic in geochemistry, with the mafites in southern TIB slightly less enriched. The trace and rare earth elements for all the mafic TIB rocks indicate volcanic-arc type magmatism, mostly in an active continental margin, but especially the rocks in the southern TIB stretching to oceanic arc signatures. Multielement diagrams demonstrate the typical pattern of arc magmatism, with depletion of HFSE and enrichment of LILE and LREE, with relative troughs for Nb-Ta (Fig. 2). The Svecofennian 1.87 Ga mafic Hedesunda rocks of northern Bergslagen, included for comparison, overlap the TIB rocks compositionally, indicating a slightly less enriched continental-arc setting.

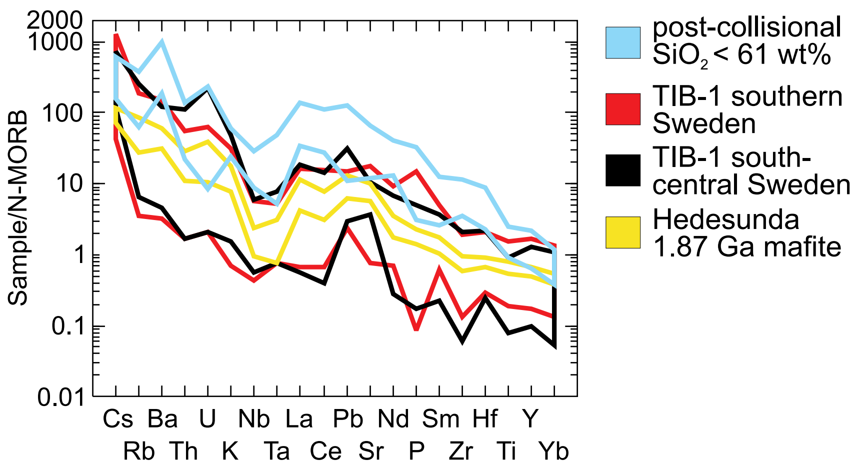

Fig. 2. N-MORB normalised multielement diagram for comparison of the geochemical signatures of the rock suites included in the present work. The geochemical data from Papers II-IV. Normalisation after Sun & McDonough (1989).

Sm-Nd and Rb-Sr isotopic data of the mafic TIB and Hedesunda rocks yielded dominantly $\varepsilon_{Nd}(t)$ values intermediate between the depleted mantle and CHUR, in the range +1 - +2, and initial $^{87}Sr/^{86}Sr$ values just above UR, at 0.7020-0.7029. This corroborates previous data on mafic TIB rocks (Wilson *et al.* 1986, Andersson 1997b, Claeson & Andersson 2000; Fig. 3), and demonstrates the presence of relatively widespread “mildly depleted” mantle sections in the area of the present southern Fennoscandian Shield at 1.8 Ga. In southeasternmost Sweden, depletion increases somewhat going southwards towards Blekinge, and the Järna rocks in Dalarna show minor enrichment in initial $^{87}Sr/^{86}Sr$ at comparable $\varepsilon_{Nd}(t)$, similarly to the nearby 1.7 Ga TIB-2 Dala basalts (Nyström 1999; Fig. 16 in Paper III), indicating some slight variation within the lithospheric mantle in the north.

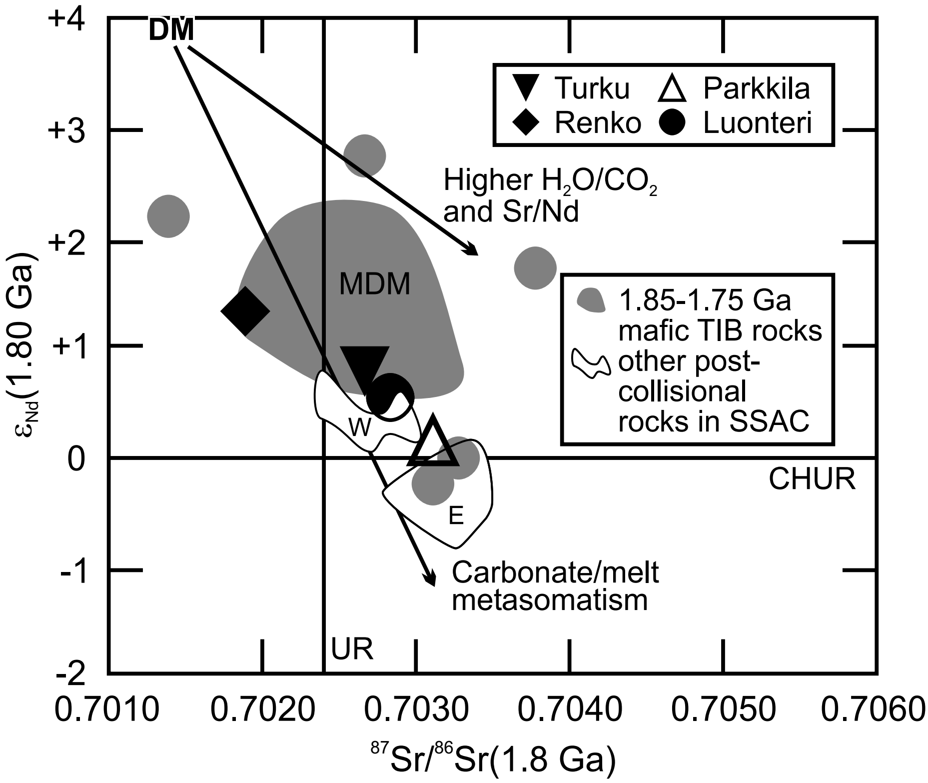

Fig. 3. $\varepsilon_{Nd}(t)$-$^{87}Sr/^{86}Sr(t)$ diagram. All values recalculated to 1.80 Ga. CHUR = chondritic uniform reservoir. DM (depleted mantle) has ε_{Nd}(1.80 Ga) of +3.9 (DePaolo 1981) and $^{87}Sr/^{86}Sr$(1.80 Ga) of 0.7014 (Taylor & McLennan 1985), and UR (uniform reservoir) has $^{87}Sr/^{86}Sr$(1.80 Ga) of 0.7024 (McCulloch & Chappell 1982, Faure 2001). The analyses of the mafic 1.8 Ga post-collisional rocks reported in Paper IV are plotted separately. Elsewhere reported 1.8 Ga post-collisional rocks from the SSAC are subdivided into rocks from the westernmost SSAC (W) and from the Russian Karelia in the eastern SSAC (E). The 1.85-1.75 Ga mafic TIB rocks define a field with the isotopic composition of a ‘mildly depleted mantle’ (MDM). Data sources: Papers II, III, IV, Wilson *et al.* (1986), Andersson (1997b), Kononova *et al.* (1999, 2000), Claeson & Andersson (2000), Andersson *et al.* (2006a), and Woodard & Huhma (in review).

Geochemistry of mafic 1.8 Ga magmatism in southern Finland

These post-kinematic intrusions are often bi- or even polymodal, consisting of ultramafites to quartz diorites and granites, but also intermediate rocks from quartz monzodiorites to tonalites and granodiorites occur. Except for a few rocks from Turku, which are calc-alkaline, the basic-intermediate rocks of the studied intrusions are distinctly shoshonitic in composition, a feature typically expected for post-collisional rocks. They are accordingly significantly more enriched in essentially all trace elements, compared with the TIB rocks (Fig. 2). Additionally, the mafic c. 1.8 Ga rocks of southern Finland are mostly more enriched in unradiogenic Nd than the TIB and Hedesunda rocks further west, falling in the range 0 to +1 (with one exception at +1.4). The initial $^{87}Sr/^{86}Sr$ ratios, at 0.7019-0.7031, overlap those of the TIB (Fig. 3).

Mantle sources for the mafic magmatism

The geochemistry demonstrate that the mantle sources for the mafic TIB magmas were pronouncedly enriched in LILE and LREE, but with only small enrichment or depletion in HFSE, and normally significant depletion in the HREE. Going eastwards, enrichments increase for essentially all trace elements, except the HREE, such that the coeval rocks in southern Finland are strongly enriched, while those in Russian Karelia are extremely enriched. In addition to metasomatic enrichment, the very strong enrichment may partly give evidence for low melt fractions in the east, much lower than in the TIB. In spite of this, all the mafic rocks preserve a common arc geochemical pattern, with strong depletion in the HREE, even more depleted than MORB (Fig. 2). This geochemistry strongly suggests mantle sources for the basic magmas that were depleted prior to metasomatic enrichment in LILE and LREE imposed by fluids/melts released from a subducted slab.

Irrespective of composition, essentially all mafic TIB-1 samples fall within the “mildly depleted” initial ε_{Nd} range +1 to +2, while the coeval rocks in southern Finland are usually somewhat more enriched, between 0 and +1. These isotopic data show that the mantle sources of the mafic rocks were either: i) originally only mildly depleted, or ii) originally more depleted and become enriched at some later stage by the addition of crustal material in some form. However, chemical parameters, such as SiO_2 or Mg#, do not vary systematically with the isotopic ratios (see Figures in the Papers), refuting a major role for contamination in the crust of the basic magmas. Thus, in combination with the geochemical evidence for strong LILE and LREE enrichment of depleted sources, the isotopic data favour an enrichment of the mantle sources through subduction zone fluids or melts, rather than contamination from crustal material.

In southern TIB a geographical variation in the isotopic data was detected, with the highest initial ε_{Nd} and lowest initial $^{87}Sr/^{86}Sr$ for the rocks in the south and lower initial ε_{Nd} and higher initial $^{87}Sr/^{86}Sr$ north of the Oskarshamn-Jönköping Belt (OJB; seen e.g. below in Fig. 5), i.e., a co-variation with increasing continental geochemical affinities and less depleted isotopic values northward. The data indicate that mantle sources for the basic intrusions on the southern side of the OJB are isotopically more depleted and trending towards oceanic arc geochemistry, while their counterparts on the northern side are more enriched and continental arc in character. Similarly, the mafic TIB-1 rocks from south-central Sweden show continental arc signatures, with subordinate less enriched oceanic tendencies only for the Svecofennian mafic 1.87 Ga Hedesunda rocks. Some rocks of the Järna suite show some isotopic variance with slightly elevated initial $^{87}Sr/^{86}Sr$ ratios, overlapping with data from 1.7 Ga TIB-2 Dala mafic volcanic rocks from the same region (Nyström 1999). This could reveal a tendency for higher Sr/Nd and H_2O/CO_2 ratios in the metasomatising fluids in the mantle sources of the Dala region, compared with other TIB areas, and particularly those of 1.8 Ga post-collisional mafic rocks further east (Fig. 3; cf. Fig. 16 in Paper III and Fig. 15 in Paper IV).

The eastwards increasing LILE and LREE enrichment was caused by fluids/melts carrying increasing amounts of partly older crustal components into the mantle source regions where the 1.8 Ga magmas were subsequently generated. A variable extent of carbonate metasomatism of the mantle may explain the geochemical differences along the 600 km long belt of c. 1.8 Ga intrusions, such that the rocks situated in Russian Karelia in the east, were most strongly affected by CO_2 metasomatism, as well as F-rich fluids, compared with rocks further west (Fig. 4). Carbon in the mantle sources is supported by the presence of carbonates with mantle isotope characteristics in coeval lamprophyres (Andersson *et al.* 2006a, Woodard & Huhma, in review) and carbonatites (Puustinen & Karhu 1999, Torppa & Karhu 2007, Woodard *et al.* 2008, Woodard & Huhma, in review). Trace element ratios show that the sources of the TIB rocks are little affected by carbonate metasomatism or melts, compared with their contemporaneous eastern counterparts. The metasomatising agents in the west thus had higher H_2O/CO_2 ratios. Increasing carbonate metasomatism co-varies with increasing sedimentary (melt) components in the magmas eastwards (Fig. 4). However, local variations in the type of source enrichment can be noted between the individual plutons. The Turku and Renko plutons have experienced relatively higher input of carbonate and H_2O fluids, as indicated by trace element ratios, while the Parkkila and

Luonteri plutons have experienced a higher input of a bulk sedimentary component (Fig. 4). The metasomatism of the mantle sources have affected the isotopic data such that more radiogenic Sr and low-radiogenic Nd was added to the mantle by the carbonic melts when advancing eastward, shifting the initial ratios increasingly down to the right in the initial ε_{Nd} vs. $^{87}Sr/^{86}Sr$ diagram (Fig. 3). The higher H_2O/CO_2 ratios of the metasomatising agents for the TIB sources in the west translates to higher Sr/Nd ratios, and higher $^{87}Sr/^{86}Sr$ ratios at comparable ε_{Nd} for many TIB rocks, compared to the rocks in the east (Fig. 3).

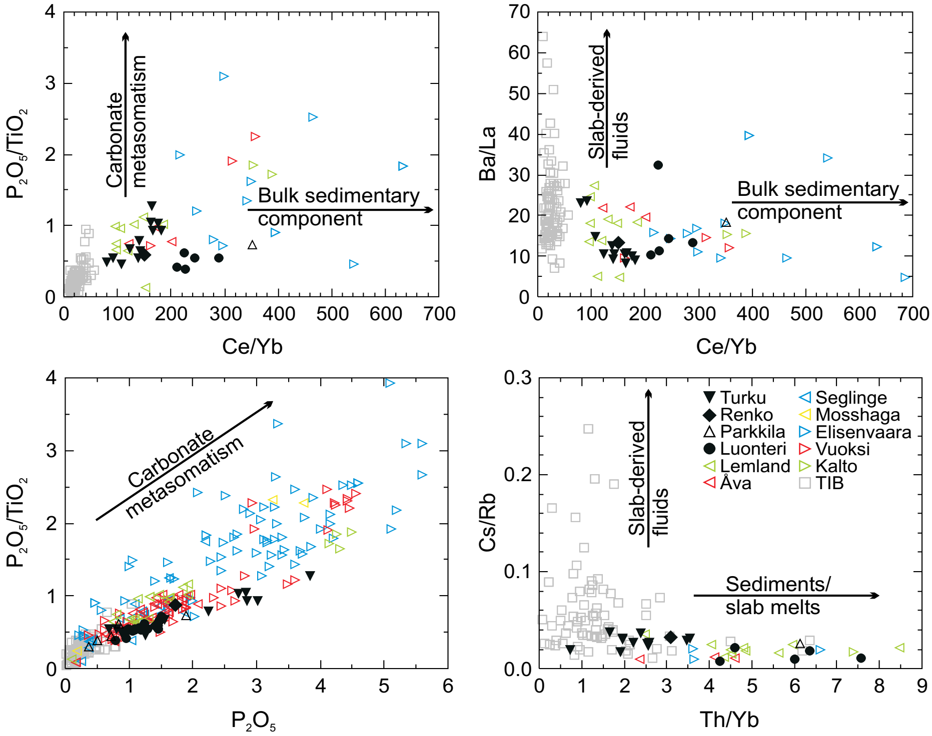

Fig. 4. Element ratio diagrams (references in the Papers) for mafic TIB-1 rocks of southern Sweden and post-collisional rocks of southern Finland, demonstrating the variation in the type and degree of enrichment in their mantle sources (only rocks with $SiO_2 < 61$ wt% plotted). References for the data as in Paper IV. See Papers I and IV for the locations and descriptions of the named individual intrusions in southern Finland and Russian Karelia (coloured symbols pointing to the left from SW Finland and to the right from the Russian Karelia).

Further, the much higher Ce/Yb (Fig. 4) and K_2O/Na_2O (Fig. 6A in Paper IV and e.g. Table 1 in Paper I) ratios in the mafic rocks of eastern Finland, and in particular Russian Karelia, indicate deep, garnet-bearing sources, where phlogopite dominate over amphibole, while towards the west more amphibole was present in the sources, probably closer to the spinel-garnet transition. The moderately enriched LREE and flat HREE patterns of the TIB rocks, suggest larger degrees of melting within a spinel lherzolite mantle (cf. Andersson *et al.* 2006a).

The fairly small enrichment of most of the isotopic ratios, and T_{DM} ages <2.1 Ga, suggest that the depleted mantle sources were enriched not long before 1.8 Ga, hence during the 2.1-1.86 Ga Svecofennian subduction and/or during the melt extraction and 1.8 Ga magmatism itself. The 1.84-1.82 Ga OJB subduction episode may have had an influence for the enrichment in the southern TIB. During the time of extensive subduction and accretion of the juvenile Svecofennian crust, a juvenile, heterogeneously enriched lithospheric mantle was established below the continent, as is evidenced by the considerable variation in initial isotopic ratios in younger mafic rocks extracted from it (cf. Söderlund *et al.* 2005). Interaction of melts from both lithospheric and asthenospheric sources are possible for the mafic 1.8 Ga magmas in southern Finland, as the trace element abundances of these rocks are similar, or exceed, that of typical OIB (e.g. Fig. 11 in Paper IV). In comparison, no imprints of asthenospheric sources have been found in the mantle sources for the TIB-1 rocks.

Granitoids associated with the 1.8 Ga mafic magmatism in southern Finland

These granitoids are of variable character, from metaluminous to distinctly peraluminous, but mostly slightly peraluminous (A/CNK = 1.0-1.1). They are predominantly calc-alkalic, but trend to alkali-calcic at increasing SiO_2. The geochemistry of the Luonteri, Petravaara and Pirilä granitoids, together with other similar 1.8 Ga granitoids from southern Finland and Russian Karelia (Branigan 1987, Konopelko 1997, Rutanen *et al.* 1997, Nironen 2005, and data received from the late Matti Vaasjoki, Geological Survey of Finland, in 2003), as well as most TIB granites (e.g. Wilson *et al.* 1986, Andersson 1997b, Ahl *et al.* 1999, Högdahl *et al.* 2004 and refs therein), demonstrate volcanic arc to post-collisional granitoid character, partly transitional to syn-collisional granite compositions. In contrast, the granites associated with the Turku complex and the granitic Renko dykes trend more pronouncedly to a syn-collisional granite character, similarly to the late-orogenic Svecofennian granites. The post-kinematic granitoids, except Petravaara, have relatively high $\varepsilon_{Nd}(t)$ values (close to 0), overlapping those of the mafic rocks, but the Turku and Renko granites have higher initial $^{87}Sr/^{86}Sr$ values, at 0.7048 and 0.7062, respectively. The isotopic compositions overlap that of the early Svecofennian calc-alkaline metaigneous crust, but differ from Svecofennian metasedimentary rocks by higher $\varepsilon_{Nd}(t)$ values (Fig. 15 in Paper IV). Thus, the granites in the Turku and Renko complexes overlap the geochemical compositions of the bulk of late-orogenic Svecofennian granites, and show relatively juvenile isotopic compositions similar to those of the early Svecofennian granitoids. This, and the mixed geochemical character, suggests that they derive from mixed mica-rich sedimentary and igneous protoliths. The granites of the post-collisional Ojajärvi, Borodino and Zavetnoe intrusions in Russian Karelia may have a similar origin (cf. Ivanikov *et al.* 1996, D. Konopelko 2001 pers. comm.). In contrast, the Luonteri and Pirilä granitoids derives mainly from Svecofennian igneous protoliths.

A pronounced exception is the Petravaara granitoid intrusion that show a more evolved isotopic signature, with $\varepsilon_{Nd}(t)$ at -2.8 and initial $^{87}Sr/^{86}Sr$ at 0.7033. The low $\varepsilon_{Nd}(t)$ suggests involvement of the Archaean basement of the Karelian Domain, in which Petravaara actually has intruded (Fig. 1), in the magma composition. In the present study a new U-Pb zircon SIMS age determination was obtained from a Petravaara sample, which resulted in a concordia age of 1811 ± 6 Ma (95 % confidence, MSWD = 1.4). In addition, Lu-Hf analyses performed on Petravaara zircons resulted in wide range of $\varepsilon_{Hf}(t)$ values from -11.9 to +2.8 ($\pm 2\sigma_m$ varies from 2.1 to 5.3, average = 3.3), with an average of -4.9 (n = 45). This, and the intermediate geochemistry, strongly suggest mixed Archaean and juvenile sources for the Petravaara intrusion.

Fractionation and mixing

Geochemical trends within the mafic Turku suite are compatible with the fractionation of mainly clinopyroxene/amphibole, Fe-Ti oxides, and apatite, with minor biotite and titanite up to c. 50 wt% SiO_2. Straight line trends between c. 50 and 70 wt% SiO_2 for essentially all elements suggest that rocks in this compositional range represent mixtures between mafic magmas from strongly enriched mantle and magmas derived from the juvenile Svecofennian crust. This holds for both the Turku and Luonteri complexes although the end members differ. Some cumulation of e.g. biotite, zircon and titanite scatters these trends.

The diversity of rock types found in the post-kinematic intrusions of Elisenvaara and Lemland was modelled to result from crystal fractionation. Based on geochemical comparison with the coeval (Andersson *et al.* 2006a, Woodard *et al.*, subm.) and co-genetic, nearby situated lamprophyric Kalto dykes (Fig. 1), Elisenvaara rocks with SiO_2 contents close to 40 wt% are considered to represent the parental magma composition for rocks in the intrusion, while rocks with lower SiO_2 contents represent apatite-rich cumulates. Thus, the Kalto lamprophyres, containing more than 4 wt% P_2O_5 and skeletal apatite (Konopelko *et al.* 1998), are considered non-cumulate-enriched, primary magmas, similar in composition to the parental magma of the plutonic Elisenvaara rocks suite. From this extremely enriched lamprophyric composition the magmas in Elisenvaara evolved by fractionation of early biotite, clinopyroxene, apatite, magnetite, titanite and allanite, and in later stages amphibole and feldspars, up to leucosyenitic compositions. This is supported, in addition to the geochemistry, by the actual presence of phenocrysts of clinopyroxene, biotite, apatite and magnetite in both the plutonic rocks and the lamprophyres, as well as ultrabasic cumulates.

For the Lemland intrusion, modelling is compatible with fractionation of about 50 wt% of biotite, amphibole, plagioclase, magnetite, apatite and titanite from a monzonitic parent to arrive at a magma composition similar to that of the coeval granites. The ubiquitous mingling structures and straight line geochemical trends (cf. Lindberg & Eklund 1988) suggests, however, that magma-mixing processes may play an important role for the intermediate rock compositions, in similarity with Luonteri and Turku.

The mafic TIB rocks in the investigated areas generally show structural relations with the hosting TIB rocks, indicative of magma mingling and mixing (e.g. Andersson 1991, Ahl *et al.* 1999, Mansfeld 2004, Högdahl *et al.* 2007). However, although contamination by felsic material is indicated for some rocks, such samples were avoided in the present work. Fractionation and cumulus effects were only studied superficially for the TIB rocks, but e.g. early, pre-emplacement fractionation of olivine, spinel and pyroxene accounts for the relatively low Mg#, Ni and Cr for some of the most primitive rocks, while olivine-pyroxene-plagioclase governed the fractionation from the least to the most evolved magmas. Cumulation of clinopyroxene, Fe-oxides and plagioclase can be recognised for some more basic samples, as well as Fe-Ti-oxide, apatite and titanite cumulation for some more evolved rocks.

Geodynamic inferences

Plate-tectonic models for the formation of the whole Fennoscandian Shield, as well as for the entire East European Craton, in which Fennoscandia is a part, have been summarised by e.g. Lahtinen *et al.* (2005, 2008, 2009) and Bogdanova *et al.* (2006). The present work has dwelled on the palaeotectonic evolution for the time period 1.87-1.75 Ga (Fig. 5).

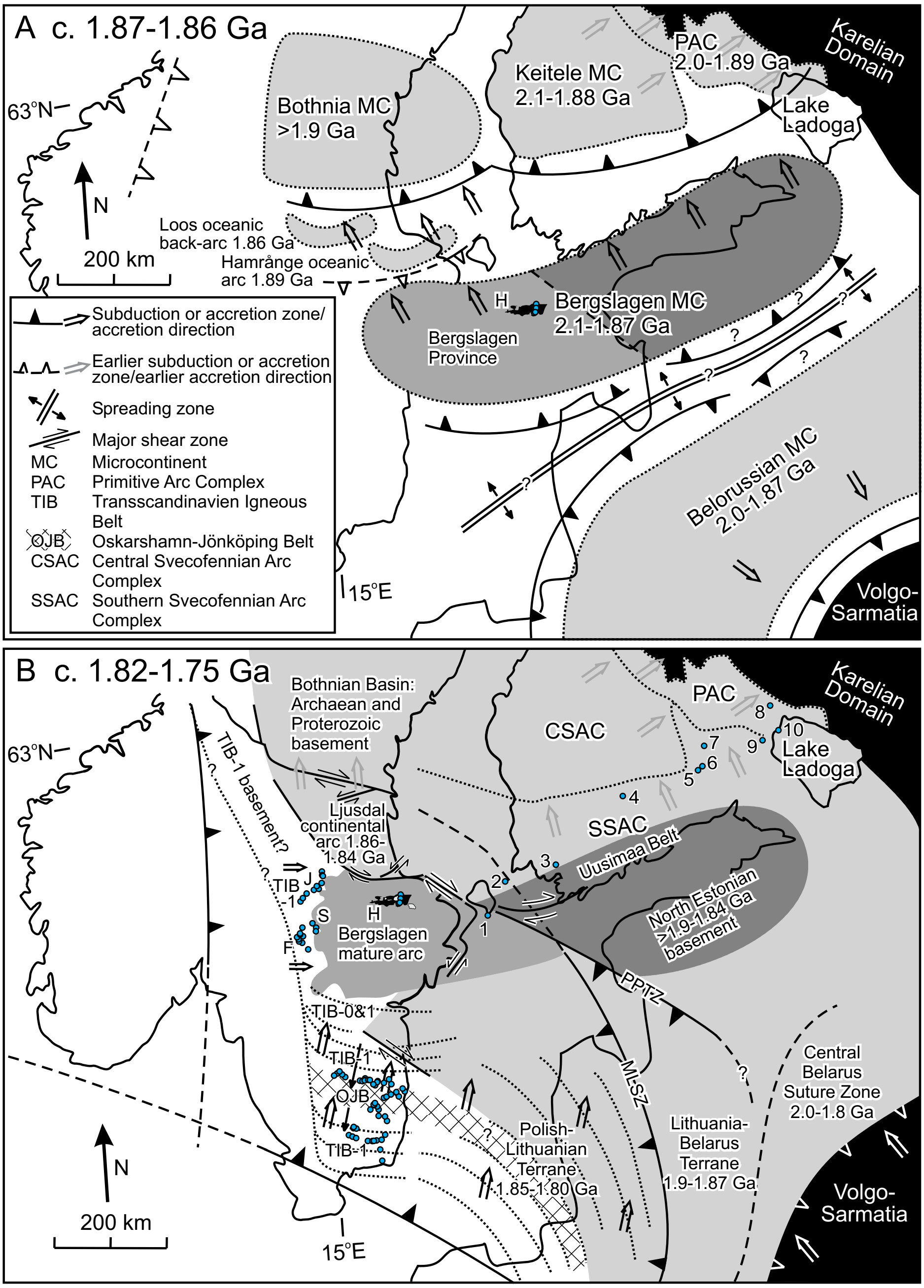

Fig. 5. Proposed palaeotectonic settings during the A) 1.87-1.86 Ga and B) 1.82-1.75 Ga magmatisms in southern Fennoscandia, including the sample spots from Papers I-IV (intrusions studied in Papers I and IV are numbered as in Fig. 1) (the figures modified after Andersson *et al.* 2004b, Bogdanova *et al.* 2006, Papers I-IV and refs therein). Lightest grey shading denotes Palaeoproterozoic Svecofennian crust in general (excluding TIB), while darker and darkest grey shadings mark the

approximate extent of the crust of the western and eastern parts of the Bergslagen microcontinent (cf. Lahtinen *et al.* 2005). Black areas (except Hedesunda) = Archaean Blocks; J = Järna suite; S = Säfsnäs area; F = Filipstad area; H = Hedesunda complex, where black mark the mainly intermediate 1.87 Ga rocks, and light grey the 1.78 Ga granites (modified after Koistinen *et al.* 2001, Bergman *et al.* 2003 and 2004; cf. Fig. 1 in Paper III); PPTZ = Paldiski-Pskov Tectonic Zone; MLSZ = Mid-Lithuanian Suture Zone; stippled lines = traces of structures/growth segments. 'TIB-1 basement?' denotes an area of TIB-2 rocks, possibly underlain by TIB-1. Thin arrows in southernmost TIB-1 show the direction of retreating subduction. See the text and Paper III for discussion.

1.87-1.86 Ga was the time of final accretion of arcs and microcontinents that amalgamated to a collage of the dominantly juvenile Svecofennian Domain (Gaál & Gorbatschev 1987, Nironen 1997, Lahtinen *et al.* 2005). The studied 1.87 Ga Hedesunda intrusive complex intruded the northern part of the Bergslagen microcontinent at a time when Bergslagen had not yet docked with the Bothnia microcontinent in the north, and the 1.86-1.84 Ga Ljusdal batholith (Högdahl *et al.* 2008) to the north was not in place (Fig. 5A). Two scenarios are possible: i) either continental-arc setting due to subduction towards the south, or ii) a continental back arc due to subduction from the south. Irrespective of whether the subduction beneath Bergslagen was towards the south or north, the Hedesunda magmas, supplemented by input from arc-type mantle sources, reworked the crust of the northernmost Bergslagen microcontinent, shortly before the collision between the Bergslagen and Bothnia microcontinents. The emplacement appears to have occurred at an active tectonic stage, probably guided by pre-existing structures, from which the 1.87 Ga magmas acquired their present E-W tectonic grain. Later, the 1.78 Ga Hedesunda granite magmas, a part of an extensive and scattered 'late-orogenic' (1.82-1.75 Ga) magmatism within the southern Svecofennian Domain, followed the same crustal weakness structures as the early Hedesunda magmas during a second magmatic pulse simultaneous with the TIB-1 development in the west and south.

In southern Sweden, post-accretional magmatism (≤1.86 Ga) started to rework the mostly juvenile, just assembled Svecofennian crust by subduction towards the N to NNE along the margin in the south and towards the east in the west (Fig. 5B). This continental-arc magmatism commenced shortly after the amalgamation by the 1.85-1.83 Ga TIB-0 magmatism, but peaked during the 1.81-1.75 Ga TIB-1 episode (cf. Högdahl *et al.* 2004). The geochemical and isotopic data reported in this work, from southernmost and south-central TIB, support previous inferences (e.g. Andersson *et al.* 2004b) of a continental arc setting for the TIB. In the southernmost part of Sweden a southwards younging of the TIB rocks suggests that the subducting slab is retreating in the time frame 1.81-1.75 Ga (cf. Gorbatschev 2004, Mansfeld 2004, Johansson *et al.* 2006). The 1.84-1.82 Ga, juvenile, calc-alkaline OJB (e.g. Åhäll *et al.* 2002, Mansfeld *et al.* 2005) divides the southernmost TIB into a northern and southern part. Granitic rocks in the north tend to be more alkali-calcic (e.g. Andersson 1997b, Andersson & Wikström 2004) and mostly derived from the juvenile Svecofennian crust (e.g. Andersen *et al.* 2009), while becoming more calc-alkaline to the south (Lindh *et al.* 2001, Gorbatschev 2004) shifting from derivation from OJB crust to increasingly more juvenile sources southwards (cf. Andersson *et al.* 2004b). The driving force in the reworking of the crust was the supply of mafic magmas to the crust during the subduction process, initializing crustal melting. Subducted slabs and large mafic intrusions in the crust have been interpreted from geophysical imaging (e.g. Balling 2000, Lund *et al.* 2001, Korja & Heikkinen 2005). In similarity with the granitoids, the present work has shown that mafic rocks north of OJB are more LILE and LREE enriched and continental in character, compared with those south of OJB that become increasingly less enriched and trend towards oceanic compositions to the south.

Further north, in south-central Sweden TIB-1 magmatism was associated with eastwards subduction beneath the Svecofennian continental margin, and thus two subduction zones at high angle with each other were probably active at the same time (Fig. 5B). This eastwards-dipping subduction zone continued to the north and gave rise to the northward extension of TIB all the way to the Lofoten Islands (see the inset in Fig. 1 in Papers II and III). The enriched character of the mafic TIB magmatism in south-central Sweden, determined in the present work, supports a continental arc setting also in that area.

Contemporaneously (1815-1760 Ma) with the TIB activity in the west, minor, essentially post-kinematic complexes, intruded the Svecofennian Domain in the present southern Finland and Russian Karelia. This occurred in the aftermaths of the continental collision with Volgo-Sarmatia from the southeast (e.g. Lahtinen *et al.* 2005, Bogdanova *et al.* 2006; Fig. 5B). The intrusions were emplaced in the essentially juvenile crust during a shift from a transpressional to a (trans)tensional tectonic regime, following the collision (e.g. Väisänen & Skyttä 2007, Torvela *et al.* 2008), i.e. in a post-collisional setting. Thus, crustal-scale shear zones, initiated by the convergence and collision, may have facilitated the magma transport and emplacement of the intrusions. Although influences from the active subduction in the west cannot be entirely precluded (Andersson *et al.* 2006a) for this magmatism, delamination or break-off of a north-dipping lithospheric slab after the collision, and upwelling of hot asthenosphere causing melting of the strongly metasomatised post-collisional Svecofennian lithospheric mantle, appears more consistent with the evidences.

These include the predominantly linear occurrence of the intrusions, their shoshonitic composition (with some indications of asthenospheric contributions for the Turku magmas), and the post-collisional palaeotectonic setting. The resulting shoshonitic magmas were intruded into the crust, where they caused local crustal melting (e.g. in the Turku and Renko complexes), and interacted with the crustal melts (magma-mingling and -mixing e.g. in Lemland, Luonteri, Turku and Petravaara complexes). A connection between the small middle to upper crustal post-collisional intrusions studied here to more widespread coeval mafic magma underplating in the lower crust is partially supported by the geophysical data (e.g. Nironen *et al.* 2006, Korja & Heikkinen 2008) and the presence of abundant 1.8 Ga mafic xenoliths in kimberlites in SE Finland (Hölttä *et al.* 2000, Peltonen & Mänttäri 2001, Peltonen *et al.* 2006). The intrusions may thus represent stitching magmatism to higher levels from widespread layers of enriched mafic magmas underplating the Svecofennian crust in southern Finland and Russian Karelia. The oldest, c. 1.81-1.82 Ga post-collisional intrusions, were emplaced deeper in the crust, when the country rocks were still relatively hot, thus interacting in a more ductile way forming e.g. mingled zones with anatectic granites in Renko and Turku (Lahtinen 1996, Väisänen *et al.* 2000). In contrast, some of the youngest intrusions in the SW, e.g. Åva and possibly Seglinge, intruded after exhumation to crustal levels of <10 km (Eklund & Shebanov 2005).

In summary, the 1.8 Ga palaeotectonic set-up of the southern part of Fennoscandia created a convergent stress field as a result of the tectonic interplay between continental collision in the SE and continental margin convergence in the SW. This resulted in dominantly NW-SE-directed dextral transpressional tectonics, caused by roughly N-S compression across the southern Svecofennian Domain (e.g. Ehlers *et al.* 1993, Sjöström & Bergman 1998, Högdahl & Sjöström 2001, Andersson *et al.* 2004d, Väisänen & Skyttä 2007, Torvela *et al.* 2008; Fig. 5B). Mafic, mantle-derived magmas associated with these processes tapped increasingly metasomatised, deep lithospheric mantle sources when moving from the TIB in the west progressively eastward into the newly amalgamated continent.

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