TURUN
YLIOPISTO
UNIVERSITY
OF TURKU

EVOLUTION OF THE SVECOFENNIAN BEDROCK IN SOUTHERN FINLAND

Spatial and temporal changes in the mantle-derived magmatism and mantle-crust interaction

Jaakko Kara

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. AII OSA – TOM. 381 | BIOLOGICA – GEOGRAPHICA – GEOLOGICA | TURKU 2021

TURUN
YLIOPISTO
UNIVERSITY
OF TURKU

EVOLUTION OF THE SVECOFENNIAN BEDROCK IN SOUTHERN FINLAND

Spatial and temporal changes in the mantle-derived magmatism and mantle-crust interaction

---

Jaakko Kara

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. AII OSA – TOM. 381 | BIOLOGICA – GEOGRAPHICA – GEOLOGICA | TURKU 2021

University of Turku

Faculty of Science
Department of Geography and Geology
Geology and Mineralogy
Doctoral programme in Biology, Geography and Geology (BGG)

Supervised by

Docent, Markku Väisänen
University of Turku
Finland

Associate Professor, Pietari Skyttä
University of Turku
Finland

University Lecturer, Karin Högdahl
Uppsala University
Sweden

Reviewed by

Dr., Kerstin Saalmann
Geological Survey of Norway
Norway

Research Professor, Raimo Lahtinen
Geological Survey of Finland
Finland

Opponent

Professor, Christoph Beier
University of Helsinki
Finland

The originality of this publication has been checked in accordance with the University of Turku quality assurance system using the Turnitin OriginalityCheck service.

ISBN 978-951-29-8473-2 (PRINT)
ISBN 978-951-29-8474-9 (PDF)
ISSN 0082-6979 (Print)
ISSN 2343-3183 (Online)
Painosalama, Turku, Finland 2021

UNIVERSITY OF TURKU
Faculty of Science
Department of Geography and Geology
Geology and Mineralogy
JAAKKO KARA: Evolution of the Svecofennian Bedrock in Southern Finland - Spatial and temporal changes in the mantle-derived magmatism and mantle-crust interaction
Doctoral Dissertation, 182 pp.
Doctoral Programme in Biology, Geography and Geology (BGG)
June 2021

ABSTRACT

The Svecofennian orogen in the central Fennoscandian Shield was formed between 1.96–1.77 Ga. This study focuses on characterizing the temporal and spatial changes of the mantle derived and related magmas in southern Finland during the early stages (1.92–1.86 Ga) of the orogeny. The findings are further used to create a magmatic evolution model for the early Svecofennian orogen in southern Finland.

Based on the on their age, geochemical features and Sm-Nd and zircon Lu-Hf isotope signature this work provides a classification of the early orogenic intrusives into six categories: (i) 1.89 Ga rift-related rocks, 1.89–1.87 Ga arc-related (ii) mafic and (iii) felsic rocks, 1.86 Ga within-plate-type rock association including (iv) high-Nb gabbros (HNB), (v) high-Mg gabbros (HMG) and (vi) adakite-lite rocks. The 1.89 Ga rocks show E-MORB type geochemistry suggesting a rift-related setting in a forearc region. The 1.89–1.87 Ga arc-related rocks are the most abundant and carry distinctive subduction-related signatures. The rare association of the 1.86 Ga igneous rocks are characterized followingly: the HNB show OIB-type geochemical features, positive initial ε_{Nd} value, and near-chondritic initial zircon ε_{Hf} values; the HMG show high MgO, Cr and Ni contents, positive ε_{Nd}, and positive zircon ε_{Hf} values, and adakite-like rocks show slight enrichment in Sr and La, relative depletion in some HFSEs, positive ε_{Nd} value, and chondritic to negative zircon ε_{Hf} values. Lower crustal (rutile-bearing) garnet pyroxenites, i.e., arclogites, are suggested to be the source of the HNB rocks. In contrast, subduction-modified mantle peridotite is the source for the HMG rocks, and a mafic lower crustal source is suggested for the adakite-like rocks.

In this work, I suggest that arc magmatism prevailed during contractional stages of the orogeny, whereas the extensional stages were characterised by MORB/within-plate type magmatism. The timing, compositional and isotopic changes of early-orogenic magmatism are broadly compatible with intervals of contraction and extension, i.e., tectonic switching model and may provide a perspective to rapid build-up of Paleoproterozoic crust. In addition, I suggest a model of formation, delamination and partial melting of arclogites to describe the evolution and shift from ~1.88 Ga arc magmatism to the 1.86 Ga within-plate type magmatism. The rutile-bearing arclogites were formed during 1.89–1.87 Ga arc magmatism followed by the arclogite delamination and partial melting during extension of the thickened

Svecofennian crust at 1.86 Ga. This model explains the features of the rare 1.86 Ga magmatic association as well as the extremely thick crust and the high velocity lower crust encountered in the central Fennoscandian Shield and possibly in other Paleoproterozoic orogens.

KEYWORDS: Svecofennian orogen, geochemistry, isotope geology, geochronology

TURUN YLIOPISTO
Matemaattis-luonnotieteellinen tiedekunta
Maantieteen ja geologian laitos
Geologia ja mineralogia
JAAKKO KARA: Evolution of the Svecofennian Bedrock in Southern Finland - Spatial and temporal changes in the mantle-derived magmatism and mantle-crust interaction
Väitöskirja, 182 s.
Biologian, maantieteen ja geologian tohtoriohjelma (BGG)
kesäkuu 2021

TIIVISTELMÄ

Fennoskandian kilven keskiosassa sijaitseva Etelä-Suomen kallioperä syntyi Svekofennisen vuorijonon poimutuksen eli orogenian aikana 1.96–1.77 miljardia vuotta sitten. Tämä tutkimus keskittyy orogenian alkuvaiheessa syntyneiden, 1.92–1.86 miljardia vuotta vanhojen, vaippaperäisten magmojen luonnehdintaan sekä vaipan ja kuoren vuorovaikutuksen tutkimiseen. Näiden perusteella luon magmatismia ja sen alueellista sekä ajallista muutosta kuvaavan mallin Etelä-Suomesta.

Magmakivet luokiteltiin niiden (i) kiteytymisiän, (ii) kemiallisen koostumuksen ja (iii) Sm-Nd ja zirkonien Lu-Hf isotooppikoostumuksen perusteella seuraaviin luokkiin: 1.89 miljardia vuotta vanhat kuoren repeytymiseen liittyvät kivet, 1.89–1.87 miljardia vuotta vanhat vulkaanisen kaaren kivet, 1.86 miljardia vuotta vanhat kuoren sisäisen magmatismin kivet, sisältäen korkean Nd-pitoisuuden gabbroja (HNB), korkean Mg-pitoisuuden gabbroja (HMG) ja adakiittisia kiviä. 1.89 miljardia vuotta vanhat kuoren repeytymiseen liittyvät kivet sisältävät E-MORB-tyyppisen geokemiallisen koostumuksen ja ehdotan niiden syntyneen kaaren edusta-altaan repeämisen seurauksena. 1.89–1.87 miljardia vuotta vanhat vulkaanisen kaaren kivet ovat selkeästi yleisimpiä ja ne sisältävät selkeän subduktiovyöhykkeen sormenjäljen. Harvinaista 1.86 miljardia vuotta vanhaa magmakiviseuruetta voidaan luonnehtia seuraavasti: HNB-kivet sisältävät OIB-tyyppisen geokemiallisen koostumuksen, positiivisen ε_{Nd}-arvon ja kondriittisen zirkonien ε_{Hf}-arvot; HMG-kivet sisältävät korkean MgO-, Cr- ja Ni-pitoisuuden, korkean ε_{Nd}-arvon ja positiiviset zirkonien ε_{Hf}-arvot; adakiittiset kivet ovat rikastuneita Sr:in ja La:in ja köyhtyneet HFSE-alkuaineista, sisältävät positiivisen ε_{Nd}-arvon ja hieman negatiiviset zirkonien ε_{Hf}-arvot. HNB-kivet ovat syntyneet arclogiittien, eli alakuoren rutiilipitoisten granaatti-pyrokseniittikumulaattien osittaissulamisen seurauksena. HMG-kivet ovat syntyneet subduktion rikastaman peridotiitin (ylävaippa) osittaissulamisesta, kun taas adakiittisten kivien lähde on mafinen alakuori.

Tulosten perusteella orogenian puristusvaiheessa (kuoren paksuuntuminen) kaarityyppinen magmatismi vallitsee, kun taas ekstension aikana E-MORB/kuoren sisäinen magmatismi on vallitseva tyyppi. Kivien kiteytymisiät sekä koostumuksellinen syklinen vaihtelu vastaa hyvin niin sanottua tectonic switchingmallia, jossa kuoren puristus/lyhentyminen ja ekstensio vaihtelevat. Tämä voi tarjota uuden mekanismin nopealle kuoren kasvulle Paleoproterotsooisella ajalla. Lisäksi malli tiheän arclogiittikerroksen muodostumisesta, hajoamisesta ja osittaissulamisesta selittää muutoksen 1.88 miljardia vuotta vanhasta kaarityypin magmatismista 1.86 miljardin vuoden ikäiseen kuoren sisäiseen magmatismiin. Mallissa rutiilipitoinen arclogiittikerros muodostui 1.89–1.87 miljardia vuotta sitten yleisen kaarityyppisen magmatismin seurauksena. Tätä seurasi tiheän arclogiittikerroksen osittainen vajoaminen ylävaippaan paksuuntuneen kuoren ekstension aikana ja arclogiittien osittaissulamista. Tämä malli selittää harvinaisen 1.86 miljardia vuotta vanhan kivilajiassosiaation geokemialliset piirteet, kuoren paksuuntumisen mekanismin sekä suuren tiheyden omaavan alakuoren syntymisen Fennoskandian kilven alueella sekä mahdollisesti muissa Paleoproterotsooisissa orogenioissa.

ASIASANAT: Svekofenninen orogenia, geokemia, geokronologia, isotooppigeologia

Table of Contents

Abbreviations

AFC	Assimilation-fractional crystallisation
BSE	Back-scattered electron
CS	Central Svecofennia
DM	Depleted mantle
DMM	Depleted MORB-mantle
E-MORB	Enriched mid-ocean ridge basalt
Ga	Giga annum, billions of years
GFGC	Central Finland granitoid complex
GrDr	Granodiorite
ICP-MS	Inductively coupled plasma mass spectrometer
HFSE	High field strength elements
HMG	High-Mg gabbro
HNB	High-Nb gabbro
HREE	Heavy rare earth elements
HVLC	High velocity lower crust
LILE	Large ion lithophile elements
LREE	Light rare earth elements
Ma	Mega annum, millions of years
MORB	Mid-ocean ridge basalt
MREE	Middle rare earth elements
OIB	Ocean island basalt
PM	Primitive mantle
REE	Rare earth elements
SEM	Scanning electron microscope
SO	Svecofennian orogen
SS	Southern Svecofennia
TAS	Total alkali vs. silica

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Kara, J., Väisänen, M., Johansson, Å., Lahaye, Y., O'Brien, H., Eklund, O. 1.90-1.88Ga arc magmatism of central Fennoscandia: geochemistry, U-Pb geochronology, Sm-Nd and Lu-Hf isotope systematics of plutonic-volcanic rocks from southern Finland. *Geologica Acta*, 2018; 16(1), 1-23.

II Kara, J., Väisänen, M., Heinonen, J. S., Lahaye, Y., O'Brien, H., Huhma, H. Tracing arclogites in the Paleoproterozoic Era–A shift from 1.88 Ga calc-alkaline to 1.86 Ga high-Nb and adakite-like magmatism in central Fennoscandian Shield. *Lithos*, 2020; 372, 105663

III Kara, J., Leskelä, T., Väisänen, M., Skyttä, P., Lahaye, Y., Tiainen, M., Leväniemi, H. Early Svecofennian rift-related magmatism: Geochemistry, U-Pb-Hf zircon isotope data and tectonic setting of the Au-hosting Uunimäki gabbro, SW Finland. *Manuscript.*

The original publications have been reproduced with the permission of the copyright holders.

1 Introduction

1.1 Mantle-derived magmatism

Mantle-derived magmas erupt in multiple modern geotectonic environments such as mid-ocean spreading centres, intraplate environments, and subduction-related settings (Wilson, 1989). These magmas are particularly useful in studying the past geotectonic settings since distinctive geochemical characteristics are associated with specific geotectonic settings (e.g., Pearce & Cann, 1973; Rollinson, 1993; Xia & Li, 2019). Due to their primitive nature compared to the granitoids the mantle-derived magmas strongly reflect the characteristics of their primary source, i.e., the type of the mantle source (Sun & McDonough, 1989) and they are sensitive to the addition of other geochemical components during their genesis (Pearce & Cann, 1973; Xia & Li, 2019). This allows us to study the compositional evolution of the Earth's mantle and crust and their interaction, and more widely the elemental cycle, i.e., differentation of the Earth (e.g., Hoffmann, 1988; Sun & McDonough, 1989; McDonough & Sun, 1995; Rudnick et al., 2000). Moreover, the major and trace element characteristics and isotope systematics of the mantle-derived rocks can be used to study multiple geological processes such as partial melting, fractional crystallisation and crustal assimilation (AFC-processes, e.g., DePaolo, 1981).

Since the pioneering work of Pearce and Cann (1973) on the development of the geotectonic discrimination diagrams, a growing number of studies have used major and trace element compositions of mafic rocks to identify the tectonic environment in which the rocks were generated. The leap in the mass spectrometry during the past years has enabled very precise analyses on trace elements, but even more importantly it has made possible the analysis on different isotope systems (e.g., Allegre, 2008). If possible, the whole rock geochemical composition can be combined, for example, with zircon U-Pb age determination, whole rock Sm-Nd isotope analysis and zircon Lu-Hf isotope analysis to reveal: (i) the age of crystallisation of the magma, (ii) possible inherited components, e.g., older recycled crustal material in the magma, (iii) mantle and crustal processes behind the geochemical composition of the magma. And perhaps, when enough data is available, it may be possible to establish extensive geodynamic models on the evolution of the continental crust, for example, during the Svecofennian orogeny.

1.2 Svecofennian orogen

Major crust-forming processes occurred in connection with the amalgamation of the supercontinent Columbia aka Nuna during the Paleoproterozoic time (e.g., Rogers and Santosh, 2002; Condie, 2020). One of its components, the Svecofennian orogen (SO) in the central Fennoscandian Shield represents the northern part of the East European Craton (Figure 1; Gorbatschev & Bogdanova, 1993) and is separated from the Archean Karelian Province by a NW-SE striking suture zone (Koistinen, 1981; Lahtinen et al., 2015). The SO covers an area of approximately 1 million km^2 (Lahtinen et al., 2009a) and is characterised by up to 60 km thick crust in eastern and south-central Finland (Luosto, 1991). It forms a part of the Great Proterozoic Accretionary Orogens, which in places have experienced the longest duration of subduction in the Earth's history, up to 900 Ma (Condie, 2013).

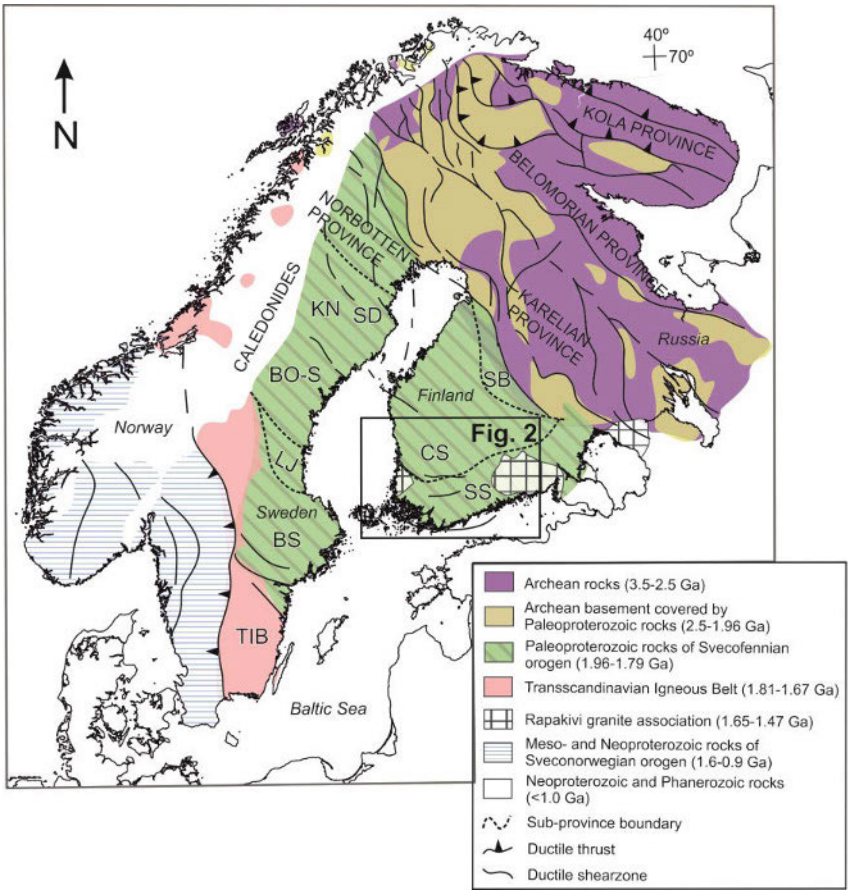

Figure 1. Simplified geological map of the Fennoscandian shield (modified after Koistinen et al., 2001). Subareas and locations: CS = Central Svecofennia, SS = Southern Svecofennia, SB = Savo belt, BS = Bergslagen lithotectonic unit, LJ = Ljusdal lithotectonic unit, BO-S = Bothia-Skellefte lithotectonic unit, KN = Knaften arc, SD = Skellefte district.

The SO is characterised by 1.96–1.77 Ga igneous rocks and is suggested to consist of several large units defined as terranes or lithotectonic units in Finland and Sweden (e.g., Lahtinen et al., 2009a; Stephens & Bergman, 2020). The oldest 1.96–1.92 Ga primitive volcanic arc-type igneous units are found in northern Sweden (Barsele and Knaften arcs; Wasström, 1993; Eliasson et al., 2001; Guitreau et al., 2014). In the central part, three main terranes are recognised in Finland, which were accreted to the Archean craton during the orogeny: the Savo belt, Central Svecofennia and Southern Svecofennia (Korsman et al., 1997, Kähkönen, 2005). The primitive arc-type ~1.92 Ga Savo belt exposes the oldest Svecofennian igneous rocks in Finland (Lahtinen, 1994; Vaasjoki et al., 2003) and can be considered an equivalent to the Knaften arc in Sweden. The northern part of Central Svecofennia is characterised by the granitoid-dominated Central Finland granitoid complex (e.g., Nironen, 2005), whereas the southern part is divided into the medium-metamorphic-grade volcano/sedimentary Tampere belt and the high-grade sedimentary Pirkanmaa belt. Southern Svecofennia is subdivided into two E-W trending volcanic belts, the Häme belt in the north and the Uusimaa belt in the south, which are separated by the late Svecofennian granite-migmatite zone (Ehlers et al., 1993; Korsman et al., 1997; Kähkönen, 2005 and references therein).

The correlation of Southern and Central Svecofennian between Finland and Sweden is ambiguous. It is considered that Southern Svecofennia and the Berglagen area in south-central Sweden belong to the same unit (e.g., Valbracht et al., 1994, Nironen 1997, Lahtinen et al., 2005), although the presence of large intervening shear zones such as the Singö shear zone along the coast in east-central Sweden and the South Finland shear zone makes such correlations problematic (Torvela and Ehlers, 2010, Bogdanova et al., 2015). New findings suggest that Central Svecofennia and the Bothia-Skellefte lithotectonic unit could be partly correlated (Lahtinen et al., 2017).

Hietanen (1975) was the first researcher to propose accretion (collision) of island arc complexes to the Archean craton for the origin of the Svecofennian orogen. Since then, this idea is accepted at a general level and two alternative tectonic models have been proposed. Lahtinen et al. (2005) and Korja et al. (2006) suggested a microcontinent and island arc accretion against the Archean continent at 1.92–1.87 Ga followed by an extensional phase between 1.87 and 1.84 Ga prior to the continent-continent collision at 1.84–1.79 Ga. An alternative view was presented by Hermansson et al. (2008), Saalmann et al. (2009) and Stephens & Andersson (2015) in which subduction beneath a single active continental margin in combination with hinge retreat and advance resulted in tectonic switching (Collins, 2002) between contractional and extensional tectonics. Evidence for both models are found regionally and locally, therefore, the question of the tectonic evolution remains open.

Mantle-derived magmatism was continuous during the entire orogenic cycle in southern Finland (e.g., Kähkönen, 2005; Peltonen, 2005; Rutanen et al., 2011; Väisänen et al., 2012a). Probably, the oldest rocks are the E-MORB type pillow lavas and basalts in the Haveri formation in the northern part of the Tampere belt with inferred age of ~1.92–1.90 Ga (Kähkönen 1999, 2005). The Pirkanmaa belt picrites (Peltonen, 1995) are possibly coeval with the Haveri formation (Lahtinen et al., 2017). The following bimodal arc-type volcanism in the Tampere belt is dated approximately at 1.90 Ga (Kähkönen, 2005 and references therein). The sporadic rift-related magmas in the Häme and Pirkanmaa belts are probably slightly younger (Sipilä and Kujala, 2014). The voluminous 1.88–1.87 Ga volcanic arc-type magmatism is the most abundant type of the mantle-derived magmas within the Pirkanmaa, Häme and Uusimaa belts (e.g., Kähkönen, 2005; Peltonen, 2005). This is followed by the relatively rare 1.87–1.84 Ga magmatism during an extensional tectonic regime and recent studies have confirmed mafic magmatic activity in southern Finland and central Sweden at the time (Väisänen et al., 2012a, b; Dahlin et al., 2014; Nevalainen et al., 2014; Johansson & Karlsson, 2020). Late- to post-tectonic 1.83–1.79 Ga mafic magmatism is small in volume but quite well documented in southern Finland (e.g., Eklund et al., 1998; Rutanen et al., 2011).

1.3 Objectives of this study

The aim of this thesis is to clarify the evolution of the Svecofennian bedrock in southern Finland and especially define the origin, evolution and plate-tectonic environment of mantle-derived rocks, such as gabbros, diorites and their subvolcanic equivalents, during the early stages of the orogeny (1.92–1.86 Ga). Special interest lies in the relationship between the volcano-sedimentary belts and, therefore, the study areas were selected to spatially cover all the belts (Figure 2) and temporally to encompass different stages of the early orogenic evolution. Ultimately, the aim is to create a comprehensive tectono-magmatic model, which describes the compositional changes between different magmatic stages. For this, I use new findings from the Pirkanmaa, Häme and Uusimaa belts and recent advancements in isotope geology, especially zircon Lu-Hf analyses. The thesis adopts a model of tectonic switching (Collins, 2002) to describe evolution of the Tampere, Pirkanmaa and Häme belts, describes the evolution of the oldest known arc-type rocks in the Uusimaa belt and represents a new model of arclogite-related magmatism (Lee et al., 2006; Tang et al., 2019). This study presents a large quantity of new whole rock geochemical and Sm-Nd data, zircon U-Pb age determinations as well as zircon Lu-Hf data in comparison with previously published data. The results partly complement the previously published models but also represent new ideas and partly redraw the orogenic evolution of the Svecofennian bedrock in southern Finland.

2 Study areas

2.1 Overview

The study areas are located in three major volcano-sedimentary belts in southern Finland: the Uusimaa, Häme and Pirkanmaa belts (Figure 2). The study areas in Paper I are located on the island of Enklinge (Ia) and in the Orijärvi area in the Uusimaa belt (Ib). Whether Enklinge is part of the Häme or Uusimaa belt remains unknown. The study areas in Papers II and III straddle the boundary between the Pirkanmaa and Häme belts.

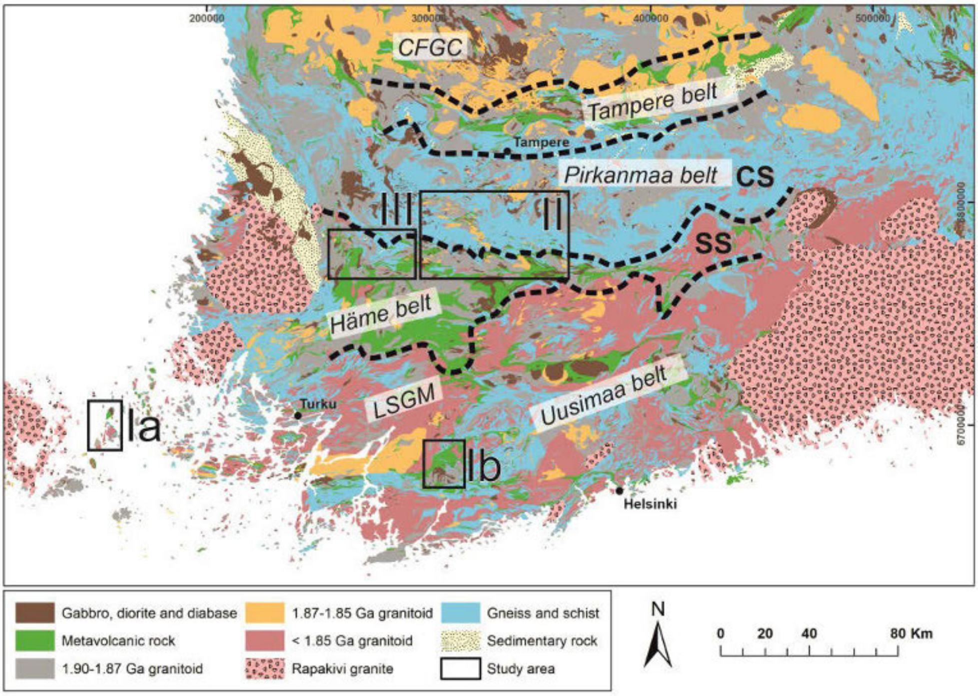

Figure 2. Generalised lithological map of southern Finland (modified after Bedrock of Finland – DigiKP). Study areas for papers I-III indicated by black boxes. CS = Central Svecofennia, SS = Southern Svecofennia, CFGC = Central Finland Granitoid Complex, LSGM = Late Svecofennian granite-migmatite belt. Coordinates in national ETRS89 realisation, EUREF-FIN coordinate system.

A terrane boundary between Southern and Central Svecofennian is traditionally inferred between Pirkanmaa and Häme belts (Korsman et al., 1997), based on the timing and magnitude of the metamorphism, crystallisation age of the igneous rocks and composition of the sedimentary rocks and leucosomes in migmatites (Lahtinen, 1994; Sipilä et al., 2011; Hölttä & Heilimo, 2017).

2.2 The Pirkanmaa and Tampere belts

The Pirkanmaa belt (Figure 2) is dominated by migmatised psammitic supracrustal rocks of turbiditic origin deposited at 1.92–1.89 Ga (Huhma et al., 1991; Kähkönen, 2005; Lahtinen et al., 2009b). The supracrustal rocks, including minor black shales (Lahtinen et al., 2017) are intruded by small ultramafic to mafic plutonic bodies with arc or transitional MORB affinities, which were interpreted as synorogenic conduits of tholeiitic arc-type magmas (Peltonen, 1995, 2005). The Pirkanmaa belt also includes minor ultramafic (picritic) to mafic volcanic rocks with MORB to WPL affinities (Peltonen, 1995; Lahtinen, 1996; Kähkönen, 2005) and various synorogenic granitoids (Nironen & Bateman, 1989) that comprise 1.89–1.87 Ga tonalites, quartz diorites and granodiorites (Nironen & Bateman, 1989; Kilpeläinen, 1998; Nironen, 2005). Metamorphism is characterised by high temperature and low pressure and is dated at ~1.88 Ga (Mouri et al., 1999; Rutland, 2004; Lahtinen et al., 2009b). The medium-grade Tampere belt is situated north of the Pirkanmaa belt and is characterised by volcanic rocks formed in a volcanic arc environment 1.91–1.89 Ga ago (Kähkönen, 2005). The Pirkanmaa belt is interpreted to be a mid-crustal expression of a fore-arc and an accretionary prism/subduction complex to the Tampere belt volcanic arc complex (Lahtinen, 1996; Kähkönen, 2005; Lahtinen et al., 2009b, Paper III).

2.3 The Häme belt

The bedrock of the Häme belt (Figure 2) was mainly formed at 1.88–1.87 Ga (Lahtinen et al., 2005; Saalmann et al., 2009). It consists of volcanic and sedimentary rocks (Lahtinen, 1996; Kähkönen, 2005) that were metamorphosed under amphibolite facies conditions (Hölttä & Heilimo, 2017). The supracrustal rocks are intruded by gabbros, diorites, granodiorites and tonalites (Nironen, 1999; Kähkönen, 2005; Saalmann et al., 2010; Tiainen et al., 2013; Mäkitie et al., 2016) and late- to post-tectonic (1.84–1.79 Ga) granites, migmatites and pegmatites (Nironen et al., 2016; Nironen, 2017). The supracrustal and plutonic rocks cover approximately equal areas at the present erosion surface. The volcanic rocks of the Häme belt were divided into four main suites by Sipilä & Kujala (2014): the Forssa, Loimaa, Nuutajärvi and Renkajärvi suites. The calc-alkaline Forssa volcanic suite ranges from basaltic to rhyolitic, andesites being the most common. The calc-alkaline Loimaa suite consists mostly of amphibolites and hornblende-gneisses and the protolith compositions are less constrained due to stronger metamorphic overprint compared to the Forssa suite. The Nuutajärvi suite differs lithologically from other units in Häme belt, consisting mostly of sedimentary and calc-alkaline felsic volcanic rocks. The rocks of the Renkajärvi suite have an E-MORB affinity and consist of mafic and intermediate volcanic rocks (Lahtinen, 1996; Sipilä & Kujala, 2014, Paper III). The volcanic rocks are often associated with plutonic rocks, which might represent magma chambers to the former (Peltonen, 2005; Sipilä & Kujala, 2014).

2.4 The Uusimaa belt

The volcanic rocks in the Uusimaa belt show continental margin and rifting type lithological associations and geochemical affinities (Kähkönen, 2005; Weihed et al., 2005). The belt has indications of an older, ~2.1–1.91 Ga contribution to the magmatism as indicated by initial ε_{Nd} values around zero (Patchett & Kouvo, 1986; Huhma 1986; Lahtinen & Huhma, 1997; Paper I) as well as detrital zircons of those ages in metasedimentary rocks and inherited zircons in igneous rocks (e.g., Claesson et al., 1993; Lahtinen et al., 2002, 2010; Ehlers et al., 2004; Bergman et al., 2008).

The relationship between the Häme and Uusimaa belts is ambiguous (see Kähkönen 2005). Korja et al. (2006) regarded the Häme and Uusimaa belts as separate terranes, whereas Väisänen and Mänttäri (2002) suggested that the belts belonged to the same arc system but were rifted apart. The rift basin was filled with felsic volcanic rocks, tholeiitic mafic/ultramafic lavas with E-MORB affinity (1.88–1.87 Ga), sedimentary carbonates (now marbles) and detrital sediments (now mica gneisses, e.g., Lahtinen et al., 2010; Nironen et al., 2016 and references therein).

3 Materials and methods

3.1 Field work and sample preparation

The field work was conducted in summer field seasons 2015, 2016 and 2017. In all, over 250 bedrock observations were made, including structural measurements, and 195 rock samples were collected. Samples selected for further investigation were cut in half in the rock laboratory of the Geohouse in the Department of Geography and Geology at the University of Turku. Half of the sample was stored as a duplicate and the other half was split in three pieces for: (i) thin section preparation, (ii) whole rock geochemistry and (iii) possible zircon separation for zircon U-Pb dating and Lu-Hf analysis.

3.2 Petrography

Thin sections were prepared at the thin section facilities at the Geohouse. Both polished and glass covered sections were prepared. Mineral identification was made using optical microscopy, and identification of the zircons, monazites and baddeleyites from epoxy mount (see preparation method in 3.4) were done using JEOL JSM-7100F FE-SEM equipped with the EDS analyser in the Finnish Geosciences Research Laboratory (SGL) at the Geological Survey of Finland, Espoo.

3.3 Whole rock geochemistry

A total of 161 samples were analysed for the whole rock geochemistry at Acme Analytical Laboratories Ltd. (Acme) in Vancouver, Canada (Papers I-III), at Activation Laboratories Ltd. (Actlabs), Ancaster, Canada (Paper I), and at Genalysis in Perth, Australia (Paper I). The analytical relative precision is 0.5–3 % for the major oxides, Cr_2O_3, Sc and F and 7 % for the other elements whereas accuracy is better than 95 % for the major oxides, Cr_2O_3, Sc and F and better than 91 % for the other elements. Full analytical descriptions can be found in the Papers I-III.

A total of 13 samples were selected for whole rock Sm-Nd analyses. Nine of the whole-rock powders of the investigated rocks were analysed for their Sm and Nd contents and Nd isotope compositions in the Laboratory for Isotope Geology at the Swedish Museum of Natural History using a Finnigan MAT261 multicollector mass spectrometer (Paper I). Four of the Sm-Nd isotope analyses were conducted with a Nu Plasma HR multicollector ICP-MS in the SGL (Paper II). Detailed analytical procedures are described in Papers I and II.

3.4 Zircon U-Pb dating

About 1–5 kg of the sample was selected for zircon separation. The zircon grains were separated using the standard procedure involving crushing, panning, heavy liquid separation, magnetic separation, and hand picking. The grains were mounted in an epoxy resin and sectioned approximately in half and polished. Back-scattered electron (BSE) images were done using JEOL JSM-7100F FE-SEM in the SGL.

Two methods were used for the zircon U-Pb analyses. Part of the analyses were performed using a Nu Plasma AttoM single collector ICP-MS in the SGL connected to a Photon Machine Excite laser ablation system. Rest of the samples were analysed using a Nu Plasma HR multicollector ICP-MS in the SGL using a technique very similar to Rosa et al. (2009), except that a Photon Machine Analyte G2 laser ablation system was used. The calibration standard zircon GJ-1 (609 ± 1 Ma; Belousova et al., 2006) and in-house standard A382 (1877 ± 2 Ma; Huhma et al., 2012) were run at the beginning and the end of analytical session and at regular intervals during the session. Plotting of the U-Pb isotopic data and age calculations were performed using the Isoplot/Ex 4.15 program (Ludwig, 2012). All the ages were calculated with 2σ errors and without decay constants errors. The full analytical conditions are described in Paper I.

3.5 Zircon Lu-Hf analysis

The zircon Hf isotope analyses were carried out on the same grains that were dated, using the Nu Plasma HR multicollector ICP-MS in the SGL with a technique similar to Heinonen et al. (2010) except that the Photon Machine Analyte G2 laser ablation system was used. Standard zircons GJ-1 and LV-11 were run at frequent intervals. Multiple analyses of GJ-1 during the course of the present study yielded a ^{176}Hf/^{177}Hf of 0.28194 ± 6 (1σ, n=132), which is just within the error of the results obtained by solution MC-ICP-MS analyses for GJ-1 (0.281998 ± 7, Gerdes and Zeh 2006; 0.282000 ± 5, Morel et al., 2008). Data obtained over a 5-year period indicate an accuracy within the observed external reproducibility on GJ-1 of ± 0.000048, which gives a conservative estimate of an uncertainty of ± 1.8 ε-units (2SD). The full analytical description can be found in Papers I and II.

4 Results

4.1 Sample description

The analysed samples are divided into six groups based on their age and geochemical features: 1.89 Ga rift-related Uunimäki gabbro (UGB; n = 8), 1.89–1.87 Ga arc-related mafic rocks (n = 71), 1.89–1.87 Ga arc-related felsic rocks (n = 36), 1.86 Ga high-Nb magmatism (n = 14), 1.86 high-Mg magmatism (n = 21) and 1.86 Ga adakite-like magmatism (n = 11). Figure 3 shows the spatial distribution of the collected samples within the study areas. In general, only arc-related felsic and mafic rocks were found from the study areas Ia and Ib whereas rift-related (Uunimäki gabbro) and arc-related mafic rocks were found from the study area III. The study area II shows wide range of sample compositions including mafic and felsic arc-related rocks and 1.86 Ga high-Nb, high-Mg and adakite-like rocks.

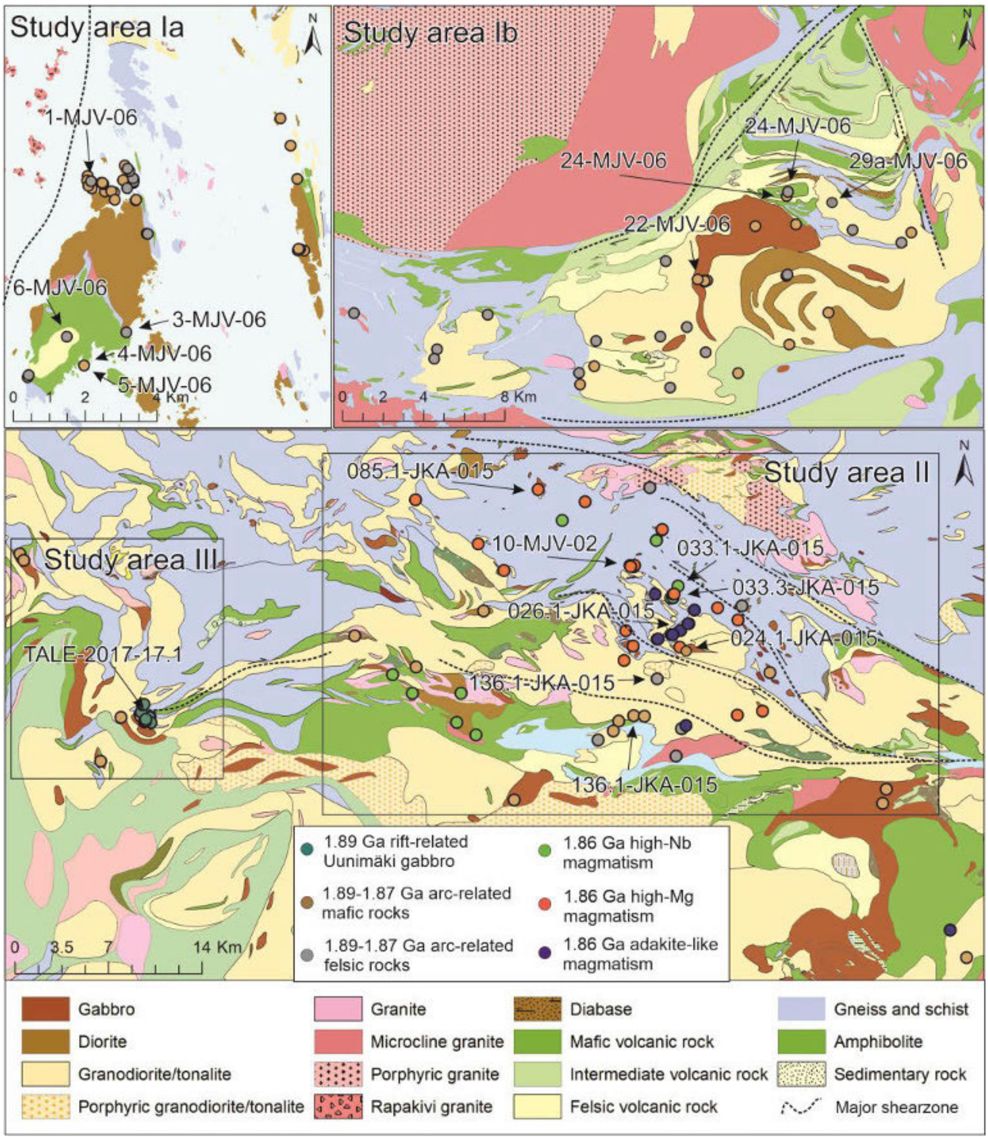

Figure 3. Simplified lithological map of the study areas (modified after Bedrock of Finland – DigiKP). with sampling sites indicated. Labelled samples refer to U-Pb, Sm-Nd and Lu-Hf samples (Tables 1, 2 and Figure 7). Location of the study areas within the southern Finland are shown in the Figure 2.

4.2 Whole rock geochemistry

The composition of the samples ranges from gabbros to granites in the Total Alkali vs. Silica diagram (TAS; Figure 4). The arc-related rocks show rather large spread in terms of alkali content whereas the rift-related, high-Nb, high-Mg and adakite-like rocks indicate more coherent compositions.

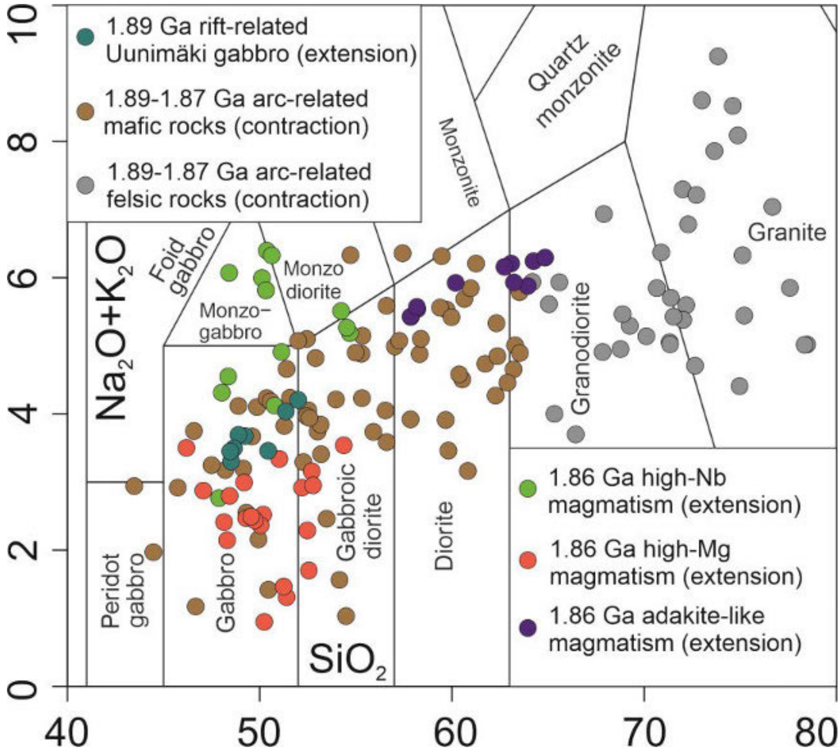

Figure 4. TAS diagram (Middlemost, 1985) for the samples of this study.

The sample groups show distinctive trace element characteristics indicating different tectonic settings (Figure 5). In general, the rift-related Uunimäki gabbro show E-MORB-like geochemical features while the arc-related rocks show enrichment in subduction mobile-elements such as LILE and LREE. Each of the 1.86 Ga groups express distinct geochemical features: the high-Nb rocks show OIB-like compositions, the high-Mg rocks have high MgO, Ni and Cr content (Figure not shown) and compositions between E-MORB and the mafic arc-related rocks whereas the adakite-like rocks show similar features as the felsic arc-related rocks except being enriched in Sr and depleted in Y and HREE.

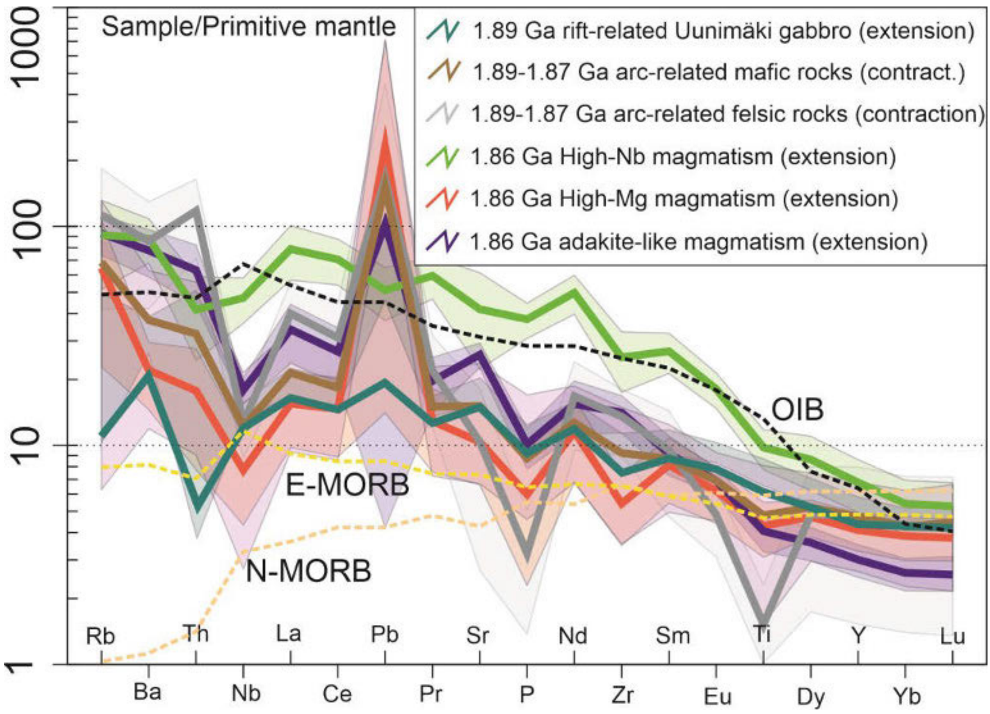

Figure 5. Primitive mantle normalised (Sun & McDonough, 1989) multielement diagram for the samples of this study. The dark lines represent average of the different groups and the transparent areas represent 2SD of the results.

4.3 Zircon and monazite U-Pb ages

Ten samples were analysed for zircon U-Pb ages and two samples for monazite U-Pb ages. Zircon and monazites morphologies, textures and possible distinctive domains were determined on the BSE images (Figure 6).

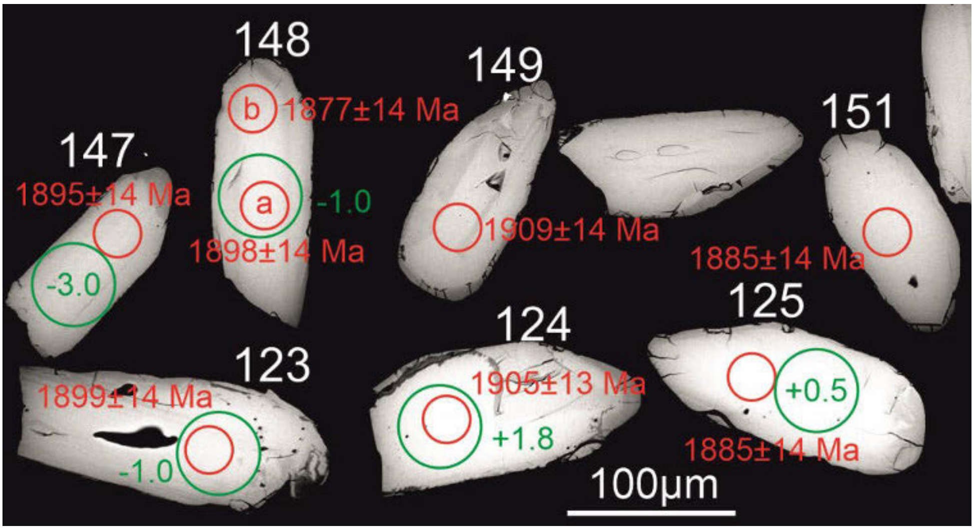

Figure 6. BSE-images of zircon from the Uunimäki gabbro with U-Pb ages (red) and Lu-Hf ε_{Hf} (green) spots indicated.

The rocks show crystallisation ages between 1892 and 1857 Ma. Inherited zircons were found from most of the samples with ages varying between 2247 and 1885 Ma. The zircon U-Pb results are shown in Table 1.

Table 1. Zircon and monazite U-Pb ages. See location in Figure 3.

Sample ID	**Rock type**	**Location**	**Crystallisation age**	**Inherited ages**	**Paper**
3-MJV-06	Granodiorite	Ia (Enklinge)	1882 ± 6 Ma (zircon U-Pb)	2247-2049 Ma	I
29a-MJV-06	Granodiorite	Ib (Orijärvi)	1892 ± 4 Ma (zircon U-Pb)	-	I
024.1-JKA-015	Gabbro	II (Urjala)	1880 ± 5 Ma (zircon U-Pb)	1921-1900 Ma	II
136.1-JKA-015	Granodiorite	II (Urjala)	1881 ± 4 Ma (zircon U-Pb)	1970-1895 Ma	II
10-MJV-02	HMG dyke[1]	II (Urjala)	1861 ± 4 Ma (zircon U-Pb)		II
085.1-JKA-015	HMG dyke	II (Urjala)	1862 ± 7 Ma (zircon Pb-Pb)	2012-1882 Ma	II
033.1-JKA-015	HNB dyke[2]	II (Urjala)	1861 ± 6 Ma (zircon U-Pb) 1861 ± 12 Ma (monazite U-Pb)	2196-1878 Ma	II
033.3-JKA-015	HNB dyke	II (Urjala)	1857 ± 5 Ma (zircon U-Pb) 1861 ± 12 Ma (monazite U-Pb)	-	II
026.1-JKA-015	Adakite-like	II (Urjala)	1862 ± 6 Ma (zircon U-Pb)	1888-1885 Ma	II
TALE-2017-17.1	Gabbro	III (Uunimäki)	1891 ± 5 Ma (zircon U-Pb)	1920-1917 Ma	III

1 HMG = high-Mg gabbro; 2 HNB = high-Nb gabbro

4.4 Whole rock Sm-Nd isotope data

Thirteen samples were analysed for the whole rock Sm-Nd isotopes. In general, the samples show mildly depleted initial ε_{Nd} values between DM and chondritic values. The whole rock Sm-Nd results are shown in Table 2.

Table 2. Whole rock Sm-Nd data. See locations in Figure 3.

Sample-ID	Rock type	Location	U-Pb age (Ma)	$^{144}Nd/^{143}Nd_i$	ε_{Nd} i	Paper
1-MJV-06	Intermediate dyke	Ia (Enklinge)	1882	0.512267	+1.9	I
3-MJV-06	Granodiorite	Ia (Enklinge)	1882	0.511825	+1.1	I
4-MJV-06	Basalt	Ia (Enklinge)	1882	0.512233	+1.9	I
5-MJV-06	Basalt dyke	Ia (Enklinge)	1882	0.512233	+2.9	I
6-MJV-06	Rhyolite	Ia (Enklinge)	1882	0.511958	+1.2	I
22-MJV-06	Gabbro	Ib (Orijärvi)	1892	0.512554	+2.0	I
23-MJV-06	Rhyolite	Ib (Orijärvi)	1892	0.511537	-0.3	I
24-MJV-06	Basalt	Ib (Orijärvi)	1892	0.511948	+0.2	I
29a-MJV-06	Granodiorite	Ib (Orijärvi)	1892	0.511506	+0.2	I
10-MJV-12	HMG dyke	II (Urjala)	1860	0.512236	+3.8	II
026.1-JKA-015	Adakite-like	II (Urjala)	1862	0.511746	+3.1	II
033.3-JKA-015	HNB dyke	II (Urjala)	1857	0.511581	+2.4	II
182.1-JKA-015	Granodiorite	II (Urjala)	1880	0.511739	+2.8	II

4.5 Zircon Lu-Hf isotope data

The zircon Lu-Hf isotopes were analysed on the same samples that were analysed for the zircon U-Pb. The zircons show mostly chondritic to subchondritic initial ε_{Hf} values, but also more depleted values occur. A few inherited grains were also analysed, which show a trend towards DM. The zircon Lu-Hf results are shown in Figure 7.

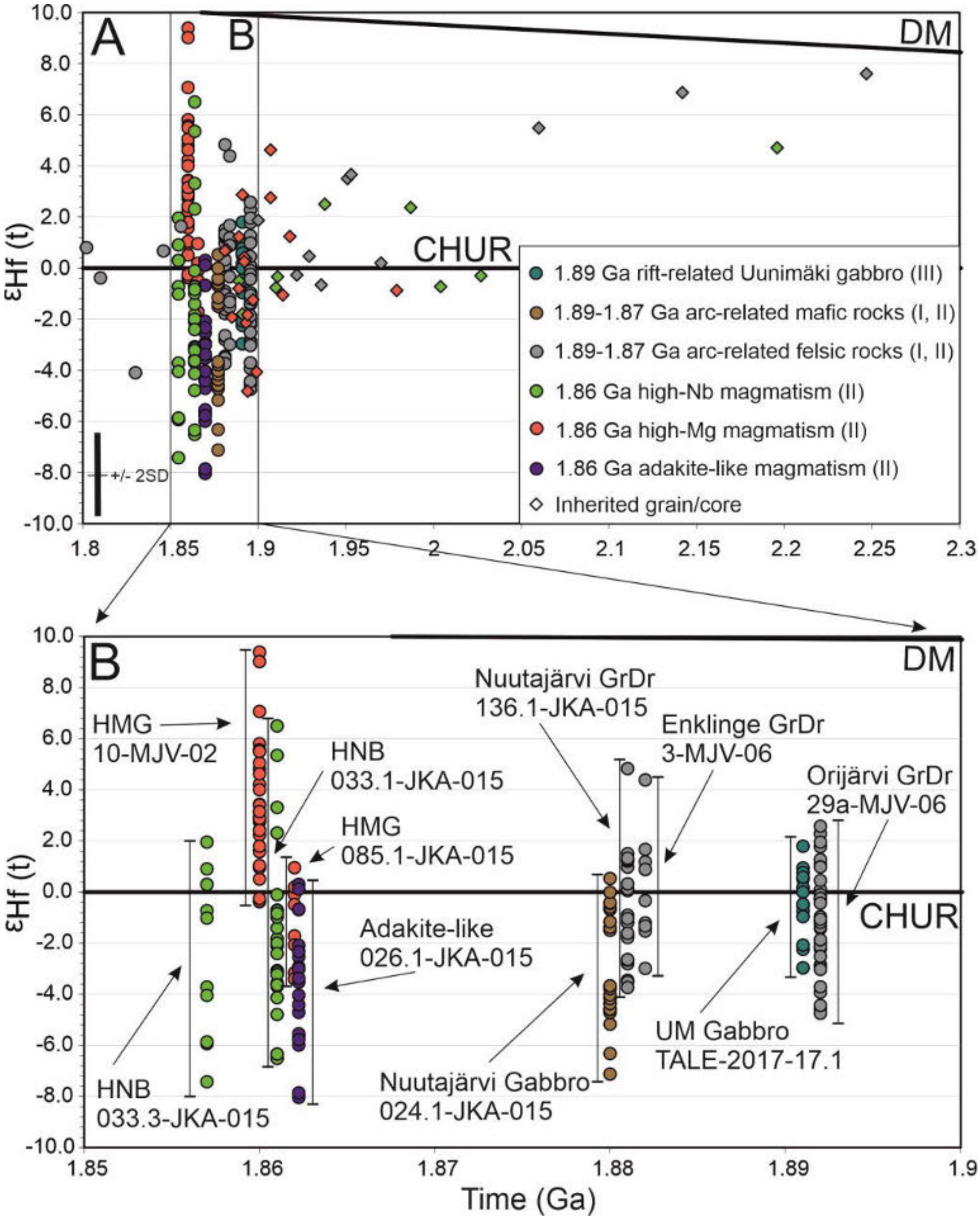

Figure 7. A: Zircon ε_{Hf} vs. age diagram for the samples of this study. B: close-up of the magmatic zircon ε_{Hf} values. CHUR=chondritic uniform reservoir (Bouvier et al., 2008); DM=depleted mantle (Griffin et al., 2000). See locations in Figure 3.

4.6 Review of the results

4.6.1 Paper I

This publication presents whole rock geochemical, U-Pb, Sm-Nd, and Lu-Hf isotope data from two 1.9–1.88 Ga magmatic centres in southern Finland: the Enklinge and Orijärvi areas. They comprise plutonic centres surrounded by extrusive volcanic rocks of corresponding ages and chemical compositions. The rock types range from gabbros to granites and indicate a subduction-related continental margin setting. The zircons from the Orijärvi granodiorite define an age of 1892 ± 4 Ma whereas the Enklinge granodiorite yields an age of 1882 ± 6 Ma. Several inherited ages of 2.25–1.95 Ga as well as younger ages of 1.86–1.80 Ga were found in the Enklinge granodiorite. The initial ε_{Nd} values of the mafic rocks from both locations fall in the range +1.1 to +2.9, whereas the felsic rocks exhibit initial ε_{Nd} values of -0.4 to +1.2. The magmatic zircons from the Orijärvi and Enklinge granodiorites show average initial ε_{Hf} values of -1.1 (at 1892 Ma) and zero (at 1882 Ma), respectively, both with a spread of about 7 ε-units. The initial ε_{Hf} values for the inherited zircons from Enklinge range from +3.5 to +7.6 with increasing age. The Sm-Nd data indicate that the mafic rocks were derived from a "mildly depleted" mantle source while the felsic rocks show some crustal contribution. Also, the variation in ε_{Hf} values indicates minor mixing between mildly depleted mantle derived magmas and crustal sources. The U-Pb ages and Hf isotopes for inherited zircons from the Enklinge granodiorite suggest the presence of juvenile Svecofennian "proto-crust" at depth.

4.6.2 Paper II

This publication presents modal compositions, whole-rock major and trace element and Sm-Nd isotopic compositions as well as zircon and monazite U-Pb ages and zircon Hf isotopes from rare 1.86 Ga high-Nb gabbros (HNB), high-MgO gabbros (HMG) and adakite-like rocks in the Pirkanmaa belt. These data are compared to the surrounding 1.90–1.87 Ga continental arc-type rocks from the area. The 1.86 Ga magmatic rocks are divided into three groups: 1) high-Nb gabbros (HNB) which are enriched in $Fe_2O_3^T$, TiO_2, P_2O_5, F, LILE, and HFSE (especially Nb; 18.9–44 ppm), show positive initial ε_{Nd} value, and near-chondritic but variable initial zircon ε_{Hf} values; 2) high-MgO gabbros (HMG) which are characterised by high MgO, CaO, Cr and Ni contents, slight enrichment in LILE, positive ε_{Nd}, and positive but variable zircon ε_{Hf} values; 3) adakite-like rocks showing high Al_2O_3 and Na_2O contents, slight enrichment in LILE, relative depletion in some HFSE, positive ε_{Nd} value, and chondritic to negative zircon ε_{Hf} values. The three groups yield zircon U-Pb ages of ~1.86 Ga and exhibit undeformed textures in contrast to the surrounding supracrustal rocks metamorphosed at ~1.88 Ga. Trace element modelling of partial melting suggests that arclogites, with compositions similar to pyroxenite xenoliths found in the kimberlite pipes of eastern Finland, are the source for the HNB rocks. In contrast, subduction-modified mantle peridotite is the source for the HMG rocks, and a mafic lower crustal source is suggested for the adakite-like rocks. The following geodynamic model is suggested: (rutile-bearing) arclogite formation at 1.90–1.87 Ga followed by arclogite delamination and partial melting during extension of the thickened Svecofennian crust at 1.86 Ga.

4.6.3 Paper III

This manuscript describes the geochemistry, zircon Lu-Hf composition, age, and structure of the Uunimäki gabbro (UGB), located in the northern part of the Häme belt. The zircon U-Pb geochronology defines an age of 1891 ± 5 Ma for the UGB, which is slightly older than most mafic intrusions in south-western Finland. The obtained chondritic initial zircon ε_{Hf} values with E-MORB type geochemical affinity suggest a sub continental lithospheric mantle or mixed asthenospheric and lithospheric mantle source for the UGB. The overall geochemistry indicates that the UGB magma as well as other E-MORB type rocks in the Pirkanmaa and Häme belts were formed in a rift-related environment in a fore-arc region at 1.89 Ga preceded by arc-type magmatism at ~1.90 Ga and back-arc magmatism at ~1.92 Ga in the Tampere belt. Tectonic switching model is applied to characterise the timing, compositional and isotopical changes of early-orogenic magmatism in intervals of chancing extension and contraction. Structural characterisation provides a framework where gold mineralisations are preferentially located within the high-strain north-eastern domain of the UGB, within the fracture networks adjoining the high-strain zones.

5 Discussion

5.1 Age constraints

The ages obtained in this study show a spread between 1892–1857 Ma with inherited ages up to 2.25 Ga (Table I; Papers I-III). The age of the rift-related submarine Haveri formation located in the northern part of the Tampere belt is inferred to be 1.92–1.90 Ga and therefore it represents the oldest magmatism in southern Finland (Paper III, Vaasjoki and Huhma, 1999; Kähkönen, 2005; Lahtinen et al., 2009b). Older units, predating the Haveri formation, have not been dated but Sm-Nd data (Lahtinen & Huhma, 1997), sedimentation ages (e.g., Lahtinen et al., 2017) and evolved arc-type magmatism within the Tampere belt (Kähkönen, 2005) suggest occurrence of older crustal units. Subduction-related arc magmatism started approximately at 1.90 Ga, which is recorded by calc-alkaline volcanism in the Tampere belt (Kähkönen, 1989; Lahtinen, 1996; Kähkönen, 2005) and continued until 1.87 Ga in Southern Svecofennia (Papers I-III; Kähkönen, 2005; Nironen, 2005 and references therein). The oldest age of 1892 Ma for the volcanic arc magmas was obtained from the Orijärvi granodiorite in the Uusimaa belt but majority of the volcanic arc magmatism shows younger ages (Paper I; Huhma, 1986; Väisänen et al., 2002). The rift-related magmatism within the border zone between the Pirkanmaa and Häme belts is dated approximately at 1.89 Ga, which is indicated by the 1891 Ma age of the UGB (Paper III). This is the first zircon U-Pb age determination for such rocks and therefore it is obscure whether the other rift-related rocks are contemporaneous or older (Paper III; Lahtinen et al., 2017). Stratigraphic relations suggest that at least the Haveri formation and the Pirkanmaa belt picrites might be older but the Renkajärvi suite probably is coeval with the UGB. This stage is followed by the voluminous volcanic arc magmatism in southern Finland (Papers I-III; Kähkönen, 2005; Saalmann et al., 2010; Mäkitie et al., 2016, Lahtinen et al., 2017). In this study, 1882 Ma, 1881 Ma and 1880 Ma ages were obtained for the Enklinge granodiorite and the Nuutajärvi granodiorite and gabbro, respectively (Papers I, II). The following extensional tectonic regime, which is inferred by opening of small rift-basins, now represented by lateritic paleosols and mature quartzites (Bergmann et al., 2008; Lahtinen and Nironen, 2010), is characterised by the rare within-plate-type magmatism, which started approximately at 1.87 Ga and lasted till 1.84 Ga (Paper II, Väisänen et al., 2012b; Nevalainen et al., 2014). During this extensional stage gabbroic (HNB and HMG) and adakite-like dykes/small intrusions were emplaced in southern Finland. Zircon U-Pb analyses yielded ages between 1862 Ma and 1857 Ma for these intrusions (Paper II). The magmatic ages obtained in this study characterise the different tectonic stages of the Svecofennian orogen in southern Finland, which are discussed more in the following chapters.

Inherited zircons and xenocrystic cores are common in majority of the samples. These ages span 2.25–1.89 Ga and are similar to ages of detrital grains found in the Svecofennian metasedimentary rocks and inherited zircons previously found in igneous rocks, expect that no Archean ages were found (Papers I-III; Huhma et al., 1991; Lahtinen et al., 2009b; Lahtinen et al., 2017). This suggests some interaction of the magmas with older Paleoproterozoic crustal wall rocks or crustal recycling processes in the source (Papers I-III). Another explanation is the possible presence of juvenile, ~2.20–1.93 Ga “proto-Svecofennian” crust at depth, predating the early Svecofennian (1.90–1.86 Ga) magmatism (Paper I; Lahtinen & Huhma 1997; Andersson et al., 2006, Andersson et al., 2011). This proto-crust is not exposed at the present erosion level but it could have been a source at least for the granodioritic melts and inherited zircons.

Unambiguous metamorphic ages were not detected but Pb-loss was recorded in many samples, which might be due to later magmatic activity, later metamorphic event(s) or tectonic/fluid activity (Papers I-III). The HT-LP upper amphibolite to lower granulite facies metamorphism peaked at ~1.88 Ga in the Tampere and Pirkanmaa belts and later metamorphic events are not recorded in the region (Mouri et al., 1999; Rutland, 2004; Lahtinen et al., 2009b). In Southern Svecofennia there are some indications of ~1.86 Ga metamorphism (Väisänen et al., 2021; Vehkamäki et al., 2021) but generally this is overprinted by the regional metamorphic peak at ~1.82 Ga (Ehlers et al., 1993; Nironen, 1999; Väisänen et al., 2002; Mouri et al., 2005). The high thermal regime and fluid activity lasted at least till 1.79 Ga (Saalmann et al., 2009, 2010). Pb-loss is recorded by (i) high common-Pb and discordancy (Papers II, III), (ii) U-Pb ages propagating along concordia curve towards younger ages (Paper III, Corfu, 2013) or (iii) gradual decrease in ^{207}Pb/^{206}Pb ages (Papers I-III).

5.2 Sources and tectonic settings of the mantle-derived magmas in Svecofennian orogen

Majority of the igneous rocks in southern Finland were formed in a subduction related volcanic arc setting. Hallmark features for these rocks are the crystallisation age approximately at 1.88 Ga, mildly depleted initial ε_{Nd} values (Table 2), chondritic initial ε_{Hf} values (Figure 8), enrichment in subduction-mobile elements such as LILE and LREE and depletion in Nb, Ta and Ti as well as several characteristic trace element ratios such as high ratios in LILE/HFSE and LREE/HREE (Figures 5 and 8; Papers I-III). Moreover, bimodality is common, which is indicated by mingling of felsic and mafic magmas in many places (Papers I, II). All these observations argue for continental arc setting, which have been proposed by numerous researchers (e.g., Nironen & Bateman, 1989; Lahtinen, 1996; Kähkönen, 2005).

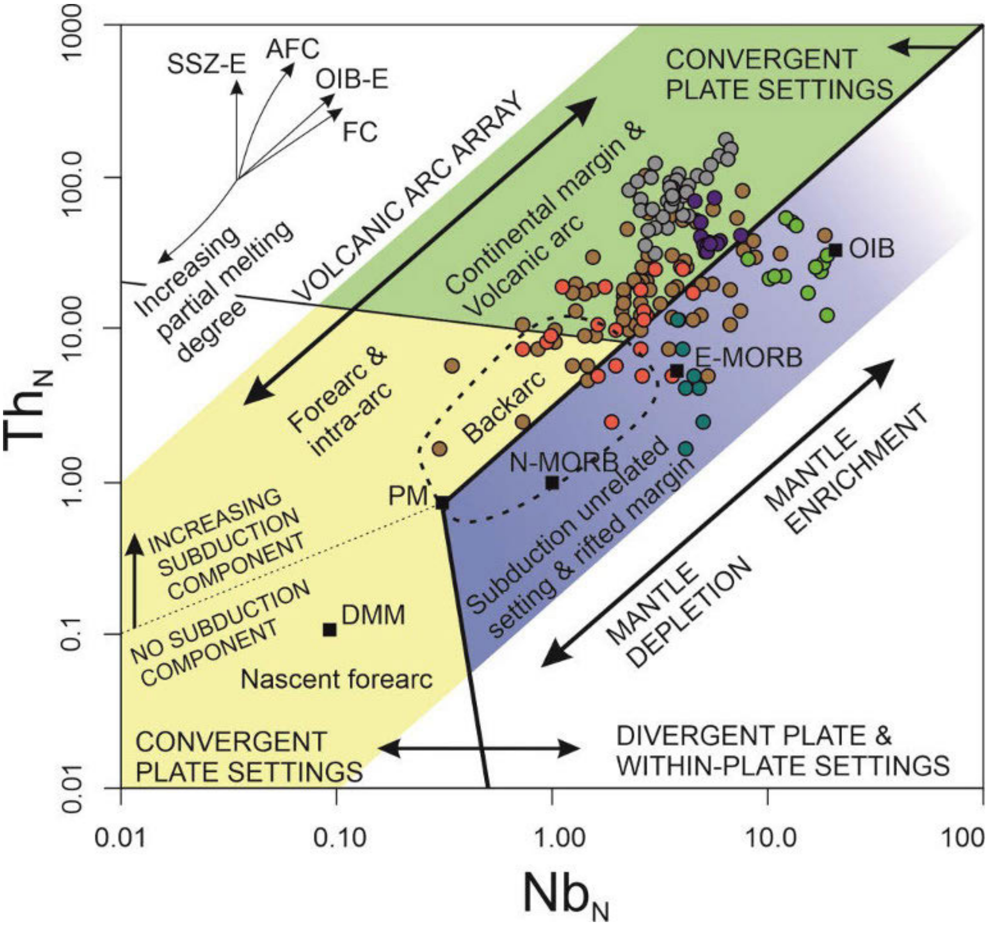

Figure 8. Th$_N$ vs. Nb$_N$ diagram (Saccani, 2015; normalised to N-MORB) for the samples of this study. DMM = Depleted MORB mantle (Workman & Hart, 2005); PM = primitive mantle, N-MORB, E-MORB, OIB (Sun & McDonough, 1989); SSZ-E = subduction zone enrichment, AFC = assimilation- fractional crystallisation, OIB-E = ocean island basalt-type enrichment, FC = fractional crystallisation. Colours as in Figure 5.

Mafic rocks with MORB signature are rare in southern Finland. The ~1.89 Ga UGB showing E-MORB type geochemical affinities is a prime example of these (Figure 8). Other rocks or the formations showing similar geochemical features are the Renkajärvi suite within border of the Häme and Pirkanmaa belts (Sipilä and

Kujala, 2014), the Haveri formation in the northern part of the Tampere belt (Kähkönen, 2005) and the Pirkanmaa belt picrites and other mafic volcanics (Peltonen, 1995). The obtained chondritic initial zircon ε_{Hf} values (Figure 7) for the UGB with E-MORB type geochemical affinity (Figures 5 and 8) suggest a subcontinental lithospheric mantle. The rather small variation within ε_{Hf} values point also to a single source. The overall geochemistry indicates that the UGB magma as well as the other E-MORB type rocks in the Pirkanmaa and Häme belts were formed in a rift-related environment. Rifting in a previously formed fore-arc region within a north-dipping subduction system (Hermansson et al., 2008; Saalmann et al., 2009; Chopin et al., 2020) is suggested for the tectonic environment. Rifting in a fore-arc region is favoured over back-arc environment due to age constraints (Paper III; Nironen, 1999; Kähkönen et al., 2005; Saalmann et al., 2010), structural vergence and overall tectonic models (Chopin et al., 2020; Mints et al., 2020). Slab retreat due to roll-back is suggested to cause the extension and related magmatism (Paper III).

The ~1.86 Ga extension- or rift-related within-plate-type magmatism show multiple sources (Figure 8). Trace element modelling of partial melting suggests that arclogites, i.e., lower crustal garnet pyroxenite cumulates (Lee et al., 2006) with compositions similar to the pyroxenite xenoliths found in the kimberlite pipes in eastern Finland (Hölttä et al., 2000; Peltonen et al., 2006), are the source for the HNB rocks. These (rutile-bearing) arclogites are suggested to have formed during the extensive felsic arc magmatism at 1.89–1.87 Ga. In contrast, subduction-modified mantle peridotite is the source for the HMG rocks, and a mafic lower crustal source is suggested for the adakite-like rocks. This model suggests that the rutile- and garnet-bearing pyroxenites are the source for the elevated Nb, Nb/Ta and OIB-like geochemical features in the HNB. The previously described ~1.86 Ga mafic intrusions from southern Finland (Väisänen et al., 2012a, 2012b; Nevalainen et al., 2014) seem to share the same features. Moreover, high Nb/Ta in the ~1.86 Ga HNB magmas seems to balance the low Nb/Ta observed in ~1.88 Ga arc rocks elsewhere in southern Finland (Figure 5) suggesting that arclogites are important Nb-reservoirs and in Nb/Ta fractionation processes during continental arc magmatism (Paper II; Tang et al., 2019).

5.3 Tectonic evolution of the early Svecofennian orogen

In general, the model of tectonic switching (Collins, 2002) with continuous subduction to the present north beneath a single continental margin with constant polarity is compatible with the early Svecofennian evolution in the Tampere, Pirkanmaa and Häme belts at 1.92–1.86 Ga as presented in Papers II, III. The tectonic switching model is supported by the HT-LP metamorphism at ~1.88 Ga

(Kilpeläinen, 1998; Mouri et al., 1999; Lahtinen et al., 2017) and cyclic change in the age and type of the magmatism, which result from hinge retreat (extension) and brief (~10 Ma) advance (contraction; Collins, 2002). Similar model has been previously applied to central Sweden (Hermansson et al., 2008; Stephens and Andersson, 2015) and southern Finland at 1.86–1.78 Ga (Saalmann et al., 2009). I infer that the rift-related magmas are related to the upper crustal extension while arc-type magmas can be related to either extension or contraction. However, when the arc-type magmas (or anatectic granites) are intruded into the axial planes of regional upright folds during crustal shortening event they can used to date the contractional phase. Here, the following magmatic evolution is suggested:

- 1.92–1.90 Ga: rift-related magmatism in the northern part of the Tampere belt (Haveri) and possibly in the Pirkanmaa belt (extension; Figure 9).
- 1.90–1.89 Ga: arc-type magmatism in the Tampere belt (extension?; Figure 9).
- 1.89 Ga: rift-related magmatism within the Tampere belt fore-arc region, i.e., in the Pirkanmaa belt and in the northern part of the Häme belt (extension; Figure 9).
- 1.89–1.87 Ga: arc-type magmatism in the Häme and Pirkanmaa belts (crustal thickening, alternating extension and contraction; Figure 10).
- ~1.86 Ga: high-Nb and adakite-like type magmatism in SW Finland (extension; Figure 11).

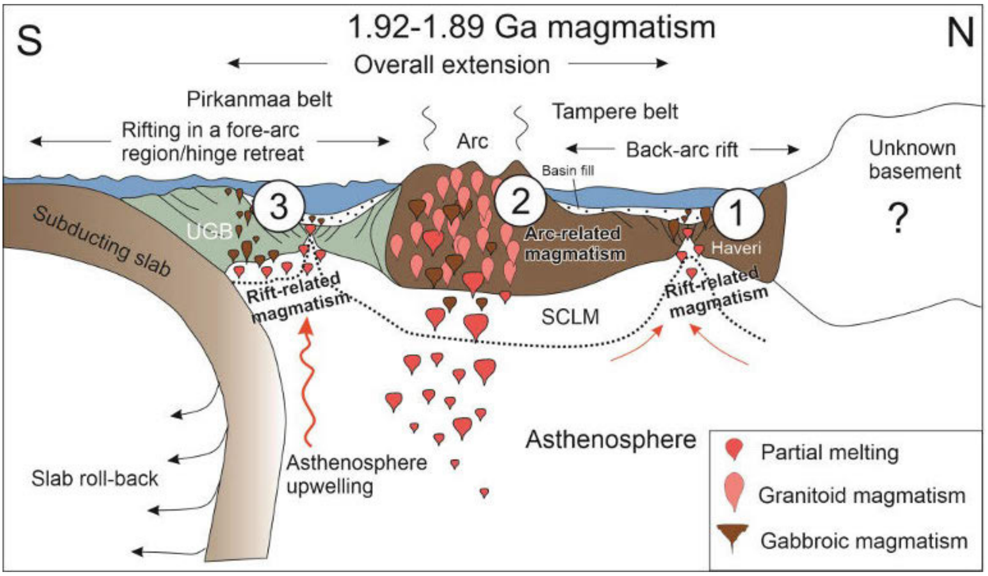

Figure 9. Schematic N-S cross-section of the Tampere and Pirkanmaa belts indicating the magmatic evolution at 1.92-1.89 Ga. 1) back-arc magmatism in the northern part of the Tampere belt at 1.92-1.90 Ga; 2) arc-type magmatism in the Tampere belt at 1.90-1.89 Ga; 3) rift-related magmatism in the forearc region (Pirkanmaa belt/northern Häme belt) of the Tampere belt at 1.89 Ga. SCLM = Sub continental lithospheric mantle. Not in scale.

In this model, the Haveri represents the back-arc of the Tampere belt (section 5.1; Staruss, 2003). The age range of the rift-related magmatism is still not very well constrained. Whether extensional tectonic regime prevailed continuously between 1.92–1.89 Ga or whether the extension at 1.92–1.90 Ga and at 1.89 Ga are separate events, would need more age determinations (Paper III). However, the quite well-documented arc-type magmatism between 1.90 and 1.89 Ga and the evidence of incipient rifting at ~1.89 Ga in the Tampere belt (Kähkönen et al., 2005 and references therein) suggest that the different types of magmatism overlapped and might be related to prolonged extensional event (Rutland et al., 2004).

The 1.89 Ga rift-related magmatism was shortly followed by crustal shortening and volcanic arc-type magmatism in the Häme and Pirkanmaa belts at ~1.88–1.87 Ga (Papers I, II; Suominen, 1988; Nironen, 1999; Kähkönen, 2005; Saalmann et al., 2009, 2010; Tiainen et al., 2013; Mäkitie et al., 2016). The contractional phase approximately at 1.88 Ga or slightly later is recorded by regional upright folding and arc-type magmas intruding the axial planes of the folds during shortening (Kilpeläinen. 1998; Nironen, 1999; Saalmann et al., 2010). During this stage vertical magmatic accretion and the formation of rutile-bearing lower crustal garnet-pyroxenite layer, i.e., arclogite, as a result of the voluminous and abundant calc-alkaline felsic magmatism is suggested (Figure 10).

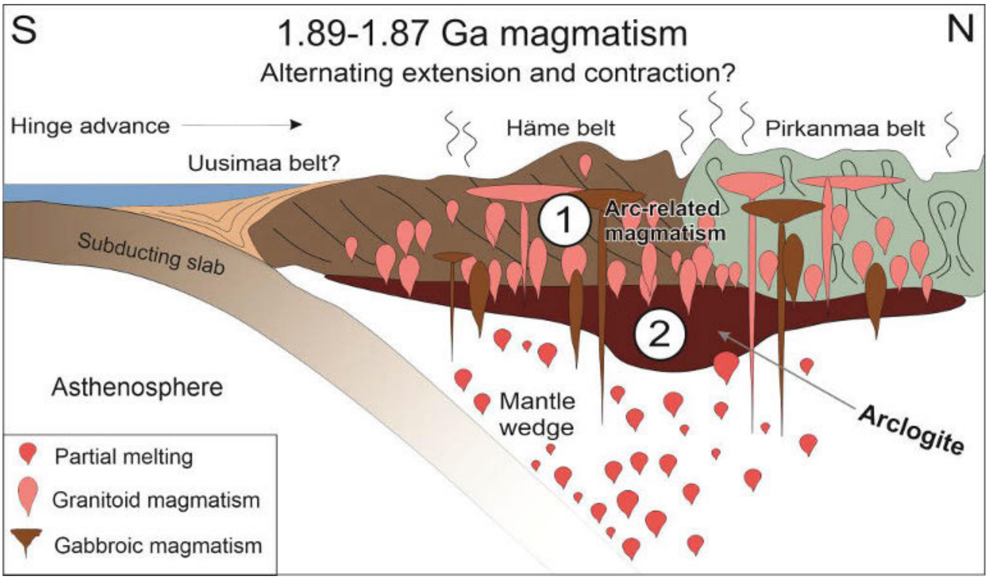

Figure 10. Schematic N-S cross-section of the Pirkanmaa and Häme belts indicating the magmatic evolution at 1.89-1.87 Ga. 1) voluminous arc-type magmatism prevailed during this stage; 2) growth of the arclogite layer complementary to the calc-alkaline felsic magmatism. Not in scale.

The change from the ~1.88 Ga calc-alkaline arc-type magmatism to the 1.86 Ga within-plate type high-Nb, high-Mg and adakite-like magmatism the following evolution is suggested: i) partial delamination of the rutile-bearing arclogites triggered by an extensional tectonic regime, the high density of the arclogites, and the presence of hot and viscous upper mantle; ii) upwelling of the juvenile and subduction-modified mantle (wedge) peridotite; and iii) partial melting of the rutile-bearing arclogites to generate the high-Nb magmas, partial melting of the mantle (wedge) peridotite to generate the high-Mg magmas and partial melting of the mafic lower crust to generate the adakite-like rocks (Figure 11).

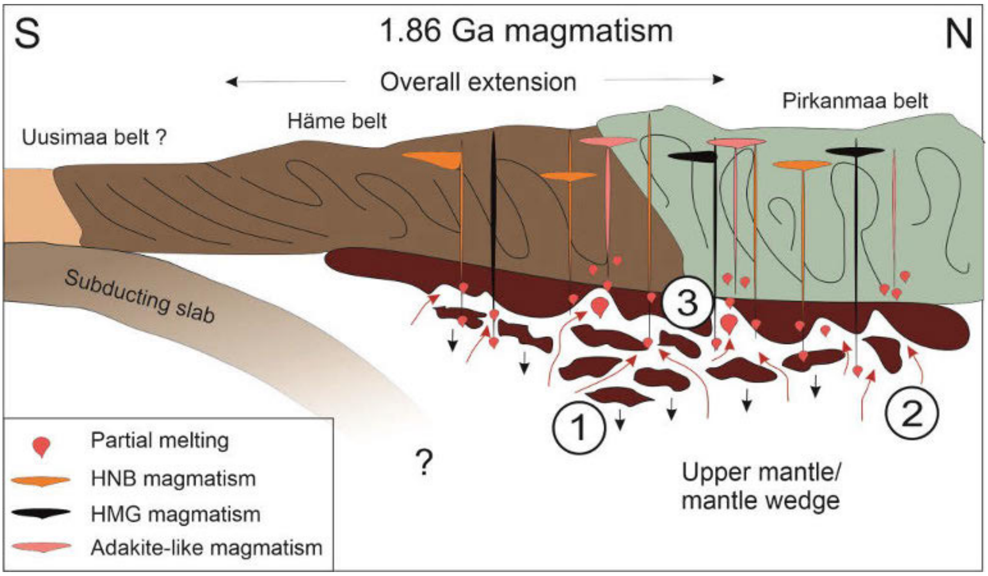

Figure 11. Schematic N-S cross-section of the Pirkanmaa and Häme belts indicating the magmatic evolution at 1.86 Ga. 1 = (partial) delamination of the dense arclogite layer and partial melting of the arclogites to produce the HNB magmas; 2) upwelling and partial melting of the upper mantle to produce the HMG magmas; 3) partial melting of the lower crust to produce the adakite-like magmas. Not in scale.

The evolution of the Uusimaa belt does not straightforwardly fit to the tectonic switching model of the rest of Southern Svecofennia. This is mostly due to the older magmatic ages within the Uusimaa belt compared to the belts in the north (Paper I). The Uusimaa belt also contains E-MORB (Väisänen & Mänttäri, 2002) to transitional MORB-type rocks (Väisänen and Westerlund, 2007) but whether these can be correlated to the MORB-type rocks in the Häme and Pirkanmaa belts is unclear. It is possible that the Häme and Uusimaa belts were rifted apart during ~1.86 Ga extensional stage (Väisänen and Mänttäri, 2002). Another alternative is that the Uusimaa belt originated from the juvenile Svecofennian proto-crust as suggested by the inherited zircon Hf-trend in the Enklinge granodiorite (Paper I). This might indicate that the Uusimaa belt had a distinct geological evolution compared to the rest of southern Finland during the early Svecofennian orogeny.

5.4 Implications to the crust generation during Paleoproterozoicum

The period around 1.9 Ga is recognised as one of the major juvenile crustal growth episodes world-wide, which is linked to the supercontinent cycle (e.g., Stein and Hofmann, 1994). The Svecofennian orogen covers an area of ~1 million km^2 (Lahtinen et al., 2009a) and roughly 50–70 % of it was formed during the first 50 m.y. period of the orogeny (Paper III). This suggests that the early Svecofennian tectonic switching cycle represents a period of very rapid crust generation (Paper III; Hermansson et al., 2008). Although the rift-related magmatic rocks comprise < 5 % of the total area of the bedrock in SW Finland, the magmatic influx to the crust was mostly juvenile during the rift-related magmatism (Paper III). The recycling processes are arguably more notable during the voluminous bimodal magmatism within or after the contraction events, which are recorded by low zircon ε_{Hf} values (Papers I-III). Besides the recycling processes, the magmatism during contraction provides magmatic vertical accretion (e.g., Cawood et al., 2009). Moreover, the ancient crustal growth pulses might be explained simply by subduction and slab retreat, i.e., by alternating extensional and contractional tectonic regimes (Paper III; Kemp et al., 2009).

The arclogite-model can explain the formation of the extremely thick crust and the high velocity lower crust present in the central Fennoscandian Shield by partial stabilization of the dense arclogite layer (Paper II). The model suggests that crustal thickening started already at ~1.89 Ga by arclogite formation during the arc-type magmatism and Andean type magmatic vertical accretion (Papers I and II; Cawood et al., 2009; Lahtinen et al., 2009a). This study indicates that the formation, delamination, and partial melting of arclogites in the Precambrian orogens might be a “normal” phenomenon rather than a special case, especially within thick continental arcs. Moreover, a new possible mechanism for the generation of high-Nb basalts/gabbros is presented (Paper II).

Finally, the results of structural characterisation of the gold-bearing UGB indicate that neither the geochemical composition nor the age of the intermediate-mafic intrusive host rocks play a major role in controlling the formation of gold mineralisation. By contrast, the localisation of orogenic gold is controlled by localised structures (shear zones, fractures), and the variation in lithological composition of the intrusive host may contribute to the style of the mineralisation (Paper III; Groves et al., 1998; Saalmann et al., 2009; Goldfarb and Groves, 2015). These observations can be applied more widely in orogenic gold exploration in deformed Precambrian terrains. As a rule of thumb, the following might be used as a proxy for gold: (i) mechanical contrast between the host-rock and country-rocks, i.e., mafic intrusive vs. metamorphosed supracrustal rocks, and (ii) 3^{rd} – 4^{th} order structures nearby the larger regional shear zones.

6 Summary

This dissertation describes the magmatic evolution of the early Svecofennian orogen in southern Finland in central Fennoscandian shield during 1.92–1.86 Ga. Six distinct rock associations were characterised based on distinctive geochemical features and ages: (i) 1.89 Ga rift-related rocks, 1.89–1.87 Ga arc-related (ii) mafic and (iii) felsic rocks, 1.86 Ga within-plate-type rock association including (iv) high-Nb gabbros (HNB), (v) high-Mg gabbros (HMG) and (vi) adakite-lite rocks. The findings in this study suggest that arc magmatism during the contractional stages of the orogenic evolution, whereas E-MORB/within-plate type magmatism was dominant during the extensional stages. Such timing and compositional and isotopic changes of early-orogenic magmatism are broadly compatible with intervals of extension and contractional, i.e., tectonic switching model and may provide a perspective to rapid build-up of Paleoproterozoic crust. In addition, a model of formation, delamination, and partial melting of arclogites is suggested to describe the evolution and shift from ~1.88 Ga arc magmatism to the 1.86 Ga within-plate type magmatism. The model explains the extremely thick crust and high velocity lower crust encountered in central Fennoscandian Shield by partial stabilization of the dense arclogite layer. Moreover, this study presents a new possible mechanism for the generation of high-Nb basalts/gabbros by partial melting of rutile-bearing arclogites beneath thickened arc crust and is the first possible example of arclogite formation in a Paleoproterozoic orogen. Finally, U-Pb ages and Hf isotopes for inherited zircons from the Enklinge granodiorite suggest the presence of juvenile Svecofennian "proto-crust" at depth.

Acknowledgements

First, I want to express my gratitude to my principal supervisor Markku Väisänen. Without his guidance through these years this thesis would have never finished. It was Väiski who had the original idea for the thesis, and although the plans were modified many times during the years this study includes a lot of things from the very first research plan we made (in Pub Kultainen Hirvi). Since then, I have admired his extremely wide knowledge in all the fields of bedrock geology - geochemistry, isotope geology, structural geology and, not the least, field work. However, it was probably writing the papers and abstracts where I most needed a helping hand. Thank you for conversations, support, advices and, most of all, patience. This really took some time. I want to thank my second supervisor Pietari Skyttä. I thought I was a proper field geologist before going to field with Pietu but it occurred me that I knew nothing. I learned more in a few days than I had learned during previous field seasons. Pietu has also showed me what it is to be really, I mean really, efficient. Whether it comes to writing, making plans, or doing field work Pietu has already done it while I am still thinking how to do it. Thank you for support, guidance and teaching me some structural geology. My third supervisor, Karin Högdahl, is thanked for the support and advices during the thesis.

The most important collaborator during this project was the Finnish Geosciences Research Laboratory (SGL) at the Geological Survey of Finland (GTK). I have spent days (and nights) in the lab running the analyses at the mass spectrometers and I also was employed at the lab for several months. It was always nice to go there, mostly because of the great and expert staff. The whole staff at the SGL is thanked for their help and support. Especially I want to thank Hugh O'Brien, Yann Lahaye, Hannu Huhma and Bo Johansson for your guidance with the equipment and interesting conversations. During the years I also worked in a cooperation project between the GTK and the University of Turku and I want to thank Janne Hokka, Markku Tiainen and Hanna Leväniemi for support and assistance during the project.

There are several colleagues, who I wish to thank. I'm grateful to the whole Geology section of the University of Turku and Geology and Mineralogy section of the Åbo Akademi. I started my undergraduate studies in 2006, so the Geology section really feels like a home. Special thanks go to my office mates Heider Al Humadi and

Evgenia Salin for the interesting conversations and support. Tuomas Leskelä, Iiro Pitkälä, Jukka Manninen and Teemu Vehkamäki are thanked for cooperation during the field seasons and Arto Peltola is thanked for the help with thin sections and epoxy mounts. I wish to thank Jussi Heinonen at the University of Helsinki and Åke Johansson at the Swedish Museum of Natural History for the extremely professional help and support during the research. Financial support was received from the Doctoral Programme in Biology, Geography and Geology, Finnish Cultural Foundation, Turku University Foundation and Suomen Tiedeseura who are all thanked for their support.

Thank you, all my friends for making me what I am. Special thanks goes to my friends from the University: Antti Mäkelä, Sami Jokinen, Jani Jäsberg, Mikko Lamberg, Jarkko Heinonen and especially to the extraordinary group of Geokehvelit™. It was great!

Finally, I wish to thank my family. I cannot express enough my gratitude. I received support, help and love during the years, which have kept me going. Thank you, mom and dad for the support and help at home. I wish to thank my sisters Anna and Maija and their spouses Ilpo and Jerry and my godson Leo for everything. Especially, for all the journeys we have taken together. The warmest thanks of all goes to my dear wife Pilvi for the support, patience, understanding and love during these years. And our beloved daughter Vilja and active dog Kuura, I am grateful for you just being here. You turn my thoughts to completely different matters and you helped me to do the final push to finish the thesis.

25.3.2021

Jaakko Kara

List of References

Andersson, U. B., Högdahl, K., Sjöström, H., & Bergman, S., 2006. Multistage growth and reworking of the Palaeoproterozoic crust in the Bergslagen area, southern Sweden: evidence from U–Pb geochronology. *Geological Magazine*, 143(5), p. 679–697.

Andersson, U.B., Begg, G.C., Griffin, W.L., & Högdahl, K., 2011. Ancient and juvenile components in the continental crust and mantle: Hf isotopes in zircon from Svecofennian magmatic rocks and rapakivi granites in Sweden. *Lithosphere*, 3(6), p. 409–419.

Allègre, C. J., 2008. Isotope Geology. *Cambridge University Press*, Cambridge, 512 p.

Belousova E.A., Griffin W.L. & O'Reilly S.Y., 2006. Zircon crystal morphology, trace element signatures and Hf isotope composition as a tool for petrogenetic modeling: examples from Eastern Australian granitoids. *Journal of Petrology,* 47(2), p. 329–353.

Bergman, S., Högdahl, K., Nironen, M., Ogenhall, E., Sjöström, H., Lundqvist, L. & Lahtinen R., 2008. Timing of Palaeoproterozoic intra-orogenic sedimentation in the central Fennoscandian Shield; evidence from detrital zircon in metasandstone. *Precambrian Research*, 161(3-4), p. 231–249.

Bogdanova, S., Gorbatschev, R., Skridlaite, G., Soesoo, A., Taran, L., & Kurlovich, D., 2015. Trans-Baltic Palaeoproterozoic correlations towards the reconstruction of supercontinent Columbia/Nuna. *Precambrian Research*, 259, p. 5–33.

Bouvier, A., Vervoort, J.D. & Patchett, P.J., 2008. The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters*, 273(1), p. 48–57.

Cawood, P. A., Kröner, A., Collins, W. J., Kusky, T. M., Mooney, W. D., & Windley, B. F., 2009. Accretionary orogens through Earth history. *Geological Society, London, Special Publications*, 318(1), p. 1–36.

Chopin, F., Korja, A., Nikkilä, K., Hölttä, P., Korja, T., Abdel Zaher, M., Kurhila, M., Eklund, O. & Rämö, O.T., 2020. The Vaasa Migmatitic Complex (Svecofennian Orogen, Finland): Buildup of a LP-HT Dome During Nuna Assembly. Tectonics, 39, 25 p.

Claesson, S., Huhma, H., Kinny, P.D. & Williams, I.S., 1993. Svecofennian detrital zircon ages implications for the Precambrian evolution of the Baltic Shield. *Precambrian Research,* 64(1-4), p. 109–130.

Collins, W.J., 2002. Hot orogens, tectonic switching, and creation of continental crust. *Geology*, 30(6), p. 535–538.

Condie, K. C., 2013. Preservation and recycling of crust during accretionary and collisional phases of Proterozoic orogens: A bumpy road from Nuna to Rodinia. *Geosciences*, 3(2), p. 240–261.

Condie, K. C., 2020. Revisiting the Mesoproterozoic. *Gondwana Research*, in Press.

Corfu, F., 2013. A century of U-Pb geochronology: The long quest towards concordance. *Geological Society of America, Bulletin,* 125(1-2), p. 33-47.

Dahlin, P., Johansson, A., & Andersson, U. B., 2014. Source character, mixing, fractionation and alkali metasomatism in Palaeoproterozoic greenstone dykes, Dannemora area, NE Bergslagen region, Sweden. *Geological Magazine*, 151(4), p. 573–590.

DePaolo, D. J., 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth and Planetary Science Letters*, 53(2), p. 189–202.

Ehlers, C., Lindroos, A., & Selonen, O., 1993. The late Svecofennian granite-migmatite zone of southern Finland—a belt of transpressive deformation and granite emplacement. *Precambrian Research,* 64(1-4), p. 295–309.

Ehlers, C., Skiöld, T. & Vaasjoki, M., 2004. Timing of Svecofennian crustal growth and collisional tectonics in Åland, SW Finland. *Bulletin of the Geological Society of Finland*, 76(1-2), p. 63–91.

Eklund, O., Konopelko, D., Rutanen, H., Fröjdö, S., & Shebanov, A. D., 1998. 1.8 Ga Svecofennian post-collisional shoshonitic magmatism in the Fennoscandian shield. *Lithos*, 45(1-4), p. 87–108.

Eliasson, T., Greiling, R., Sträng, T. & Triumf, C., 2001. Bedrock map 23H Stensele NV. *Sveriges Geologiska Undersökning*, Ai126.

Gerdes A. & Zeh A., 2006. Combined U-Pb and Hf isotope LA-(MC-) ICPMS analyses of detrital zircons: Comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in Central Germany. *Earth and Planetary Science Letters*, 249(1-2), p. 47–61

Goldfarb, R.J., Groves, D.I., 2015. Orogenic gold: Common or evolving fluid and metal sources through time. Lithos 233, p. 2–26.

Gorbatschev, R., & Bogdanova, S., 1993. Frontiers in the Baltic shield. *Precambrian Research*, 64(1-4), p. 3–21.

Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., Van Achterbergh, E., O'Reilly, S.Y. & Shee, S.R., 2000. The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. *Geochimica et Cosmochimica Acta*, 64(1), p. 133–147.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G. & Robert, F., 1998. Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geology Reviews 13, p. 7–27.

Guitreau, M., Blichert-Toft, J. & Billström, K., 2014. Hafnium isotope evidence for early-Proterozoic volcanic arc reworking in the Skellefte district (northern Sweden) and implications for the Svecofennian orogen. *Precambrian Research*, 252, p. 39–52.

Hölttä, P., Huhma, H., Mänttäri, I., Peltonen, P., & Juhanoja, J., 2000. Petrology and geochemistry of mafic granulite xenoliths from the Lahtojoki kimberlite pipe, eastern Finland. *Lithos*, 51(1-2), p. 109–133.

Hölttä, P., & Heilimo, E., 2017. Metamorphic map of Finland. *Geological Survey of Finland, Special Paper,* 60, p. 77–128.

Heinonen, A. P., Andersen, T. & Rämö, O. T., 2010. Re-evaluation of rapakivi petrogenesis: Source constraints from the Hf isotope composition of zircon in the rapakivi granites and associated mafic rocks of southern Finland. *Journal of Petrology*, 51(8), p. 1687–1709.

Hermansson, T., Stephens, M. B., Corfu, F., Page, L. M., & Andersson, J., 2008. Migratory tectonic switching, western Svecofennian orogen, central Sweden: Constraints from U/Pb zircon and titanite geochronology. *Precambrian Research*, 161, p. 250–278.

Hietanen, A., 1975. Generation of potassium-poor magmas in the northern Sierra Nevada and the Svecofennian of Finland. *Journal of Research, US Geological Survey*, 3(6), p. 631–645.

Hofmann, A. W., 1988. Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust. *Earth and Planetary Science Letters*, 90(3), p. 297–314.

Huhma, H., 1986. Sm–Nd, U–Pb and Pb–Pb isotopic evidence for the origin of the Early Proterozoic Svecokarelian crust in Finland. *Geological Survey of Finland, Bulletin*, 337, 48 p.

Huhma, H., Claesson, S., Kinny, P. D., & Williams, I. S., 1991. The growth of Early Proterozoic crust: new evidence from Svecofennian detrital zircons. *Terra Nova*, 3(2), p. 175–178.

Huhma, H., Mänttäri, I., Peltonen, P., Kontinen, A., Halkoaho, T., Hanski, E., Hokkanen, T., Hölttä, P., Juopperi, H., Konnunaho, J., Layahe, Y., Luukkonen. E., Pietikäinen. K., Pulkkinen, A., Sorjonen-Ward, P., Vaasjoki, M. & Whitehouse, M., 2012. The age of the Archaean greenstone belts in Finland. *Geological Survey of Finland, Special Paper*, 54, p. 74−175.

Johansson, Å., & Karlsson, A., 2020. The "intraorogenic" Svecofennian Herräng mafic dyke swarm in east-central Sweden: age, geochemistry and tectonic significance. *GFF*, 142(1), p. 1–22.

Kähkönen, Y., Huhma, H., & Aro, K., 1989. U-Pb zircon ages and Rb-Sr whole-rock isotope studies of early Proterozoic volcanic and plutonic rocks near Tampere, southern Finland. *Precambrian Research*, 45(1-3), p. 27–43.

Kähkönen, Y., 1999. Stratigraphy of the central parts of the Palaeoproterozoic Tampere Schist Belt, southern Finland: review and revision. *Bulletin of the Geological Society of Finland*, 71(1), p. 13–29.

Kähkönen, Y., 2005. Svecofennian Supracrustal Rocks. In: Lehtinen, M., Nurmi, P., & Rämö, T. (Eds.), Precambrian Geology of Finland. *Developments in Precambrian Geology,* Elsevier, 14, p. 343–405.

Kemp, A. I. S., Hawkesworth, C. J., Collins, W. J., Gray, C. M., & Blevin, P. L., 2009. Isotopic evidence for rapid continental growth in an extensional accretionary orogen: The Tasmanides, eastern Australia. *Earth and Planetary Science Letters*, 284(3-4), p. 455–466.

Koistinen, T. J., 1981. Structural evolution of an early Proterozoic strata-bound Cu-Co-Zn deposit, Outokumpu, Finland. *Earth and Environmental Science Transactions of The Royal Society of Edinburgh*, 72(2), p. 115–158.

Koistinen, T., Stephens, M.B., Bogatchev, V., Nordgulen, Ø.,Wennerström, M., & Korhonen, J., 2001. Geological map of the Fennoscandian Shield, scale 1:2000 000. Geological Surveys of Finland, Norway and Sweden and the North-West Department of Natural Resources of Russia.

Korja, A., Lahtinen, R., & Nironen, M., 2006. The Svecofennian orogen: a collage of microcontinents and island arcs. *Geological Society, London, Memoirs*, 32(1), p. 561–578.

Korsman, K., Koistinen, T., Kohonen, J., Wennerström, M., Ekdahl, E., Honkamo, M., Idman, H., & Pekkala, Y. (Eds.), 1997. Bedrock map of Finland 1:1000000. Geological Survey of Finland, Espoo.

Lahtinen, R., 1994. Crustal evolution of the Svecofennian and Karelian domains during 2.1–1.79 Ga, with special emphasis on the geochemistry and origin of 1.93–1.91 Ga gneissic tonalites and associated supracrustal rocks in the Rautalampi area, Central Finland. *Geological Survey of Finland, Bulletin*, 378, 128 p.

Lahtinen, R., 1996. Geochemistry of Palaeoproterozoic supracrustal and plutonic rocks in the Tampere-Hämeenlinna area, southern Finland. *Geological Survey of Finland, Bulletin*, 389, p. 1–113.

Lahtinen, R., & Huhma, H., 1997. Isotopic and geochemical constraints on the evolution of the 1.93-1.79 Ga Svecofennian crust and mantle in Finland. *Precambrian Research*, 82(1-2), p. 13–34.

Lahtinen, R., Huhma, H., & Kousa, J., 2002. Contrasting source components of the Paleoproterozoic Svecofennian metasediments: detrital zircon U–Pb, Sm–Nd and geochemical data. *Precambrian Research*, 116(1), p. 81–109.

Lahtinen, R., Korja, A., & Nironen, M., 2005. Paleoproterozoic tectonic evolution. In: Lehtinen, M., Nurmi, P., & Rämö, T. (Eds.), Precambrian Geology of Finland. *Developments in Precambrian Geology,* Elsevier, 14, p. 481–531.

Lahtinen, R., Korja, A., Nironen, M., & Heikkinen, P., 2009a. Palaeoproterozoic accretionary processes in Fennoscandia. *Geological Society, London, Special Publications,* 318(1), p. 237–256.

Lahtinen, R., Huhma, H., Kähkönen, Y., & Mänttäri, I., 2009b. Paleoproterozoic sediment recycling during multiphase orogenic evolution in Fennoscandia, the Tampere and Pirkanmaa belts, Finland. *Precambrian Research*, 174, 310–336.

Lahtinen, R. & Nironen, M., 2010. Paleoproterozoic lateritic paleosol–ultra-mature/mature quartzite–meta-arkose successions in southern Fennoscandia—intra-orogenic stage during the Svecofennian orogeny. *Precambrian Research*, 183, p. 770–790.

Lahtinen, R., Huhma, H., Lahaye, Y., Kousa, J., & Luukas, J., 2015. Archean–Proterozoic collision boundary in central Fennoscandia: Revisited. *Precambrian Research*, 261, p. 127–165.

Lahtinen, R., Huhma, H., Sipilä, P., & Vaarma, M., 2017. Geochemistry, U-Pb geochronology and Sm-Nd data from the Paleoproterozoic Western Finland supersuite–A key component in the coupled Bothnian oroclines. *Precambrian Research*, 299, p. 264–281.

Lee, C. T. A., Cheng, X., & Horodyskyj, U., 2006. The development and refinement of continental arcs by primary basaltic magmatism, garnet pyroxenite accumulation, basaltic recharge and delamination: insights from the Sierra Nevada, California. *Contributions to Mineralogy and Petrology*, 151(2), p. 222–242

Ludwig, K. R., 2012. User's Manual for Isoplot 3.75, a geochronological toolkit for Microsoft Excel. *Berkeley Geochronology Center Special Publication,* 5 (5), p. 1–72.

Luosto, U., 1991. Moho depth map of the Fennoscandian Shield based on seismic refraction data. In: Korhonen, H., Lipponen, A. (Eds.), Structure and Dynamics of the Fennoscandian Lithosphere. Proceedings of the Second Workshop on Investigation of the Lithosphere in the Fennoscandian Shield by Seismological Methods. *Intitute of Seismology, University of Helsinki, Report*, S-25, p. 43–49.

Mäkitie, H., Kärkkäinen, N., Sipilä, P., Tiainen, M., Kujala, H., & Klami, J., 2016. Hämeen vyöhykkeen granitoidien luokittelua. *Geological Survey of Finland, Archive Report,* 33, 146 p.

McDonough, W. F., & Sun, S. S., 1995. The composition of the Earth. *Chemical geology*, 120(3-4), p. 223–253.

Middlemost, E. A. K., 1985. Magmas and Magmatic Rocks. *Longman, London*, 266 p.

Mints, M.V., Glaznev, V.N., Muravina, O.M. &Sokolova, E.Y., 2020. 3D model of Svecofennian Accretionary Orogen and Karelia Craton based on geology, reflection seismics, magnetotellurics and density modelling: Geodynamic speculations. Geoscience Frontiers 11, 999-1023.

Morel, M. L. A., Nebel O., Nebel-Jacobsen Y. J., Miller J. S. & Vroon P. Z., 2008. Hafnium isotope characterization of the GJ-1 zircon reference material by solution and laser-ablation MC-ICPMS. *Chemical Geology*, 255(1-2), 231–235.

Mouri, H., Korsman, K., & Huhma, H., 1999. Tectono-metamorphic evolution and timing of the melting processes in the Svecofennian Tonalite-Trondhjemite Migmatite belt: An example from Luopioinen, Tampere area, southern Finland. *Bulletin of the Geological Society of Finland*, 71(1), p. 31–56.

Mouri, H., Väisänen, M., Huhma, H., & Korsman, K., 2005. Sm-Nd garnet and U-Pb monazite dating of high-grade metamorphism and crustal melting in the West Uusimaa area, southern Finland. *GFF*, 127(2), p. 123–128.

Nevalainen, J., Väisänen, M., Lahaye, Y., Heilimo, E., & Fröjdö, S., 2014. Svecofennian intra-orogenic gabbroic magmatism: A case study from Turku, southwestern Finland. *Bulletin of the Geological Society of Finland*, 86(2), p. 93–112.

Nironen, M., & Bateman, R., 1989. Petrogenesis and syntectonic emplacement in the early Proterozoic of south-central Finland: a reversely zoned diorite-granodiorite and a granite. *Geologische Rundschau*, 78(2), p. 617–631.

Nironen, M., 1997. The Svecofennian Orogen: a tectonic model. *Precambrian Research*, 86(1), p. 21-44.

Nironen, M., 1999. Structural and magmatic evolution in the Loimaa area, southwestern Finland. *Bulletin of the Geological Society of Finland*, 71(1), p. 57–71.

Nironen, M., 2005. Proterozoic orogenic granitoid rocks. In: Lehtinen, M., Nurmi, P., & Rämö, T. (Eds.), Precambrian Geology of Finland. *Developments in Precambrian Geology,* Elsevier, 14, p. 443–479.

Nironen, M., Kousa, J., Luukas, J., & Lahtinen, R., 2016. Geological Map of Finland – Bedrock 1:1 000 000. Geological Survey of Finland.

Nironen, M., 2017. Guide to the geological map of Finland – Bedrock 1:1 000 000. *Geological Survey of Finland, Special Paper*, 60, p. 41–76

Patchett, J. & Kouvo, O., 1986. Origin of continental crust of 1.9-1.7 Ga age: Nd isotopes and U-Pb zircon ages in the Svecokarelian terrain of South Finland. *Contributions to Mineralogy and Petrology,* 92(1), p. 1–12.

Pearce, J., & Cann, J., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth and Planetary Science Letters,* 19(2), p. 290–300.

Peltonen, P., 1995. Petrogenesis of ultramafic rocks in the Vammala Nickel Belt: implications for crustal evolution of the early Proterozoic Svecofennian arc terrane. *Lithos*, 34(4), p. 253–274.

Peltonen, P., 2005. Svecofennian mafic-ultramafic intrusions. In: Lehtinen, M., Nurmi, P., & Rämö, T. (Eds.), Precambrian Geology of Finland. *Developments in Precambrian Geology,* Elsevier, 14, p. 407–441.

Peltonen, P., Mänttäri, I., Huhma, H., & Whitehouse, M. J., 2006. Multi-stage origin of the lower crust of the Karelian craton from 3.5 to 1.7 Ga based on isotopic ages of kimberlite-derived mafic granulite xenoliths. *Precambrian Research*, 147(1-2), p. 107–123.

Rogers, J. J., & Santosh, M., 2002. Configuration of Columbia, a Mesoproterozoic supercontinent. *Gondwana Research*, 5(1), p. 5–22.

Rollinson, H. R., 2014. Using geochemical data: evaluation, presentation, interpretation. *Routledge*, London, 384 p.

Rosa D. R. N., Finch A. A., Andersen T. & Inverno C. M. C., 2009. U-Pb geochronology and Hf isotope ratios of magmatic zircons from the Iberian pyrite belt. *Mineralogy and Petrology*, 95(1-2), p. 47–69.

Rudnick, R. L., Barth, M., Horn, I., & McDonough, W. F., 2000. Rutile-bearing refractory eclogites: missing link between continents and depleted mantle. *Science*, 287(5451), p. 278–281.

Rutanen, H., Andersson, U. B., Väisänen, M., Johansson, Å., Fröjdö, S., Lahaye, Y., & Eklund, O., 2011. 1.8 Ga magmatism in southern Finland: Strongly enriched mantle and juvenile crustal sources in a post-collisional setting. *International Geology Review*, 53(14), p. 1622–1683.

Rutland, R. W. R., Williams, I. S., & Korsman, K., 2004. Pre-1.91 Ga deformation and metamorphism in the Palaeoproterozoic Vammala Migmatite Belt, southern Finland, and implications for Svecofennian tectonics. *Bulletin of the Geological Society of Finland*, 76(1–2), p. 93–140

Saalmann, K., Mänttäri, I., Ruffet, G., & Whitehouse, M. J., 2009. Age and tectonic framework of structurally controlled Palaeoproterozoic gold mineralisation in the Häme Belt of southern Finland. *Precambrian Research,* 174(1-2), p. 53–77.

Saalmann, K., Mänttäri, I., Peltonen, P., Whitehouse, M. J., Grönholm, P., & Talikka, M., 2010. Geochronology and structural relationships of mesothermal gold mineralisation in the Palaeoproterozoic Jokisivu prospect, southern Finland. *Geological Magazine,* 147(4), p. 551–569.

Saccani, E., 2015. A new method of discriminating different types of post-Archean ophiolitic basalts and their tectonic significance using Th-Nb and Ce-Dy-Yb systematics. *Geoscience Frontiers*, 6(4), p. 481–501.

Sipilä, P., Mattila, J., & Tiainen, M., 2011. Pirkanmaan vyöhykkeen ja Hämeen vyöhykkeen välinen terraanirajatulkinta. *Geological Survey of Finland, Archive Report*, 2, p. 27 p.

Sipilä, P., & Kujala, H., 2014. Hämeen vyöhykkeen vulkaniittien geokemia. *Geological Survey of Finland, Archive Report*, 119, 23 p.

Stein, M., & Hofmann, A.W., 1994. Mantle plumes and episodic crustal growth. *Nature*, 372(6501), p. 63–68.

Stephens, M. B., & Andersson, J., 2015. Migmatization related to mafic underplating and intra- or back-arc spreading above a subduction boundary in a 2.0–1.8 Ga accretionary orogen, Sweden. *Precambrian Research*, 264, p. 235–257.

Stephens, M., B., & Bergman, S., 2020. Regional context and lithotectonic framework of the 2.0–1.8 Ga Svecokarelian orogen, eastern Sweden. In: Stephens, M., & Bergman, S. (Eds.), Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources. *Geological Society, London, Memoirs*, 50, p. 19–26.

Strauss, T.A.L., 2004. The geology of the Proterozoic Haveri Au-Cu deposit, southern Finland. PhD thesis, Rhodes University, 306 p.

Sun, S. S., & McDonough, W. F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geological Society, London, Special Publications*, 42(1), p. 313–345.

Tang, M., Lee, C. T. A., Chen, K., Erdman, M., Costin, G., & Jiang, H., 2019. Nb/Ta systematics in arc magma differentiation and the role of arclogites in continent formation. *Nature Communications*, 10(1), p. 1–8.

Tiainen, M., Molnar, F., & Koistinen, E., 2013. The Cu-Mo-Au mineralization of the Paleoproterozoic Kedonojankulma intrusion, Häme Belt, Southern Finland. *Proceedings of the 12th Biennial SGA Meeting* 2, p. 892–895.

Torvela, T. & Ehlers, C., 2010. From ductile to brittle deformation: structural development and strain distribution along a crustal-scale shear zone in SW Finland. *International Journal of Earth Sciences*, 99(5), p. 1133–1152.

Vaasjoki, M. & Huhma, H., 1999. Lead and neodymium isotopic results from metabasalts of the Haveri Formation, southern Finland: evidence for Palaeoproterozoic enriched mantle. Bulletin of the Geological Society of Finland, 71, 143-153.

Vaasjoki, M., Huhma, H., Lahtinen, R. & Vestin, J., 2003. Sources of Svecofennian granitoids in the light of ion probe U-Pb measurements on their zircons. *Precambrian Research*, 121(3), p. 251–262.

Väisänen, M., & Mänttäri, I., 2002. 1.90-1.88 Ga arc and back-arc basin in the Orijärvi area, SW Finland. *Bulletin of the Geological Society of Finland*, 74, p. 185–214.

Väisänen, M., Mänttäri, I. & Hölttä, P., 2002. Svecofennian magmatic and metamorphic evolution in southwestern Finland as revealed by U-Pb zircon SIMS geochronology. *Precambrian Research*, 116(1-2), p. 111–127.

Väisänen, M., & Westerlund, G., 2007. Palaeoproterozoic mafic and intermediate metavolcanic rocks in the Turku area, SW Finland. *Bulletin of the Geological Society of Finland*, 79(2), p. 127–141.

Väisänen, M., Eklund, O., Lahaye, Y., O'Brien, H., Fröjdö, S., Högdahl, K., & Lammi, M., 2012a. Intra-orogenic Svecofennian magmatism in SW Finland constrained by LA-MC-ICP-MS zircon dating and geochemistry. *GFF*, 134(2), p. 99–114.

Väisänen, M., Johansson, Å., Andersson, U. B., Eklund, O., & Hölttä, P., 2012b. Palaeoproterozoic adakite-and TTG-like magmatism in the Svecofennian orogen, SW Finland. *Geologica Acta*, 10(4), p. 351–371.

Väisänen, M., Kara, J., Penttinen, H., Lahaye, Y., O'Brien, H., & Skyttä, P., 2021. U-Pb zircon dating of igneous rocks in the Salo area, SW Finland. *Extended abstract, 11th Lithosphere Symposium*, p. 151–154.

Valbracht, P. J., Oen, I. S. & Beunk, F. F., 1994. Sm-Nd isotope systematics of 1.9-1.8-Ga granites from western Bergslagen, Sweden: inferences on a 2.1-2.0-Ga crustal precursor. *Chemical Geology*, 112(1), 21–37.

Vehkamäki, T., Väisänen, M., Kurhila, M., O'Brien, H., Hölttä, P., & Syrjänen, J. K., 2021. Metamorphic zones in SW Finland: monazite and zircon U-Pb dating of leucosomes in paragneisses. *Extended abstract, 11th Lithosphere Symposium*, p. 139–142.

Wasström, A., 1993. The Knaften granitoids of Västerbotten county, northern Sweden. *Sveriges Geologiska Undersökning, Series C: forskningsrapporter*, 823, p. 60–64.

Weihed, P., Arndt, N., Billström, K., Duchesne, J. C., Eilu, P., Martinsson, O., Papunen, H., & Lahtinen, R., 2005. Precambrian geodynamics and ore formation: The Fennoscandian Shield. *Ore Geology Reviews*, 27(1-4), p. 273–322.

Workman, R. K., & Hart, S. R., 2005. Major and trace element composition of the depleted MORB mantle (DMM). *Earth and Planetary Science Letters*, 231(1-2), p. 53–72.

Wilson, M., 1989. Igneous Petrogenesis, A Global Tectonic Approach. *Unwin Hyman*, London, 464 p.

Xia, L., &Li, X., 2019. Basalt geochemistry as a diagnostic indicator of tectonic setting. *Gondwana Research,* 65, p. 43–67.

TURUN
YLIOPISTO
UNIVERSITY
OF TURKU

Painosalama Oy, Turku, Finland 2021

ISBN 978-951-29-8473-2 (PRINT)
ISBN 978-951-29-8474-9 (PDF)
ISSN 0082-6979 (Print)
ISSN 2343-3183 (Online)