

# The prehistory of Suomussalmi, eastern Finland; the first billion years as revealed by isotopes and the composition of granitoid suites

Perttu Mikkola



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**THE PREHISTORY OF SUOMUSSALMI, EASTERN FINLAND;  
THE FIRST BILLION YEARS AS REVEALED BY ISOTOPES AND  
THE COMPOSITION OF GRANITOID SUITES**

by

Perttu Mikkola

Geological Survey of Finland  
P.O. Box 1237  
FI-70211 Kuopio  
Finland

**ACADEMIC DISSERTATION**

Department of Geosciences and Geography, Faculty of Science

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Supervisors:

Prof. O. Tapani Rämö  
Department of Geosciences and Geography  
University of Helsinki, Finland

Dr. Pentti Hölttä  
Geological Survey of Finland  
Espoo, Finland

Reviewers:

Docent Ulf B. Andersson  
University of Uppsala  
Uppsala, Sweden

Docent Mikko Nironen  
Geological Survey of Finland  
Espoo, Finland

Opponent:

Professor Hervé Martin  
Laboratoire Magmas et Volcans  
Université Blaise Pascal  
Clermont-Ferrand, France

Cover: Migmatized TTG suite granitoid in a road cut near the Suomussalmi church village. Light grey leucosome and dark grey mesosome form a banded structure that is folded and then cross cut by younger pink leucogranite dykes, some of which have also been deformed. The length of the hammer is 60 cm. Photo: Perttu Mikkola, GTK.

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## ABSTRACT

The four papers summarized in this thesis deal with the Archean and earliest Paleoproterozoic granitoid suites observed in the Suomussalmi district, eastern Finland. Geologically, the area belongs to the Kianta Complex of the Western Karelian Terrane in the Karelian Province of the Fennoscandian shield. The inherited zircons up to 3440 Ma old together with Sm–Nd and Pb–Pb data confirm the existence of previously anticipated Paleoproterozoic ‘protocrust’ in Suomussalmi. The general timeline of granitoid magmatism is similar to that of the surrounding areas. TTG magmatism occurred in three distinct phases: ca 2.95 Ga, 2.83–2.78 Ga and 2.76–2.74 Ga. In Suomussalmi the TTGs *sensu stricto* ( $K_2O/Na_2O < 0.5$ ) belong to the low-HREE type and are interpreted as partial melts of garnet amphibolites, which did not significantly interact with mantle peridotites. Transitional TTGs ( $K_2O/Na_2O > 0.5$ ), present in Suomussalmi and absent from surrounding areas, display higher LILE concentrations, but otherwise closely resemble the TTGs *sensu stricto* and indicate that recycling of felsic crust commenced in Suomussalmi 200 Ma earlier than in surrounding areas.

The youngest TTG phase was coeval with the intrusion of the Likamännikkö quartz alkali feldspar syenite ( $2741 \pm 2$  Ma) complex. The complex contains angular fragments of ultrabasic rock, which display considerable compositional heterogeneity and are interpreted as cumulates containing clinopyroxene (generally altered to actinolite), apatite, allanite, epidote, and albite. The quartz alkali feldspar syenite cannot be regarded as alkaline *sensu stricto*, despite clear alkaline affinities. Within Likamännikkö there are also calcite carbonatite patches, which display mantle-like O- and C-isotope values, as well as trace element characteristics consistent with a magmatic origin, and could thus be among the oldest known carbonatites in the world. Sanukitoid (2.73–2.71 Ga) and quartz diorite suites (2.70 Ga) overlap within error margins and display compositional similarities, but can be differentiated from each other on the basis of higher Ba,  $K_2O$  and LREE contents of the sanukitoids. The Likamännikkö complex, sanukitoids and quartz diorites are interpreted as originating from the metasomatized mantle and mark the diversification of the granitoid clan after 200 Ma of evolution dominated by the TTG suite.

Widespread migmatization and the intrusion of anatectic leucogranitoids as dykes and intrusions of varying size took place at 2.70–2.69 Ga, following collisional thickening of the crust. The leucogranitoids and leucosomes of migmatized TTGs are compositionally alike and characterized by high silica contents and a leucocratic appearance. Due to compositional overlap, definitive discrimination between leucogranitoids and transitional TTGs requires isotope datings and/or knowledge of field relationships. Leucogranitoids represent partial melts of the local TTGs, both the *sensu stricto* and transitional types, mostly derived under water fluxed conditions, with possible fluid sources being late sanukitoids and quartz diorites as well as dehydrating lower crust.

The Paleoproterozoic 2.44–2.39 Ga A-type granitoids of the Kianta Complex emplaced in an extensional environment are linked to the coeval and more widespread mafic intrusions and dykes observed over most of the Archean nucleus of the Fennoscandian shield. The A-type intrusions in the Suomussalmi area are interpreted as partial melts of the Archean lower crust and display differences in composition and magnetite content, which indicate differences in the composition and oxidation state of the source.

Keywords (GeoRef Thesaurus, AGI): granites, leucogranite, A-type granites, geochemistry, isotopes, genesis, magmatism, tonalite-trondhjemite-granodiorite magmas, Paleoproterozoic, Archean, Suomussalmi, Finland

*Perttu Mikkola, Geological Survey of Finland,  
P.O. Box 1237, FI-70211 Kuopio,  
Finland*

*E-mail: [perttu.mikkola@gtk.fi](mailto:perttu.mikkola@gtk.fi)*

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## LIST OF ORIGINAL PUBLICATIONS

The original papers on which this thesis is based are referred to in the text by the Roman numerals I through IV.

I Mikkola, P., Huhma, H., Heilimo, E. & Whitehouse, M. 2011. Archean crustal evolution of the Suomussalmi district as part of the Kianta Complex, Karelia; constraints from geochemistry and isotopes of granitoids.  
*Lithos* 125, 287–307.

II Mikkola, P., Salminen, P., Torppa, A. & Huhma, H. 2011. The 2.74 Ga Likamännikkö complex in Suomussalmi, East Finland: Lost between sanukitoids and truly alkaline rocks?  
*Lithos* 125, 716–728.

III Mikkola, P., Lauri, L. & Käpyaho, A. Geochemistry of the Neoproterozoic leucogranitoids from the Kianta complex, Karelian Province, Finland.

*Submitted to Precambrian Research 15.3.2011.*

IV Mikkola, P., Kontinen, A., Huhma, H. & Lahaye, Y. 2010. Three Paleoproterozoic A-type granite intrusions and associated dykes from Kainuu, East Finland.

*Bulletin of the Geological Society of Finland* 82, 81–100.

### **The contributions of the first-author (PIM\$) and the co-authors to the original publications are the following:**

I: PIM\$ was responsible for the field work and selected the sample locations, some of them together with E. Heilimo. SIMS analyses were performed by PIM\$ with technical assistance from M. Whitehouse and other members of the NORDSIM staff. H. Huhma was responsible for TIMS analysis and sample preparation. The main responsibility for the manuscript and interpretation was carried by PIM\$. E. Heilimo contributed especially to the interpretation of the post-2.75 Ga events. H. Huhma contributed to the interpretation of U-Pb and Sm-Nd data and M. Whitehouse to the interpretation of O-isotope data.

II: PIM\$ located the Likamännikkö complex and supervised P. Salminen's Master's thesis (Salminen 2009), which forms the material base of the article. H. Huhma was responsible for U-Pb and Sm-Nd analysis. A. Torppa and P. Salminen carried out the O- and C-isotope analyses. PIM\$ prepared the manuscript in association with P. Salminen with other authors contributing.

III: PIM\$ was responsible for sampling and mapping in the central part of the study area, A. Käpyaho for sampling in the southern part and L. Lauri in the northern parts. PIM\$ as the first author had main responsibility for preparing the manuscript and interpretations, with other authors contributing.

IV: PIM\$ was responsible for the field work concerning the Rasinkylä and Ryysyranta intrusions and dykes surrounding them. A. Kontinen was responsible for field work concerning the Pussisvaara intrusion and adjacent dykes. As the first author, PIM\$ had the main responsibility for preparing the manuscript, while interpretations and conclusions were jointly done with A. Kontinen. H. Huhma was responsible for isotope sample preparation and TIMS isotope analysis and also contributed to the interpretation of the isotope data. Y. Lahaye was responsible for the LA-MC-ICPMS analysis.

## 1 INTRODUCTION

With respect to plate tectonics, how far back in time can we use the principle of uniformitarianism; the present is the key to the past? Is there a point in geological time when the modern key no longer opens the lock and uniformitarianism can thus no longer be applied? One such point interpreted as marking a change in plate tectonics is the Neoproterozoic, indicated for example by the appearance of the first carbonatites and alkaline intrusives (Sutcliffe et al. 1990, Blichert-Toft et al. 1995, Zozulya et al. 2007, 2009, Chakhmouradian et al. 2008, Lukkarinen, 2008, Paper II), the main phase of sanukitoid (high-Mg granitoids) activity for references, see Heilimo et al. 2011) and the assembly of the first supercraton(s) (Bleeker 2003). The notability of this purported Neoproterozoic change is under dispute; was it merely related to a gradual steepening of the subduction angle (Martin & Moyen 2002, Martin et al. 2010) or to a fundamental change from crustal growth dominated by the melting of mafic lower crust, thickened either tectonically (Condie 2005) or by magmatic underplating (Bédard 2006, Smithies & Champion 2007), to one dominated by subduction zone magmatism. Further questions arise from the causes of the change: did it result from gradual cooling of the Earth (Martin et al. 2005) or was it abruptly triggered by an outside force, for example by a giant impact (Hansen 2007).

Prior to the Neoproterozoic, granitoid magmatism mainly consisted of TTG (Tonalite-Trondhjemite-Granodiorite) suite rocks, which are commonly interpreted as partial melts of basaltic rocks under varying pressures, resulting in notable differences in trace element compositions (Martin 1987, Martin et al. 2005, Condie 2005, Halla et al. 2009, Moyen 2009, 2011), although fractional crystallization of mantle-derived melts is presented as an alternative model in some areas (Kleinbans et al. 2003, Samsonov et al. 2005). It is commonly envisioned that the hotter Archean mantle led to subduction at a lower angle and partial melting

of the subducting slab instead of melting of the metasomatized mantle wedge, as in modern systems. Martin et al. (2005) concluded that the gradual steepening of the subduction angle during the Archean can be observed as rising Mg#, Cr, and Ni levels in TTGs caused by increasing interaction with the progressively thickening mantle wedge. Simultaneously, Sr, CaO and Na<sub>2</sub>O concentrations rose as melting depth increased to pressures outside the stability field of plagioclase. Andean adakites, formed in a geodynamic setting in which an abnormally hot oceanic plate is subducted and partially melted, have been regarded as potential modern analogues of Archean TTGs (Martin 1993, Martin et al. 2005). This analogue between TTGs and adakites has also been questioned due to significantly higher mantle compatible element levels in the latter, and it has been argued that the Archean TTGs are melts from lower crust thickened either tectonically (Smithies 2000, Condie 2005) or through magmatic underplating (Bédard 2006, Champion & Smithies 2007). The low angle subduction hypothesis has also been challenged due to the lack of negative buoyancy of the presumably hotter Archean oceanic plate and thus the lack of slab pull (van Thienen et al. 2004). Numerical models suggest that in the case of a hot Archean mantle the subduction, if it occurred, was steep angled (van Hunen & van den Berg 2008). Smithies et al. (2003) suggested a model of flat subduction, although it is closer to underthrusting than subduction. This involves progressive thickening and stacking of the oceanic lithosphere until the lower parts partially melt to generate TTG magmas, which is followed by delamination of the eclogite residue. Numerical models of Cooper et al. (2006) showed that such stack piles could form and develop over downwelling areas of mantle convection cells and in favorable conditions could be stabilized to form cratons.

As outlined above, the models for TTG genesis do not necessarily involve plate tectonics resem-

bling the modern system, unlike the ones for sanukitoids (high-Mg granitoids), which are linked to subduction in slightly variable ways (Moyen et al. 2003, Lobach-Zhuchenko et al. 2005, Heilimo et al. 2010a, Martin et al. 2010). Heilimo et al. (2010a) suggested a model involving, in addition to the commonly interpreted metasomatism of the mantle wedge by fluids and melts from the subducting slab, a second phase of metasomatism by alkaline fluids following slab break off. Sanukitoids typically yield Neoproterozoic ages, with some slightly older examples (see references in Heilimo et al. 2011), and two explanations are offered: either that by the Neoproterozoic the subduction angle had steepened enough to allow room for interaction between melts and fluids from the subducting slab and the mantle wedge (Martin et al. 2010), or alternatively they mark the beginning of widespread subduction as whole. Since the original, rather strict, sanukitoid definition (Stern et al. 1989), the term has commonly been used in a wider sense, leading to the concept of a sanukitoid suite for Archean granitoid rocks with higher than average contents of MgO, Cr, Ni, K<sub>2</sub>O/Na<sub>2</sub>O, Sr and Ba (Heilimo et al. 2010a). Some mantle-derived quartz diorites superficially resemble the sanukitoids, but do not share all the pertinent characteristics, possibly due to less intense metasomatism of the source area in the mantle Steinfeld et al. 2005, Mueller et al. 2010, Paper I). The alkaline rocks and carbonatites that appear in the Neoproterozoic are also typically linked to variably metasomatized mantle melted during or following subduction (Sutcliffe et al. 1990, Blichert-Toft et al. 1995, Chakhmouradian et al. 2008, Zozulya et al. 2009, Paper II). The two-phase metasomatism model of Heilimo et al. (2010a), inherently involving a heterogeneous metasomatized lithospheric mantle, has the potential to explain the existence of coeval, but compositionally differing mantle-derived granitoids (Papers I, II). However, in the Yilgarn Craton the alkaline rocks have been interpreted to result from intracrustal melting following delamination of lower crust and metasomatization of the source (Smithies & Champion 1999).

The last major group of Archean granitoids comprises the leucogranitoids, which are commonly found as the final voluminous phase of magmatism in Archean cratons. Leucogranitoids are commonly interpreted to result from continental collisions leading to partial melting of pre-existing crust, in most cases predominantly consisting of TTGs and in some cases of metasediments with an insignificant role of juvenile input from mantle (Sylvester 1994, Sawyer 1998, Kampunzu

et al. 2003, Käpyaho et al. 2006, Manya et al. 2007, Paper III). However, both laboratory results (Lopez et al. 2005) and natural systems (Almeida et al. 2010) suggest that input from and interaction with mantle-derived melts, i.e. sanukitoids, is in certain cases necessary to explain all of the compositional characteristics of leucogranitoids.

The Archean–Proterozoic transition also marks the appearance of the first A-type granitoids, the oldest Neoproterozoic examples being from southern Africa (Moore et al. 1993: 2785 Ma), northern Brazil (Sardinha et al. 2006: 2743 Ma) and Kola (Zozulya et al. 2005: 2680–2620 Ma), whereas early Paleoproterozoic examples are known from Finland (Lauri & Mänttari 2002, Paper IV: 2.44–2.39 Ga) and China (Zhang et al. 2007: 2410 and 2340 Ma). Like their younger counterparts, these earliest examples are typically associated with mantle upwelling following pauses of varying length after major collisional events. Although the exact mechanism of A-type granitoid genesis remains unresolved (Martin 2006, Bonin 2007), their appearance at the Archean–Proterozoic boundary, slightly after the introduction of sanukitoids and alkaline rocks, must be taken into account when considering the changes in plate and mantle dynamics at that time.

Since the first isotope age determinations in Finland (Kouvo 1958, Wetherill et al. 1962), the Archean of Finland has been the target of extensive geochronological as well as geochemical studies. The pioneering work mainly in the Kuhmo area (Jahn et al. 1980, Hyppönen 1983, Martin et al. 1983, 1984, Martin 1985, 1987a, 1987b, Querre 1985, Barbey & Martin 1987, Martin & Barbey 1988, Vaasjoki 1988, Luukkonen 1988a, 1992) answered numerous questions, both local and global, in addition to raising new ones. The beginning of the new millennium marked a new surge of interest in the Finnish Archean (Halla 2002, 2005, Lauri et al. 2006, 2011, Käpyaho et al. 2006, 2007, Käpyaho 2006, 2007, Kontinen et al. 2007, Papunen et al. 2009, Heilimo et al. 2010a, 2011, Papers I–III). The foundation to this thesis was laid when the Geological Survey of Finland (GTK) decided to commence bedrock mapping in northeast Kainuu in 2003. This subarea of the Finnish Archean had been more thoroughly studied only in areas belonging to the ore potential Tipasjärvi-Kuhmo-Suomussalmi greenstone belt (henceforth TKSB) (Engel & Dietz 1989, Vaasjoki et al. 1999, Luukkonen et al. 2002, Papunen et al. 2009), but had otherwise remained largely unstudied since the 1:400 000 bedrock mapping performed in the 1950s (Matisto 1954, 1958, Enkovaara et al. 1952, 1953). Earlier work on grani-

toids had concerned only single samples and small subareas near TKSB (Martin et al. 1983, 1984, Martin 1985, Querre 1985, Käpyaho et al. 2007). The idea to use the material collected during bedrock mapping for separate articles and finally this thesis evolved during the first mapping summer (2003) and the following winter.

Papers I–IV present varying aspects of the Archean and earliest Proterozoic geology of the

Kianta Complex and especially the Suomussalmi area, a previously relatively unstudied part with both similarities and differences compared to the adjacent areas. These new data together with previously published data were used to evaluate and discuss possible settings of genesis for different types of granitoids within the Kianta Complex and especially in Suomussalmi from the Mesoarchean to the earliest Paleoproterozoic times.

## 2 SAMPLING, METHODOLOGY, TERMINOLOGY

### 2.1 Sampling

Sampling for the original papers was mainly carried out during and in connection with the fieldwork (during 2003–2006) for the bedrock map of Northeast Kainuu (Mikkola 2008). For Paper IV, part of the material was collected by the second author in 2007 based on his own earlier fieldwork (Kontinen 1989). In Paper I, some zircons from

previous age samples were used to achieve better areal and temporal coverage. Sampling for southern and northern parts of the study area of Paper III had earlier been done in connection with previous projects (Räsänen et al. 2004, Käpyaho et al. 2006).

### 2.2 Methodology

All whole-rock analyses (Papers I–IV) were performed in GTK's geochemistry laboratory, later Labtium Ltd, using X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS), plus a carbon analyzer for total carbon. A detailed description of the methods can be found from Rasilainen et al. (2007). Microanalyses reported in Paper II were performed using GTK's Cameca SX100 electron microprobe in Espoo, and a description of the method is provided in the appendix of Paper II. VG Sector 54 thermal ionization mass spectrometer (TIMS) at the Espoo laboratory of GTK was used for the multigrain zircon U-Pb analyses and whole-rock Sm-Nd isotope analyses (Papers I, II, IV) to determine the crystallization ages and crustal residence times of the granitoids, respectively. TIMS procedures are described in the appendix of Pa-

per I. Cameca II IMS 1270 secondary ion mass spectrometer (SIMS) at the Museum of Natural History of Sweden, Stockholm, was used for zircon single-grain U-Pb age determinations and O-isotope analyses of the same spots (Paper I). Laser ablation multicollector inductively coupled plasma mass spectrometer (LA-MC-ICPMS) at GTK in Espoo (SIGL facility, i.e. Finland Isotope Geosciences Laboratory) was used for single-grain U-Pb age determinations in Paper IV, which also includes a detailed description of the applied method. The isotope ratios of C and O in calcite used in Paper II were measured using a Thermo Finnigan DeltaPLUS Advantage isotope ratio mass spectrometer at the Department of Geosciences and Geography, University of Helsinki; the method is described in the appendix of Paper II.

### 2.3 Terminology

The subdivision of the Archean nucleus of the Fennoscandian shield used in this synopsis, as well as in the original papers, follows that of Hölttä et al. (2008) (Fig. 1), which divides it into five provinces: Murmansk, Kola, Belomorian, Karelian and Norrbotten. The Karelian Province (hereafter

Karelia) is further subdivided into the Vodlozero, Central Karelian and Western Karelian terranes (hereafter Western Karelia). The Kianta Complex (hereafter Kianta) is one of the three complexes of Western Karelia, the two other being Iisalmi and Pudasjärvi.

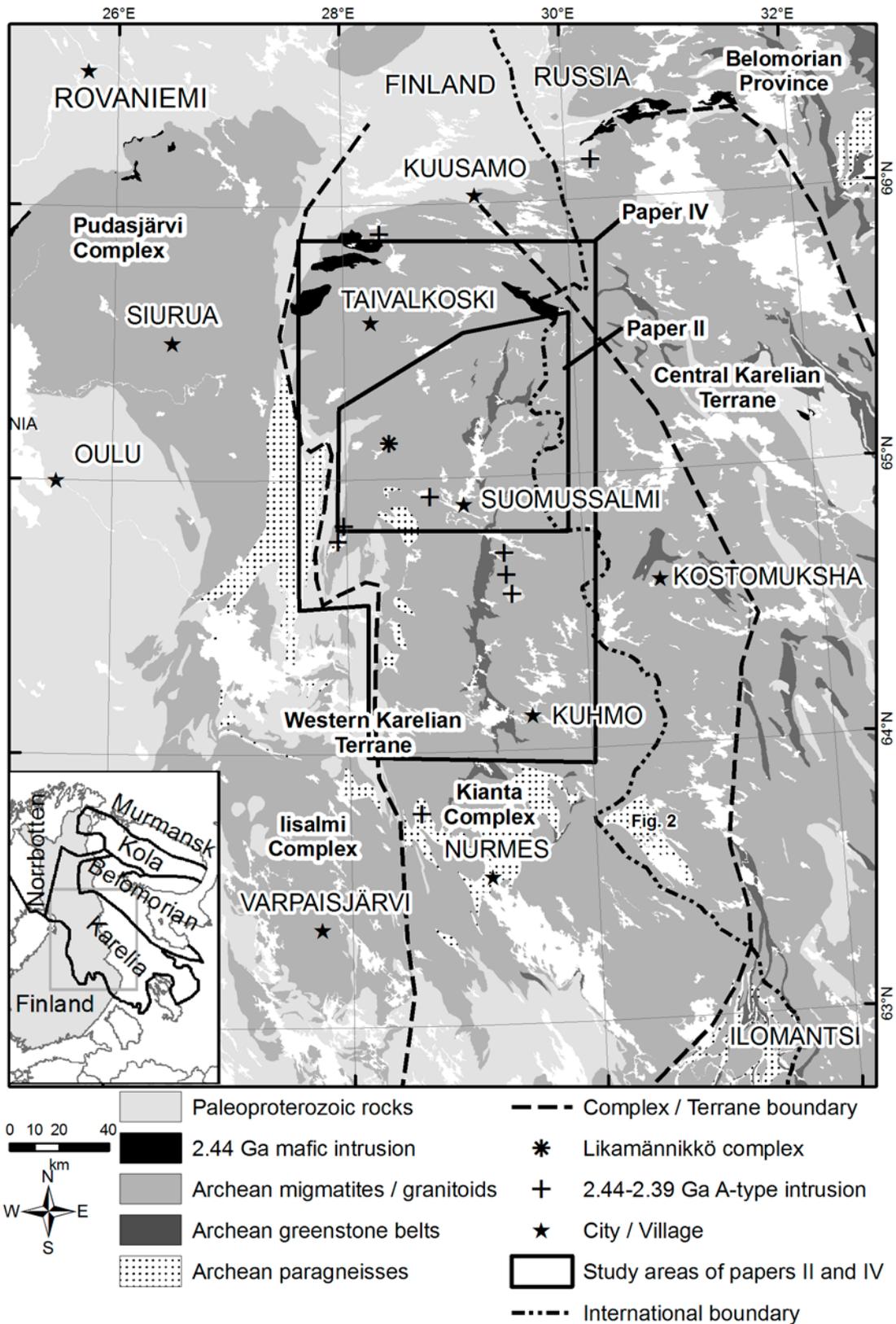


Figure 1. Main map showing the geological complexes of the Western Karelian terrane, one of which is the Kianta Complex. Also shown are the study areas of Papers I and III, together with the locations of the Likamännikkö complex (Paper II) and the 2.44–2.39 Ga A-type granitoids (Paper IV). Geological subdivision according to Hölttä et al. (2008). Basemap simplified from Koistinen et al. (2001). In the inset the Archean provinces of the Fennoscandian shield are shown.

The definition of Martin et al. (2005) is used for the TTGs, i.e. these are characterized by low Mg# and low concentrations of compatible trace elements Cr and Ni, as well as high Na<sub>2</sub>O and SiO<sub>2</sub> and K<sub>2</sub>O/Na<sub>2</sub>O < 0.5. For those samples fulfilling other criteria but having K<sub>2</sub>O/Na<sub>2</sub>O > 0.5, the term ‘transitional TTG’ of Champion and Smithies (2001) is used. TTG *sensu lato* (hereafter s.l.) is used to refer to both TTGs and transitional TTGs. TTGs in this study are subdivided into low-HREE and high-HREE types according to Halla et al. (2009). This subdivision reflects the melting depth, low-HREE TTGs being the product of partial melting under higher pressure within the garnet stability field and high-HREE TTGs under lower pressure, outside the garnet stability

field. For sanukitoids, the criteria of Heilimo et al. (2010a) are used, i.e. SiO<sub>2</sub> = 55–70 wt %, K<sub>2</sub>O = 1.5–5.0 wt %, K<sub>2</sub>O/Na<sub>2</sub>O = 0.5–3.0, MgO = 1.5–9.0 wt %, Mg# = 45–65, Ba+Sr ≥ 1400 ppm and (Gd/Er)<sub>N</sub> = 2–6. Quartz diorites resemble the sanukitoids but are differentiated from them by the lower Ba, K<sub>2</sub>O, Cr, Ni, Mg# and (La/Sm)<sub>N</sub> of the former (Paper I). The term leucogranitoid is used to refer to both the ca 2.7 Ga leucosomes, dykes and intrusions, which are distinctly rich in SiO<sub>2</sub>, commonly over 72 wt %, and poor in FeO and MgO, although compositional overlap with the transitional TTGs exists (Paper III). The nomenclature of Papunen et al. (2009) is used for the rock units of the TKSB.

### 3 REVIEW OF THE PAPERS

#### 3.1 Paper I

Paper I presents isotopic and geochemical data from all observed Archean granitoid suites from Suomussalmi, excluding compositional data for the leucogranitoids. Isotope methods include TIMS and SIMS zircon U-Pb ages, as well as O-isotope data from zircons. Whole-rock Sm-Nd data were used to evaluate the crustal residence times of the granitoids. The aim of this paper was to study the differing granitoid types with multiple methods to evaluate their possible tectonic settings and age distribution. Single grain age determinations confirmed the existence of crust older than 3.0 Ga previously interpreted based on Sm-Nd and Pb-Pb isotope data. Ca 2.95 Ga TTGs s.l., coeval with oldest parts of the TKSB and previously known east of the greenstone belt, were also recognized west of it. A major period

of TTG s.l. magmatism in Suomussalmi was at 2.83–2.78 Ga, an age span similar to that further south in Kuhmo. The next TTG phase took place at 2.76–2.74 Ga and was followed by a pause of ca 20 Ma prior to the intrusion of the sanukitoid suite. Sanukitoids show partial temporal overlap with the quartz diorites and are also coeval with one transitional TTG sample. Migmatization of the older rocks and intrusion of anatectic leucogranitoids took place at 2.71–2.67 Ga. Prior to 2.78 the data support TTG s.l. genesis via partial melting of crust thickened either via underplating or tectonic stacking. After 2.75 Ga the dominance of TTGs s.l. ends with the introduction of sanukitoids, quartz diorites and leucogranitoids, possibly indicating the involvement of a subduction environment.

#### 3.2 Paper II

Paper II describes the geology, geochemistry as well as Sm-Nd whole-rock and carbonate O and C data of the Likamännikkö complex from western Suomussalmi (Fig. 1). This Neoproterozoic (TIMS zircon U-Pb age 2741 ± 2 Ma) quartz alkaline feldspar syenite intrusion with P<sub>2</sub>O<sub>5</sub>-rich ultrabasic fragments and carbonatite patches has alkaline affinities, but cannot be considered as alkaline *sensu stricto*. The complex is interpreted to consist of two or more silicate magma pulses and the ultrabasic fragments as cumulates of older magma

pulse(s), containing apatite, clinopyroxene, albite and epidote as cumulating phases, brecciated by younger pulse(s). Carbonatite patches are most likely products of separate carbonatite magmas. Alternatively, they could be result of magma immiscibility, but carbohydrothermal residue and sedimentary enclave alternatives can be ruled out. The age of the carbonatite patches could not be determined exactly, but all three rock types yielded similar Sm-Nd characteristics. The quartz alkali feldspar syenite has a certain resemblance to

the sanukitoid suite, but cannot be regarded as a member of it: the intrusion is also 20 Ma older than the known sanukitoids within Kianta. However, the rock types in Likamännikkö are interpreted as products of mantle metasomatized in

possibly similar process(es) to those responsible for modifying the sanukitoid source, i.e. subduction-related fluids/melts and/or asthenospheric upwelling.

### 3.3 Paper III

Paper III describes the geochemistry of the 2.7 Ga leucogranitoid dykes and stocks as well as migmatite leucosomes from the northern half of Kianta (Fig. 1). The data together with previously published isotope results were used to evaluate the possible sources of these rocks. Leucogranitoids are interpreted to be mainly partial melts of local TTGs s.l. In some cases, middle and lower crust amphibolites can also be regarded as potential sources. Paragneisses, sanukitoids and quartz diorites can be ruled out as a significant source, based on spatial distribution, geochemistry and

isotopes. However, crystallizing sanukitoids and quartz diorites could have liberated fluids, which would have lowered the melting point of TTGs. Another possible fluid source could have been metamorphic dehydration of the lower crust. Pathways for migrating fluids and melts were provided by crustal-scale shear zones. Compositional heterogeneity, especially in trace elements, of the leucogranitoid suite, are attributed to heterogeneities of the source, variable residue mineralogy and feldspar accumulation.

### 3.4 Paper IV

Paper IV presents geochemical and U-Pb age data (TIMS and LA-MC-ICPMS) on Paleoproterozoic A-type granitoid intrusions and associated dykes intruding Kianta. The aim of the paper was to study the general aspects of these granitoids, which at the same time display both consanguinity and differences in geophysical properties and composition. The data clearly demonstrate that the intrusives have ages between 2.43 and 2.39 Ga and belong to the Paleoproterozoic Tuliniemet suite, which thus extends over longer time span and larger area than previously known. The in-

trusions and dykes have clear A-type characters, including a negative Eu anomaly as well as high HREE, Fe/Mg, and Nb values: more precisely, they belong to the A<sub>2</sub> type, interpreted to result from the partial melting of pre-existing crustal rocks. Based on available data, the differing magnetic properties as well as compositional differences in the intrusions are related to the variable properties of their sources, and are not due to differences in fractionation processes or post-crystallization events.

## 4 DISCUSSION

### 4.1 Archean and early Paleoproterozoic events in Suomussalmi and their continuations in northern Kianta

The well-known field geology of Suomussalmi, together with extensive geochemical and isotopic data from the different granitoid suites, allows evaluation of the potential sources and settings of each suite. Based on new and pre-existing data, several distinct phases can be recognized in the crustal evolution of Suomussalmi and Kianta as a whole. Some of these phases, at least the youngest ones, probably have their continuations on the neighboring complexes. These phases are summa-

rized in the text below and in Figure 2.

#### 4.1.1 Indications for >3 Ga bedrock

No rocks older than 3 Ga have been observed in Kianta. Based on isotope data, however, their local existence has at least been anticipated (Luukkonen 1992). Sm-Nd data from northern Kianta (Luukkonen 2001, Käpyaho et al. 2006, Lauri et al. 2006, Paper I) as well as Pb-Pb data from Suo-

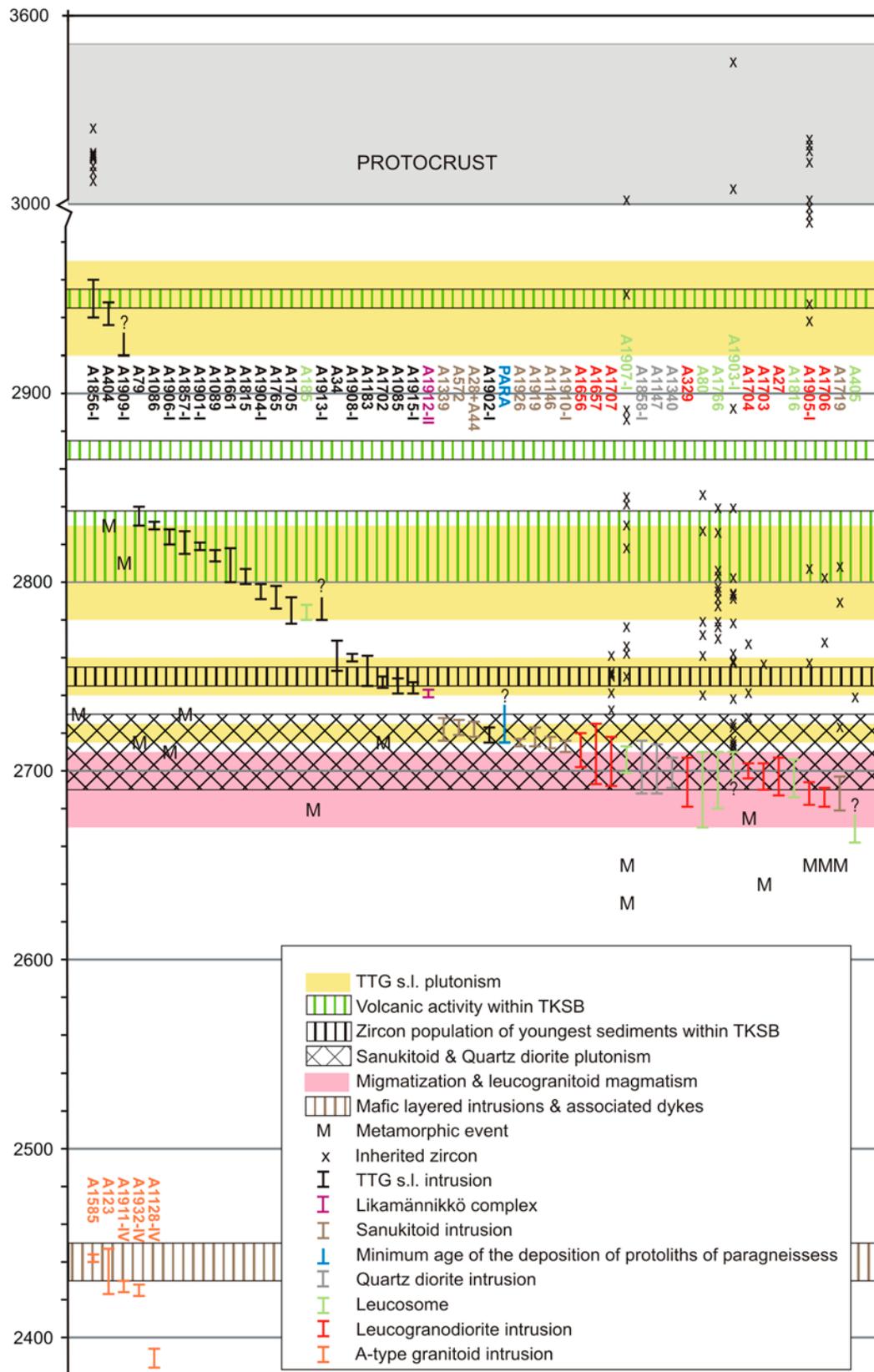


Figure 2. Summary of age data for granitoid rocks of Kianta (Papers I–IV, Luukkonen 1989, Vaasjoki et al. 1999, Halla 2002, Käpyaho et al. 2006, 2007, Lauri et al. 2006, 2011, Heilimo et al. 2011). Periods of activity within and detrital zircon data of the Tipasjärvi-Kuhmo-Suomussalmi greenstone belt (TKSB) according to Huhma et al. (2010). Siikalaiti intrusion (A1719) is excluded from the main sanukitoid phase due to poorly constrained age (Käpyaho 2007). A1926 is the new age sample from the Loso diorite (Kontinen & Huhma, unpublished data) setting the minimum age of deposition of the protoliths of Nurmes-type paragneisses at 2715 Ma. Age of mafic layered intrusions and associated dykes drawn based on Alapieti (1982). Error bars with question marks at one end mark samples yielding only minimum or maximum age estimates. Roman numbers after a sample number refer to the original papers summarized in this thesis.

mussalmi (Vaasjoki et al. 1999), both indicating prolonged crustal residence times for the source, together with inherited zircons aged up to 3.44 Ga (Paper I, Lauri et al. 2011) are sufficient evidence and the existence of such a ‘protocrust’ seems inevitable.

#### 4.1.2 2.95 Ga, the first TTG and volcanic event

The 2.95 Ga event in Kianta is marked by the Luoma group volcanic rocks of the TKSB (Vaasjoki et al. 1999, Luukkonen et al. 2002) and oldest generation of TTGs (Käpyaho et al. 2007, Paper I). These rocks are of limited areal extent and met within and near the TKSB in its northern parts. Käpyaho (2007) concluded that by 2.94 Ga sialic crust existed at least east of the TKSB, but new data demonstrate that it is present on both sides (Paper I). The fragmentary data concerning these 2.95 Ga rocks do not allow detailed interpretation of their tectonic setting.

#### 4.1.3 2.93–2.85 Ga, silence

There is only one age sample with an age between 2.93 and 2.85 Ga in the whole of Kianta: a 2.87 Ga mafic rock from the eastern branch of the TKSB in Suomussalmi (Huhma et al. 2010). Furthermore, only few detrital zircons from paragneisses (Kontinen et al. 2007) and some inherited zircons from leucogranitoids (Paper I) yield ages falling in this bracket. It is uncertain whether the ages of these zircons are indeed crystallization ages of so far unknown rocks in the area, or an artifact of Archean lead loss producing concordant but meaningless ages (Paper I). In the case of the paragneisses, the detrital zircons could have been derived from the Central Karelian terrain (Käpyaho 2007), as well as from unknown Archean fragment(s) separated from Karelia during Paleoproterozoic rifting. Nevertheless it seems evident that, if not absent, magmatic activity in Suomussalmi and the whole Kianta Complex at this time was insignificant. This has been previously noted from the Kuhmo area (Käpyaho 2007).

#### 4.1.4 2.83–2.78 Ga, the main magmatic event

It is well established that 2.83–2.78 Ga was a major crust-forming phase in Kianta, indicated by both TTGs s.l. (Vaasjoki et al. 1999, Käpyaho et al. 2006, 2007, Lauri et al. 2006, Paper I) and volcanic rocks that comprise the majority of the TKSB (Hyppönen 1983, Huhma et al. 2010) (Fig. 2). Some of the older rocks record this younger event as a strong metamorphic event, causing at

least local anatexis (Luukkonen 1989, Käpyaho et al. 2007, Paper I). Despite similarities in crystallization ages, clear differences are also present between different areas of Kianta. Samples from Suomussalmi typically yield older  $t_{DM}$  model ages than their counterparts from Kuhmo, this is true for both the TTGs s.l. (Käpyaho et al. 2006, Paper I) and the volcanic rocks (Huhma et al. 2010). Transitional TTGs suggesting a stronger input from felsic material are present in Suomussalmi (Paper I) and absent from Kuhmo (Käpyaho 2006). TTGs of this age group from both sides of the TKSB belong to the low-HREE type (Paper I), and asymmetry like that observed in Kostomuksha seems to be absent. In Kostomuksha, the asymmetrical distribution of low-HREE and high-HREE TTGs has been interpreted as evidence for a subduction setting (Samsonov et al. 2005). Relatively low and uniform  $\delta^{18}O$  (5.78–6.08) values together with the fact that TTGs from Suomussalmi show no compositional indications of interacting with the mantle wedge during ascent favor a source in the lower crust, rather than a subduction setting, for the TTGs (Paper I). If the lower crust melting hypothesis for these low-HREE TTGs (Halla et al. 2009, Paper I) is valid, the observed differences between Suomussalmi and Kuhmo areas could be a result of older rocks in the source area and/or contamination from older crust during ascent. In the case of slab melt origin, only the contamination hypothesis would be valid.

According to Huhma et al. (2010), the main mafic-ultramafic volcanic activity within the TKSB is coeval with the TTGs, instead of being slightly younger (2.79–2.77 Ga) as suggested by Papunen et al. (2009). The overlapping ages of felsic plutonism (lacking signs of subduction) and mafic-ultramafic volcanism fit an interpretation of the TTGs having been generated from crust, thickened either through stacking or underplating, and the mafic-ultramafic sequence represents partial melts from upwelling mantle (Paper I). Alternatively, the TKSB could be interpreted as an allochthonous piece of oceanic plateau. However, as the Sm-Nd ages of the volcanic rocks show the same areal variation as the underlying granitoids, i.e. older in the north, this seems unlikely.

#### 4.1.5 Subtle magmatic activity at 2.78–2.76

In Suomussalmi and also within the whole Kianta Complex, the 2.83–2.78 Ga crust forming event is followed by a distinct pause in or period of low magmatic activity lasting ca 20 Ma (Fig. 2).

#### 4.1.6 2.76–2.65 Ga: Diversity of granitoids followed by metamorphism

After 2.76 Ga, Kianta was intruded by late TTGs (Luukkonen 2001, Käpyaho et al. 2006, Paper I), with the locus of magmatic activity east of the TKSB. All of these late TTGs belong to the low-HREE group (Käpyaho 2006, Paper I) and have been interpreted as partial melts of garnet bearing amphibolites, either from the subducting slab (Paper I) or thickened lower crust (Halla et al. 2009, Paper I).

The  $2741 \pm 2$  Ma Likamännikkö quartz alkali feldspar syenite, hosting ultrabasic cumulate fragments and carbonatite patches, represents atypical Neoproterozoic mantle-derived magmatic rock (Paper II). The cumulate assemblage consisted of clinopyroxene, commonly altered to amphibole, epidote, albite and prominent amounts of fluorapatite, with a whole-rock  $P_2O_5$  content of up to 13.5 wt %. The carbonatite patches are likely to be products of separate carbonatite magma or alternatively a result of magma immiscibility, and they are possibly among the oldest known carbonatites, although their exact age could not be established. The quartz alkali feldspar syenite has certain sanukitoid affinities, but cannot be regarded as a member of the suite; furthermore, it is 20 Ma years older than the known sanukitoids in Suomussalmi (Heilimo et al. 2011, Paper I). During recent bedrock mapping east and south of Kuhmo, several syenitoid intrusions have been located (Mikkola & Paavola, unpublished data), and it seems that the Likamännikkö complex is not a unique feature, but part of a wider suite.

Based on differences in age and composition, Lobach-Zhuchenko et al. (2005) suggested that the sanukitoid intrusions of Karelia form two distinct zones: a younger western and an older eastern zone. Recent single grain ages (Heilimo et al. 2011) clarified the age division of sanukitoids in Finland by showing that the majority of the intrusions belong to the ca 2.72 Ga western sanukitoid zone, and only the intrusions in the Ilomantsi area belong to the ca 2.74 Ga eastern zone. The Siikalahti intrusion is younger at  $2683 \pm 9$  Ma (Käpyaho et al. 2006), but the quality of the age can be questioned (Käpyaho 2007). It must also be noted that zircons from Siikalahti yielded  $\delta^{18}O$  values (Paper I:  $8.50 \pm 0.51\%$ ) distinctly different from the lower values of other Western Karelian sanukitoids (Heilimo et al. 2010b:  $\delta^{18}O = 5.02\text{--}6.58\%$ ), and the intrusion should therefore be treated as atypical for the area. Sanukitoid activity was partly coeval with another mantle-derived rock group: quartz diorites, a group with

some sanukitoid affinities, but also differences, such as lower levels of Ba,  $K_2O$ , Cr, Ni, Mg# and  $(La/Sm)_N$  that prevent their inclusion in the sanukitoid suite (Paper I). Regionally, the quartz diorites are more common in Pudasjärvi and the northern half of Iisalmi, whereas sanukitoids are more voluminous in Kianta, although both types are present there.

Sanukitoids, quartz diorites and the Likamännikkö complex all are interpreted as melts from the subcontinental mantle modified during and possibly also after subduction (Lobach-Zhuchenko et al. 2005, Halla 2005, Heilimo et al. 2010a, Papers I, II). Active Neoproterozoic arc systems existed in the Central Karelian area (Sorjonen-Ward & Luukkonen 2005, Bibikova et al. 2005), but the exact link between them and the coeval granitoids of Kianta remains unresolved. If, for example, the 2.75 Ga TTGs were derived from a subducting slab, why do they not display evidence of interaction with the mantle wedge (e.g. high Cr, Ni, Mg#) during ascent (Paper I), like modern adakites, which are interpreted as slab melts (Condie 2005). However, their location predominantly east of the TKSB, relatively close to the Central Karelian terrane, could indicate derivation from a slab subducting below Kianta. If the TTGs were derived from thickened crust, a viable model should answer the question of how the thickening was connected to the events further east. It should also be born in mind that the answer to the genesis of at least some of the mantle-derived granitoids could alternatively have been linked to events in the west instead of the east, and thus related to rock units lost during the Paleoproterozoic breakup of the Archean craton.

Close to 2.7 Ga, Nurmestype paragneisses derived from turbidite wackes with MORB-type volcanic intercalations were thrust on top of Kianta as a result of continent-continent collision (Kontinen & Paavola 2006, Kontinen et al. 2007). Coevally, or nearly coevally, Kola collided with Karelia, leaving the Belomorian in between (Vlodichev et al. 2004). Together, these collisions thickened the crust and resulted in widespread migmatization and intrusion of leucogranitoids (Luukkonen 1988b, Käpyaho et al. 2006, 2007, Lauri et al. 2006, 2011, Papers I, III). Based on new age determination of the Loso diorite (Kontinen & Huhma unpublished data:  $2715 \pm 2$  Ma) cross-cutting the Nurmestype paragneisses, the deposition of the turbidite wackes, migmatization and the leucogranitoid magmatism are not coeval (Fig. 2), as the minimum age of the paragneiss protolith deposition and onset of collisional tectonics is shifted from 2700 Ma (Kontinen et al.

2007) to 2715 Ma. Due to this more precise age of the Loso diorite, the Änäkäinen alkaline intrusion must be regarded as syncollisional and thus belonging to a different tectonic setting than the 30 Ma older and clearly pre-collisional Likamännikkö complex, contrary to the interpretation in Paper II. This adjusted sequence of events, where crustal thickening and partial melting follow each other, instead of being coeval, also better explains the heat budget of the leucogranitoid event by allowing time for the thickened crust to sufficiently heat via radioactive decay. The majority of the leucogranitoids were produced by water-fluxed melting of TTGs s.l., possible fluid sources being late sanukitoids, quartz diorites and dehydration reactions of lower crust (Paper III). Some of the leucogranitoids could have been derived from middle and lower crust amphibolites, such as those observed in Iisalmi as uplifted blocks that were partially melted at 2.7 Ga (Nehring et al. 2009). As melting commenced during active deformation, the generated melts concentrated in crustal scale shear zones, leaving relatively undeformed and unmigmatized elongated domains in between. Zircons older than the hosting mesosome observed in some migmatite leucosomes indicate that the melting cannot be regarded as fully *in situ* (Paper I).

#### 4.1.7 2.65–2.40 Ga: Silence ending in mafic and felsic magmatism

After 2.5 Ga, 2.45 Ga in Kianta, the whole Archean nucleus of the Fennoscandian Shield was intruded by voluminous mafic layered intrusions (Alapieti 1982, Amelin et al. 1995, Lobach-Zhuchenko et al. 1998, Iljina & Hanski 2005) as well as small volume carbonatites (Lokhov et al. 2009). This event is also evidenced by A-type granitoids aged 2.44–2.39 Ga (Luukkonen 1988b, Lobach-Zhuchenko et al. 1998, Lauri & Mänttari 2002, Paper IV). In Kianta the A-type granitoids belong to two geochemically differing groups: Kynsijärvi stock in Taivalkoski is interpreted as a product of assimilation and fractional crystallization (A<sub>1</sub>-type of Eby 1992) (Lauri & Mänttari 2002), while other representatives are products of partial melting of local Archean basement (A<sub>2</sub>-type of Eby 1992) (Paper IV). A<sub>2</sub>-type intrusives do not form a homogeneous group, but have compositional differences and differing magnetic properties that cannot be interpreted as a result of late stage crystallization processes, metamorphism or post-crystallization alteration: rather, they were caused by compositionally differing

sources within the heterogeneous Archean basement (Paper IV).

Based on zircon saturation temperatures, the 2.7 Ga leucogranitoids were derived from distinctly lower temperature melting than the A<sub>2</sub>-type granitoids (Papers III, IV), and thus these suites could have been derived from the same source area, yielding the second melt generation due to the raised temperature. This derivation of A-type granitoids from a source that has already experienced one melting event is a common, yet criticized (Martin 2006) hypothesis. If these two granite suites share their source rocks, they must have been metasomatized after the first melting to be able to produce two generations of melts, both enriched in i.e. K<sub>2</sub>O, Ba and Th. In Kianta, these two suites probably had differing sources, as the leucosomes in TTGs and leucogranite dykes/stocks resemble each other compositionally (Paper III), suggesting that both were melted under similar conditions and the generated melts did not experience significant ascent prior to crystallization. Furthermore, there is no evidence for penetrative and widespread alteration of the Archean rocks at the current erosion level (Mikkola 2008, Paper I). Obviously, this model of different sources does not exclude a possible metasomatism of the sources of the A-type granitoids to increase their melt fertility, especially if the lower crust was dehydrated at 2.7 Ga (Paper III).

The Paleoproterozoic bimodal event shows considerable similarities with the mid-Proterozoic rapakivi magmatism in South Finland (Paper IV), which might provide additional insights into the reasons and mechanism underlying both of these events. An interesting question is the distribution of the A<sub>1</sub>- and A<sub>2</sub>-types within Kianta, and why the A<sub>2</sub>-type intrusions are concentrated in Kuhmo and Suomussalmi, where the coeval mafic magmatism at the current erosion level is of limited volume. This could be related, for example, to differences in the extensional tectonics; in Suomussalmi and Kuhmo, under weaker extension, the majority of the mafic magma would have intruded lower crustal levels, and beneath an insulating ‘lid’ of felsic crust effectively heated their surroundings, resulting in a larger degree of partial melting and the genesis of the A<sub>2</sub>-type granites. In Taivalkoski, under stronger extension, majority of the mafic magmas would have reached higher crustal levels and their heat was more effectively conducted to the surface, resulting in a lower degree of partial melting and the generation of A<sub>1</sub>-type intrusives via assimilation and fractional crystallization processes.

## 4.2 Kianta as part of the Western Karelian terrane

Rocks older than 3 Ga in Western Karelia are few and far apart, but known from the Pudasjärvi and Iisalmi Complexes and inferred in Kianta, clearly the oldest observed one being the 3.5 Ga Siurua gneiss (Fig. 1) in Pudasjärvi (Mutanen & Huhma 2003). In Iisalmi, granulite mesosome and gneiss samples yield ages in the range of 3.2–3.1 Ga (Paavola 1986, Mänttari & Hölttä 2002), but lower crustal xenoliths from kimberlites also indicate the existence of 3.5 Ga crust there (Peltonen et al. 2006). Regarding the next age group, outside Kianta the only known rock aged 2.95 Ga is a felsic granulite from Pudasjärvi (Mutanen & Huhma 2003) near the old Siurua gneiss (Fig. 1). With respect to the voluminous TTG magmatism in Kianta at 2.8 Ga, only one representative of this age group has been located from the Pudasjärvi Complex (Lauri et al. 2011) and none from the Iisalmi Complex. The lack or low volume of ~2.8 Ga plu-

tonic rocks in the other complexes can be either an artefact of inadequate sampling of the TTG suite or a true phenomenon. However, volcanic rocks from the Oijärvi greenstone belt within the Pudasjärvi complex yield ages similar to those from the TKSB, i.e. 2.80 and 2.82 Ga (Huhma et al. 2010). Based on current knowledge, all of the three complexes of Western Karelia have a geological history extending, at least in places, into the Paleoproterozoic, but their mutual relationships cannot be constrained prior to 2.75 Ga, after which they display similar evolution from mantle-derived rocks to migmatization and the intrusion of anatectic leucogranitoids, followed by an extended period of high-grade metamorphism (Mänttari & Hölttä 2002, Mutanen & Huhma 2003, Käpyaho 2006, Heilimo et al. 2011, Lauri et al. 2011, Paper I).

## 4.3 Suomussalmi and Kianta in the global context

In a global context, the Suomussalmi area contributes interestingly to Archean crustal evolution by containing, in a relatively small (~6000 km<sup>2</sup>) area, a nearly complete set of granitoid suites described from Archean cratons globally, and within them evidence of geological history spanning 1 Ga from Paleoproterozoic to the earliest Paleoproterozoic. As the versatility of the TTG s.l. suite, and Archean granitoid suites in general, is increasingly recognized (Steenfelt et al. 2005, Moyen et al. 2007, Champion & Smithies 2007, Halla et al. 2009, Almeida et al. 2011, Heilimo et al. 2011, Moyen 2011, Papers I, II), it is becoming difficult to force, for example, the genesis of all the TTG s.l. subtypes and their appearance combinations into a single tectonic setting. Therefore, it is possible that we should not be looking for ‘the’ place for TTG genesis, but instead for a tectonic framework that allows TTG genesis in a variety of settings (Moyen 2011).

The low-HREE and high-HREE TTGs display variable mutual relations by being coeval and areally overlapping each other, for example in the East Pilbara Terrane (Champion & Smithies 2007) and the Carajás Province (Almeida et al. 2011), whereas in Suomussalmi and in the majority of the Kianta Complex only the low-HREE type is present (Paper I). In the Barberton Terrain, low-HREE and high-HREE TTGs alter from one period of plutonic activity to another (Moyen et al. 2007). According to recent inter-

pretations, the low-HREE TTGs of the Carajás Province and the Barberton Terrain represent partial melts from subducting slabs, and in the case of the two other examples, they represent partial melts from the lower crust. Linking different TTG types from different areas into a possible subduction setting is controversial; Halla et al. (2009) interpret, based on data from the Archean of Finland, that the high-HREE TTGs are slab melts that have interacted with mantle wedge and that low-HREE TTGs represent partial melts of lower crust, whereas Almeida et al. (2011) interpret the low-HREE TTGs as slab melts and high-HREE TTGs as a result of lower crustal melting. In the case of partial melting of thickened crust, the low- and high-HREE TTGs would simply represent melting of intra- and underplated mafic magmas at different depths, which could possibly indicate paleocrustal thicknesses (Champion & Smithies 2007).

Transitional TTGs add to the complexity of the picture by being an important constituent of the major TTG s.l. event(s) in some cases (East Pilbara Terrane, Suomussalmi), present but volumetrically less significant in some cases (Barberton Terrain), and in some cases lacking (Carajás Province). As the transitional TTGs have been interpreted as partial melts of pre-existing TTGs, their presence indicates the existence of an older nucleus containing abundant felsic material (Champion & Smithies 2007, Paper I). In

the Carajás Province and the Barberton Terrain, examples (Moyen et al. 2007, Almeida et al. 2011) where transitional TTGs are missing or insignificant, the subduction is interpreted to occur beneath predominantly mafic protocrust. This could mean that if subduction occurred in the Archean it could, for some dynamic reason, only initiate under oceanic plateau-type crust (Moyen et al. 2007, Nair & Chacko 2008, Almeida et al. 2011) and not below already formed continental crust, where the oceanic crust will be stacked at the base of the crust (Smithies et al. 2003, Paper I). If the thickening of the crust occurred via magmatic underplating (Bédard 2006, Champion & Smithies 2007), the framework becomes more complex, but it should be born in mind that the tectonic stacking and magmatic underplating options do not exclude each other on global scale. Therefore, the Archean tectonic framework could well have included all of the above-mentioned settings.

The mostly Neoproterozoic emergence of mantle-derived felsic plutonic suites, i.e. syenites, quartz diorites and sanukitoids, undoubtedly indicates a global change in the tectonic framework by allowing the formation of a variably metasomatized mantle source and partial melting of it. The required metasomatism is now typically attributed to the subduction setting (e.g. Blichert-Toft et al. 1995, Martin et al. 2005, Steenfelt et al. 2005, Heilimo et al. 2010a, Papers I, II), often based on modern analogues. The global simultaneousness of the appearance of these suites in the Neoproterozoic with two known older examples (Smithies & Champion 2000, Oliveira et al. 2009) is interesting in many ways, but especially regarding the interpretations that plate tectonics and subduction have been running since Paleoproterozoic. As the age of the subducting slab largely controls the subduction angle, this would require that in the Archean the subducting plates were of roughly similar age, so that the subduction angles steepened globally at the same time to allow the enough room for efficient interaction between melts and fluids from the subducted slab. Alternatively, the simultaneousness of the appearance would fit the model of super events (Condie 1998) consisting of ‘mantle avalanches’, i.e. subducted slabs piled up at the 660-km seismic discontinuity sank through it and resulted in a surge of mantle upwellings. Thus, the trigger could be global instead of more local, i.e. slab break-off (Lobach-Zhuchenko et al. 2008, Heilimo et al. 2010a), which would explain the sudden emergence of mantle-derived granitoids in general, not only the sanukitoids. The volumetrically minor TTG s.l. rocks coeval with or immediately following sanukitoid activity are likely

to be products of lower crustal melting triggered by heating caused by upwelling magmas (Paper I, Almeida et al. 2010).

Regarding nomenclature, the most problematic of the Archean granitoid suites are the leucocratic granitoids, referred to here as leucogranitoids, presenting significant crustal recycling at cratonization stages of each individual craton. The leucogranitoids are given names that change from location to location, reflecting the local variety in mineralogy and chemistry. Examples include potassic leucogranite and leucogranodiorite-granite suites in the Carajás Province (Almeida et al. 2010), K-rich granites in Tanzania (Manya et al. 2007) and biotite-granites and two-mica granites in the Dharwar Craton (Moyen et al. 2003). A number of these leucogranitoids could be classified as transitional TTGs (Almeida et al. 2010, Paper III), but not all, as for example the leucogranitoids of Kianta include samples with REE patterns displaying extreme positive Eu anomalies and low REE levels, or alternatively non-fractionated REE patterns with strongly negative Eu anomalies (Paper III). The inclusion of such samples into the transitional TTG suite would contradict the common view that TTGs display fractionated REE patterns with modest or no Eu anomalies and at least a certain degree of LREE enrichment (Martin et al. 2005, Moyen 2011).

The appearance of A-type granitoids near the Archean-Proterozoic boundary also has implications for plate and mantle dynamics, just like the appearance of sanukitoids, quartz diorites and syenites 100–300 Ma earlier. Kianta experienced voluminous mafic magmatism close to 2.8 Ga (Papunen et al. 2009, Huhma et al. 2010) and again at 2.44 Ga (Alapieti 1982), but only the latter event also includes A-type granites. However, both events are interpreted in fundamentally similar ways: upwelling mantle partially melted and the melts intruded into, and extruded onto, continental crust in an extensional environment (Iljina & Hanski 2005, Papunen et al. 2009). One possible explanation is that in the Archean event most of the mafic magmas reached the surface and thus did not heat the crust sufficiently to partially melt it. This could be due to the small size of the continental fragments prior to the 2.7 Ga amalgamation, so that the small fragments extended too easily in response to the upwelling mantle due to the lack of sideways support and resistance provided by the larger Archean fragment at 2.44 Ga. An alternative explanation would be the lack of penetrative fenitization to enhance the melt fertility and to alter the source compositions prior to the mantle-derived melts, features interpreted as prerequisites

for A-type granitoids (Martin 2006). This lack of metasomatism by alkaline fluids is also manifested by the lack of carbonatites and truly alkaline rocks

prior to the Neoproterozoic and, if the two phase metasomatism model of Heilimo et al. (2010a) is correct, also by the lack of sanukitoids.

#### 4.4 Further research

More detailed studies of the quartz diorite suite of Western Karelia could reveal further insights into the mechanism(s) responsible for Neoproterozoic mantle metasomatism, both locally and globally. The studies should include both geochemical aspects and age determinations to better constrain the time frame of their emplacement in respect to the sanukitoid magmatism.

Regarding the leucogranitoid suite, the next step forward would be to globally determine the compositional limits of transitional TTGs, or whether all rocks interpreted as derived from TTGs qualify as transitional TTGs. Such a usage would, however, make the latter a new 'waste bin' name. After a certain consensus is reached on transitional TTGs, the subdivision and study of the 'left over' leucogranitoids could provide addi-

tional insights to the last phases of cratonization.

The age of the felsic volcanism within the TKSB is reasonably well established and correlates with the observed ages of the surrounding TTGs. A study of the trace element geochemistry of these volcanic rocks could provide answers concerning their relationship with the surrounding granitoids, a point also raised by Käpyaho (2007).

Paleoproterozoic A-type granitoids are so far known from Kianta, while the coeval mafic dykes and intrusions are also known from the Pudasjärvi Complex (Fig. 1). This could be either a real situation or an artifact of less intense studies. If the difference is real, study of it could provide insights into the subtle differences controlling the genesis or non-genesis of A-type granitoids in general.

## 5 CONCLUSIONS

Sm-Nd and Pb-Pb isotopic data as well as U-Pb ages of inherited zircons (up to 3440 Ma) demonstrate that a Paleoproterozoic 'protocrust' has existed in the northern parts of Kianta. The oldest actual rocks in Kianta are 2.95 Ga TTGs s.l. and volcanic rocks, all located in areas with evidence for the existence of Paleoproterozoic 'protocrust'.

TTGs from Suomussalmi belong to the low-HREE type and are compositionally consistent with partial melting of garnet-bearing amphibolites, and show no obvious signs of interaction with the mantle. The presence of transitional TTGs in Suomussalmi indicates that recycling of pre-existing felsic rocks already commenced, at least locally, at 2.95 Ga. Based on the compositional and age data from the granitoid suites, the Tipasjärvi-Kuhmo-Suomussalmi greenstone belt does not form a suture dividing Kianta into separate units.

Ca 2.75 Ga marks a shift in Kianta from granitoid magmatism consisting solely of TTGs s.l. to one with varying compositional types: TTGs s.l., sanukitoids, quartz diorites, alkaline rocks and leucogranitoids. This could be linked to a shift in granitoid genesis from lower crustal partial melting to modern-style subduction involving partial

melting of variably enriched mantle.

The  $2741 \pm 2$  Ma old Likamännikkö quartz alkali feldspar syenite has alkaline affinities and presents a whole new Neoproterozoic rock type in Karelia. The associated carbonatite patches are potentially among the oldest known carbonatites on Earth.

The main migmatization event occurred at 2.7 Ga as a result of collisional tectonics. Leucosomes are partly mobile and not fully *in situ* melts. As melting occurred during active deformation, melts and melting concentrated in crustal scale shear zones, leaving elongated domains of unmigmatized rocks in between. The leucogranitoids of the northern Kianta Complex are compositionally similar to the leucosomes in TTGs s.l. and are interpreted to represent mainly partial melts of the TTG suite granitoids.

The Paleoproterozoic A-type granite magmatism within Kianta extended over a longer time span (2.44–2.39 Ga) and a larger area than previously known. The suite shows compositional differences that are inherited from a heterogeneous source area. Heat required for the partial melting was carried by the coeval mafic magmas.

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[www.gtk.fi](http://www.gtk.fi)  
[info@gtk.fi](mailto:info@gtk.fi)

This PhD thesis comprises a synopsis and four original papers dealing with Archean and earliest Proterozoic granitoids from northern parts of the Kianta Complex. Results show that the geological history in the area extends into the Paleoproterozoic and that crustal recycling already commenced in the Mesoproterozoic. Prior to 2750 Ma the granitoid activity was dominated by TTG (tonalite-trondhjemite-granodiorite) suite intrusions. Between 2750 and 2700 Ma, most of the granitoids were derived from variably metasomatized mantle, probably indicating the beginning of subduction. Close to 2700 Ma the older granitoids were variably migmatized and intruded by anatectic leucogranitoids. The next phase of magmatic activity in the area followed 250 Ma later, when A-type granitoids linked to the coeval mafic magmatism intruded the Archean complex.