Archaean crustal evolution in eastern Finland: New geochronological and geochemical constraints from the Kuhmo terrain and the Nurmes belt

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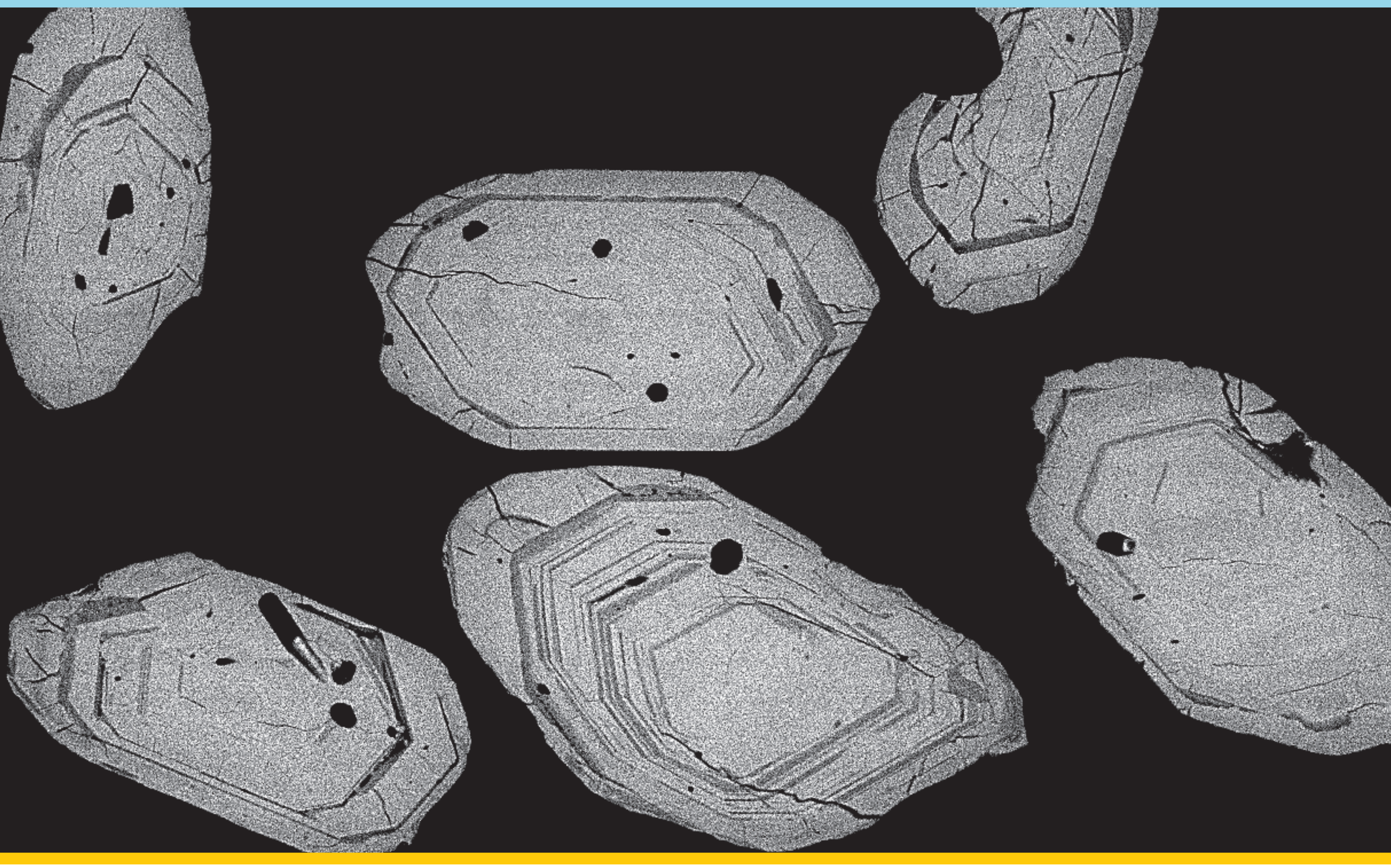

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by

Asko Käpyaho

Geological Survey of Finland
P.O. Box 96
FI-02151 Espoo
Finland

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Supervisors: Prof. O. Tapani Rämö
Department of Geology
University of Helsinki, Finland

Dr. Pentti Hölttä
Geological Survey of Finland
Espoo, Finland

Reviewers: Prof. Hugh Rollinson
Sultan Qaboos University
Muscat, Sultanate of Oman

Dr. Wouter Bleeker
Geological Survey of Canada
Ottawa, Canada

Opponent: Prof. G. Nelson Eby
University of Massachusetts
Lowell, U.S.A.

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Cover: Back-scattered electron image showing representative zircon crystals from the ca. 2.75 Ga Purnu tonalite (sample A1702). The short dimension of the middle grain at the bottom is ca. 100 µm. Picture taken by I. Mänttäri and A. Käpyaho.

Abstract

This thesis summarises the results of four original papers concerning U-Pb geochronology and geochemical evolution of Archaean rocks from the Kuhmo terrain and the Nurmes belt, eastern Finland. The study area belongs to a typical Archaean granite-greenstone terrain, composed of metavolcanic and metasedimentary rocks in generally N-S trending greenstone belts as well as a granitoid-gneiss complex with intervening gneissic and migmatised supracrustal and plutonic rocks. U-Pb data on migmatite mesosomes indicate that the crust surrounding the Tipasjärvi-Kuhmo-Suomussalmi greenstone belt is of varying age. The oldest protolith detected for a migmatite mesosome from the granitoid-gneiss complex is 2.94 Ga, whereas the other dated migmatite protoliths have ages of 2.84–2.79 Ga. The latter protoliths are syngenetic with the majority of volcanic rocks in the adjacent Tipasjärvi-Kuhmo-Suomussalmi greenstone belt. This suggests that the genesis of some of the volcanic rocks within the greenstone belt and surrounding migmatite protoliths could be linked. Metamorphic zircon overgrowths with ages of 2.84–2.81 Ga were also obtained.

The non-migmatised plutonic rocks in the Kuhmo terrain and in the Nurmes belt record secular geochemical evolution, typical of Archaean cratons. The studied tonalitic rocks have ages of 2.83–2.75 Ga and they have geochemical characteristics similar to low-Al and high-Al TTD (tonalite-trondhjemite-dacite). The granodiorites, diorites, and gabbros with high Mg/Fe and LILE-enriched characteristics were mostly emplaced between 2.74–2.70 Ga and they exhibit geochemical characteristics typical of Archaean sanukitoid suites. The latest identified plutonic episode took place at 2.70–2.68 Ga, when compositionally heterogeneous leucocratic granitoid rocks, with a variable crustal component, were emplaced. U-Pb data on migmatite leucosomes suggest that leucosome generation may have been coeval with this latest plutonic event. On the basis of available U-Pb and Sm-Nd isotopic data it appears that the plutonic rocks of the Kuhmo terrain and the Nurmes belt do not contain any significant input from Palaeoarchaean sources.

A characteristic feature of the Nurmes belt is the presence of migmatised paragneisses, locally preserving primary sedimentary structures, with sporadic amphibolite intercalations. U-Pb studies on zircons indicate that the precursors of the Nurmes paragneisses were graywackes that were deposited between 2.71 Ga and 2.69 Ga and that they had a prominent 2.75–2.70 Ga source. Nd isotopic and whole-rock geochemical data for the intercalated amphibolites imply MORB sources. U-Pb data on zircons from the plutonic rocks and paragneisses reveal that metamorphic zircon growth took place at 2.72–2.63 Ga. This was the last tectonothermal event related to cratonisation of the Archaean crust of eastern Finland.

TABLE OF CONTEST

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following four papers, which are referred to by Roman numerals I through IV in the text:

I Käpyaho, A., Mänttäri, I., Huhma, H., 2006. Growth of Archaean crust in the Kuhmo district, eastern Finland: U-Pb and Sm-Nd isotope constraints on plutonic rocks.
Precambrian Research ***146*** *(3-4), 95-119.*

II Käpyaho, A., 2006. Whole-rock geochemistry of some tonalite and high Mg/Fe gabbro, diorite, and granodiorite plutons (sanukitoid suites) in the Kuhmo district, eastern Finland.
Bulletin of the Geological Society of Finland ***78*** *(2), 121-141.*

III Käpyaho, A., Hölttä, P., Whitehouse, M., 2007. U-Pb zircon geochronology of selected Neoarchaean migmatites in eastern Finland.
Bulletin of the Geological Society of Finland ***79*** *(1), 95-115.*

IV Kontinen, A., Käpyaho, A., Huhma, H., Karhu, J., Matukov, D. I., Larionov, A., Sergeev, S.A., 2007. Nurmes paragneisses in eastern Finland, Karelian craton: Provenance, tectonic setting and implications for Neoarchaean craton correlation.
Precambrian Research ***152****, (3-4) 119-148.*

The author's (A.K.) contribution to the multi-authored papers is as follows:

In *Paper I* A.K. carried out the field work, performed U-Pb sampling and collected approximately half of the Sm-Nd isotopic samples. A.K. was responsible for most of the zircon separation procedures, except for crushing of the samples. A.K. hand-picked the zircons and carried out the U-Pb analytical work together with I. Mänttäri, who supervised the work and handled and interpreted the U-Pb data. Part of the Sm-Nd analytical work was done by A.K. in co-operation with H. Huhma and his laboratory staff. As the first author A.K. had the main responsibility for preparing the manuscript, interpretations and making the conclusions.

In *Paper III* A.K. carried out field work, participated in sampling, zircon separation, and sample preparation. Single zircon U-Pb analyses were done in co-operation with the other two authors. A.K. had the main responsibility for preparing the manuscript and making the conclusions.

In *Paper IV* A.K. participated in U-Pb zircon sample preparation and U-Pb analysis with the SHRIMP, in co-operation with researchers at VSEGEI Saint Petersburg. Sampling and zircon separation was performed by A. Kontinen. C isotopes were analysed by J. Karhu, while Nd isotopic and conventional TIMS U-Pb isotopic analysis was done by H. Huhma. The first and second author had the main responsibility of preparing the manuscript, and the first author finalised the work. The study was planned by A. Kontinen and H. Huhma.

1. INTRODUCTION

The Geological Survey of Finland (GTK) launched a project studying the evolution of the Archaean crust in Finland in 2002. At around the same time, a new vacancy for the Graduate Research School of Geology was opened, and a study plan was proposed that culminated in the present thesis. Because this study was associated with Archaean studies at GTK from the outset, close co-operation with the GTK isotopic laboratory was also established. The Kuhmo greenstone belt and surrounding granitoids, referred to collectively as the Kuhmo terrain in Paper IV and the paragneisses of the Nurmes belt (*op.cit.*) being representative of the Archaean bedrock of eastern Finland, granite-greenstone terrains, were selected as the focus for study (Fig. 1). This segment of the Finnish Archaean had already been mapped in detail through the GTK 1:100 000 mapping program (e.g., Hyppönen, 1983; Luukkonen, 1988; Luukkonen, 2001) and available studies indicated that the area would provide a useful framework for further geochronological and geochemical studies with crustal growth processes as a focus (for a summary of previous work, see Sorjonen-Ward & Luukkonen, 2005; Luukkonen, 1992).

Previous studies in the Archaean bedrock of eastern Finland have demonstrated that, in some cases, interpretation of isotopic geochemical data is not straightforward, as later tectonothermal events may have caused secondary fractionation of the isotopes (e.g., Vaasjoki, 1988; Huhma et al., 1999; Kontinen et al., 1992; O´Brien et al., 1993). The U-Pb isotopic systematics of zircon are, however, generally considered relatively resistant to secondary disturbances, even in granulite facies metamorphism, and thus primary protolith ages can often be recovered (e.g., Mänttäri & Hölttä, 2002). The Sm-Nd isotopic method is also a rather widely used tool for interpreting the primary sources of rocks, although it has been shown to be more susceptible to secondary alteration (e.g., Gruau et al., 1992; O´Brien et al., 1993; Lauri et al., 2006). However, by critical interpretation and evaluation of the results, these methods together with whole-rock geochemical data and geological observations provide a good tool for studying the origin and age of Archaean rocks.

One of the key issues in Archaean geology is the growth of continental crust, and the rate of the growth in particular (for a summary, see Arndt, 2004). As plutonic rocks form a voluminously significant component of Archaean cratons, monitoring their secular evolution is potentially one of the best sources of information and constraints on concepts of crustal growth. In most Archaean granite–greenstone terrains, secular changes in the geochemical composition of plutonic rocks have been identified (Zegers, 2004). In general, the oldest plutonic rocks often belong to the TTG (tonalite-trondhjemite-granodiorite) association and are temporally followed by GGM (granodiorite-granite-monzogranite) and SG (syenite-granite) suites (Zegers, *op.cit.*). Even though these temporal relations are commonly observed, there is still no general consensus on the tectonic regime in which these plutonic suites formed.

For TTG magmas in Archaean regimes, several tectonic settings have been invoked. For example, according to Martin (1999) and Martin & Moyen (2002), TTG association rocks may have originated by slab melting in active subduction zones. This may explain some of the similarities between the Archaean TTG association and Cenozoic adakites, which were produced by melting of subducted slab material (see Martin, 1999; Martin et al., 2005). Some authors emphasise that, instead of slab melting, Archaean high-Al TTGs may have formed after partial melting of lower crust in arc systems or at the base of oceanic plateaus (e.g., Condie, 2005). Taking into account that partial melting of crustal sources at the base of thickened crust is also considered to produce some of the adakites (e.g., Xiao & Clemens, 2007), the relationship between the adakites and TTGs certainly deserves more, and careful study.

Some of the GGM suites have been considered to contain a component of metasomatised (enriched) man-

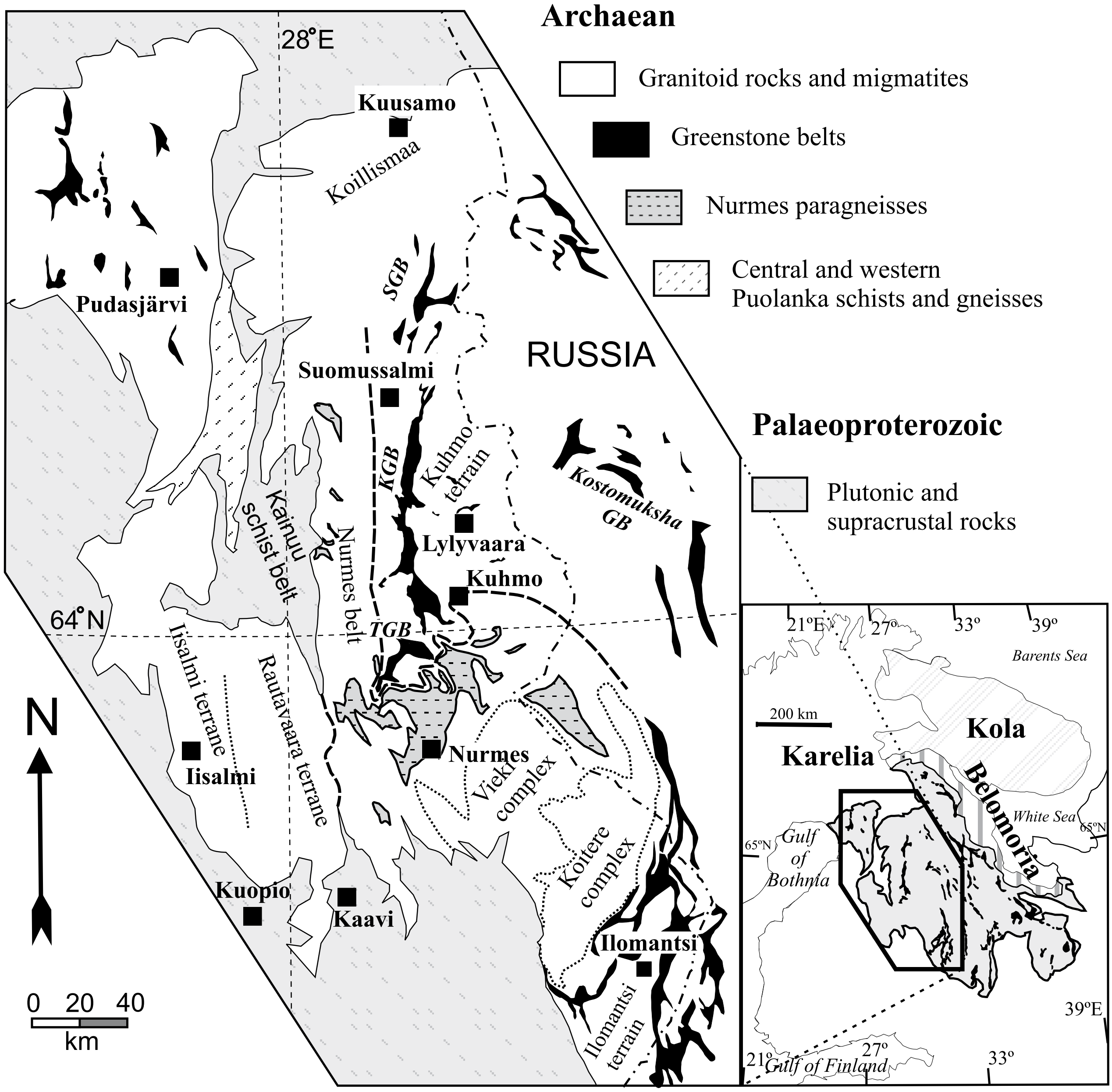

Fig. 1. Generalised bedrock map of eastern Finland (redrawn after Korsman et al., 1997 and Koistinen et al., 2001). Approximate boundaries between terrains and belts are from Paper IV and from Mänttäri & Hölttä (2002). SGB=Suomussalmi greenstone belt, KGB= Kuhmo greenstone belt, and TGB=Tipasjärvi greenstone belt. Inset shows the major Archaean crustal domains in the Fennoscandian shield.

tle (e.g., Feng & Kerrich, 1992). Granitoids belonging to one distinct type of GGM suite have become widely known as "sanukitoids" because of their chemical similiarity to high-Mg andesites (sanukites) described from the Miocene of Japan (cf. Tatsumi & Ishizaka, 1982). Originally, Shirey & Hanson (1984) defined the term sanukitoid to cover LREE and LILE enriched mafic-intermediate rocks such as monzodiorites and trachyandesites, but Stern & Hanson (1991) also included rocks from the diorite–granodiorite range, and introduced the term "sanukitoid suite". Rocks associated with the sanukitoid suite have recently been identified from nearly all Archaean cratons (see Halla, 2005; Kovalenko et al., 2005; Stevenson et al., 1999 and references therein). Currently, according to Le Maitre et al. (2002) the term sanukitoid is applied to Archaean high-Mg monzodiorite and granodiorite.

In order to comprehend geochemical evolution with respect to time, accurate dating of plutonic suites is crucial. For understanding the role of crustal recycling and addition of juvenile magmatic material in relation to these plutonic associations (TTG, GGM, SG) additional techniques, such as the Sm-Nd isotopic system, are often essential. Within the Kuhmo and Nurmes regions of eastern Finland, the typical temporal pattern, proceeding from the TTG association through high-Mg/Fe granodiorites to leucogranites, was already demonstrated by the Rb-Sr isotopic studies of Martin et al. (1984) and Querré (1985) (see also Vaasjoki, 1988). As an extension of this topic, new U-Pb ages and Sm-Nd isotopic data are presented from the area (Paper I). The results are evaluated with respect to the concept of crustal growth in the Neoarchaean and new whole-rock geochemical data are presented, in order to study and assess possible secular variations in the geochemical characteristics of the plutonic rocks (Paper II).

Another key issue related to Archaean granite-greenstone terrains is the relationship between greenstone belts and the surrounding bedrock. A fundamental question, of which is applicable in general to Archaean greenstone belts, is whether they are allochthonous or autochthonous with respect to their present tectonic positions. As Van Kranendonk´s (2004) summary shows, there is no simple, general solution to this problem, although establishing the age relationships between the greenstone belts and surrounding granitoids may bring us closer to an answer. Geochronological data on migmatites surrounding the Tipasjärvi–Kuhmo–Suomussalmi greenstone belt are presented in Paper III, and these are discussed within the framework of tectonic relationships between for the greenstone belts and the surrounding granite-gneiss complexes.

In addition to plutonic rocks, Archaean sedimentary rocks are valuable in modelling crustal growth processes, as detrital material may provide insights into age and relative extent of provenance areas. In particular, combined single zircon dating and geochemical characterisation have proven valuable in studying Precambrian terrains (e.g., Yamashita et al., 2000). Archaean sedimentary rocks are also important sources on the evolution of ancient life (see summary by Schopf, 2004). In Paper IV, new geochemical data, combined with radiogenic and stable isotope data, are presented for greywacke-derived paragneisses from the Nurmes belt (*sensu* Paper IV) (Fig. 1). Based on these data, the likely geotectonic setting of eastern Finland at 2.7 Ga is discussed and U-Pb data are further applied for evaluating Neoarchaean craton correlations.

This synopsis summarises the new geochemical and geochronological data presented in the four papers (Papers I–IV) and discusses these data in the context of previously published material in order to provide a more robust geochronological framework for crustal formation and reworking in eastern Finland. Although particular emphasis is given to the Kuhmo terrain and Nurmes belt, an attempt is also made to relate some of the more important results to the crustal evolution at craton scale (Papers I, IV).

2. METHODOLOGY

The sampling performed by the author for Papers I–III was done during the years 2002 and 2003. In addition, some previously collected samples were also used, including: some of the A-series samples from the GTK isotope laboratory, as well as samples collected by geologists who have previously worked in the study area (for more details, see acknowledgements in Papers I–III). Some of the key areas were mapped by the author in detail (e.g., the Arola granodiorite and Viitavaara tonalite; Paper II). Altered samples were avoided, as the target of the studies was to detect the primary geochemical characteristics of the rocks. Information on sample treatment procedures and sample descriptions are available in the original papers. Coordinates for the U-Pb samples analysed for the Papers I, III and IV are given in Appendix I.

The U-Pb isotopic composition of zircon and titanite were studied to determine the crystallisation ages of the plutonic rocks (Papers I, IV), to identify protolith ages of migmatite mesosomes (Paper III), to reveal metamorphic events (Papers I, III, IV), and to constrain the sedimentation ages (Paper IV). The Sm-Nd isotopic method was used to constrain the crustal residence ages of the plutonic and metasedimentary rocks (Papers I, IV). Whole-rock major and trace element data on plutonic and metasedimentary rocks were investigated in order to assess the geochemical signatures indicative of their origin (Papers II, IV).

U-Pb geochronological data on zircons are presented in three of the papers (Papers I, III, IV) and U-Pb multigrain data on titanite are presented in Papers I and IV. The zircon multigrain U-Pb data presented in Papers I and IV were analysed by a VG Sector 54 thermal ionisation mass spectrometer (TIMS) at the Espoo laboratory of the Geological Survey of Finland. The single grain zircon U-Pb data were obtained with the Cameca II IMS 1270 secondary ion mass spectrometer (SIMS) in the Museum of Natural History of Sweden, Stockholm (Papers I, III) and the sensitive high resolution ion mass spectrometer (SHRIMP-II) in the SVEGEI Centre of Isotopic Research Institute in St. Petersburg (Paper IV). Detailed methodological descriptions for the TIMS method are provided by Vaasjoki (2001). The SIMS methodology is available in Whitehouse et al. (1999) and that for SHRIMP in Williams (1998) and Larionov et al. (2004).

For Sm-Nd isotopic studies, the samples were analysed using the VG Sector 54 TIMS situated at Geological Survey of Finland isotope laboratory at Espoo. The analytical procedure used follows that given in Lahtinen & Huhma (1997).

3. REVIEW OF THE PAPERS

3.1. Paper I

Paper I presents new U-Pb SIMS and TIMS data on zircon and titanite, and also whole-rock Sm-Nd isotopic data for the plutonic rocks intruding and surrounding the Kuhmo greenstone belt and Nurmes belt (Fig. 1). The aim of this paper was to study Archaean crustal growth by dating and analysing the Nd isotopic compositions of selected plutonic rocks. The age data show that the studied plutonic rocks were emplaced during the period 2.83–2.68 Ga. The tonalites were emplaced in at least three separate episodes between 2.83–2.74 Ga. Most of the sanukitoids (sanukitoid suites) have crystallisation ages of 2.74–2.70 Ga. The leucocratic granites and granodiorites have emplacement ages of 2.70–2.68 Ga and show relatively abundant zircon inheritance. SIMS data also show that some zircons have metamorphic rims with ages of 2.71–2.63 Ga. Nd isotopic data indicate that the tonalites generally had a relatively short crustal pre-history, whereas the 2.70–2.68 Ga granitoid rocks show a varied, yet predominantly recycled, component. Age data, together with Nd isotopic results suggest that the plutonic rocks of the study area were formed without any significant input from Palaeoarchaean sources, and that the U-Pb ages from the plutonic rocks resemble those of adjacent areas in Russian Karelia.

3.2. Paper II

Paper II presents new whole-rock geochemical data on tonalites and high-Mg/Fe gabbros, diorites, and granodiorites intruding and surrounding the Tipasjärvi-Kuhmo-Suomussalmi greenstone belt and the Nurmes belt (Fig. 1). The aim of this paper was to study the geochemical properties, identify contrasting sources, and study the time-integrated evolution of the plutonic rocks. The age data for most of these intrusions are given in Paper I. The high-Mg/Fe rocks have geochemical characteristics that are typical of Archaean sanukitoid suites worldwide, including elevated abundances of Cr and Ni, and large-ion lithophile elements (LILE), such as Ba and Sr. These features are considered to reflect an enriched mantle source component to the magmas. The three separate tonalite intrusions show varied LREE/HREE fractionation trends. The weakly LREE/HREE fractionated Viitavaara (type II) tonalite resembles rocks of the low-Al TTD (tonalite-trondhjemite-dacite) association, attributed to an absence of garnet residue (cf. Drummond et al., 1996). In contrast, tonalite of the Purnu type resembles high-Al TTD, which is considered to reflect the presence of garnet during melting in the source region. These differences may in fact result from melting at varying depths.

3.3. Paper III

Paper III presents new U-Pb SIMS results for zircons from four migmatite samples from eastern Finland. The aim of Paper III was to provide age data on the migmatites (leucosomes and mesosomes), facilitating comparisons and correlations between the migmatites, adjacent plutonic rocks and rocks from greenstone belt. The results show that the mesosomes have heterogeneous protolith ages; most of the dated zircons were 2.84–2.79 Ga, but there were also zircon cores with ages of 2.94 Ga in one sample (Lylyvaara migmatite mesosome). Age data suggest that the 2.84–2.79 Ga protoliths were generated at broadly the same time as the metavolcanic rocks in the adjacent Tipasjärvi-Kuhmo-Suomussalmi greenstone belt. This, in turn, suggests that some of the studied mesosomes may represent crustal material equivalent to some lithological units in the adjacent greenstone belt. Zircons analysed from leucosomes imply that the leucosomes may have formed within the time-period of 2.73 Ga to 2.68 Ga. However, scattered age data, inheritance and the large number of discordant data complicate the interpretation.

3.4. Paper IV

Paper IV presents new radiogenic isotopic data (U-Pb on zircon and titanite, whole-rock Nd), stable isotopic data (C on graphite) and whole-rock geochemical data on the migmatitic Nurmes paragneisses from eastern Finland. The main aim of this paper was to constrain the age of sedimentation, to provide information on provenance and tectonic setting, and to study the origin of the graphite. The age data show that the Nurmes paragneiss protoliths were deposited between 2.71 Ga and 2.69 Ga, with most of the detrital zircons having ages between 2.75 Ga and 2.70 Ga. These data are consistent with the Nd isotopic data, which imply a relatively short crustal prehistory for the paragneiss protoliths. The intercalated amphibolites mostly have depleted mantle characteristics. Back-arc or intra-arc tectonic settings are considered as the most probable environment for sedimentation. Remarkable similarities exist in the timing of sedimentation and in the zircon populations of the Nurmes paragneisses and some of the Archaean sedimentary belts of the Superior Province in the Canadian Shield. These features are considered to provide further support to the previously proposed hypothesis of Karelia and Superior Province having been contiguous parts of an Archaean supercraton. (e.g., Heaman, 1997; Bleeker, 2003)

4. DISCUSSION

4.1. Major events of Archaean crustal evolution in eastern Finland with special emphasis to the Kuhmo terrain and the Nurmes belt

The Archaean rocks in the Fennoscandian shield have been traditionally divided into three crustal domains: Karelia, Kola, and Belomoria (Fig. 1) (Gaál & Gorbatchev, 1987). The Karelian domain (craton) has often been considered as part of a much larger Archaean supercraton (e.g., Bleeker, 2003). Karelian domain is thought to have formed by accretion of crustal fragments with different ages (e.g., Hölttä et al., 2000; Mänttäri & Hölttä, 2002), in a manner analogous to modern continent-continent type collisions (Kontinen & Paavola, 2006). On the basis of geological, geochemical and geochronological data, the Karelian domain is subdivided into smaller units, for which boundaries are often difficult to define precisely (Sorjonen-Ward & Luukkonen, 2005). In this section, the geochronological and geochemical data for the Kuhmo terrain and Nurmes belt, as defined in Paper IV, are briefly summarised in chronological order.

4.1.1. Pre-2.90 Ga crustal fragments

The oldest recognised volcanic events in the Tipasjärvi-Kuhmo-Suomussalmi greenstone belt have conventional (TIMS) U-Pb ages of 3.01 Ga and 2.95 Ga (Luukkonen et al., 2002) (Fig. 2). A 2.94 Ga protolith age was obtained from the Lylyvaara migmatite (Paper III), which is located about 30 km east of the greenstone belt (Fig. 1). Some detrital zircon grains also indicated the presence of 2.94–3.07 Ga igneous source material in the Nurmes belt paragneisses. For comparison, 3.5 Ga plutonic rocks with 3.7 Ga xenocrystic zircons have been reported from Siurua, Pudasjärvi (Mutanen & Huhma, 2003) (Fig. 1). This is apparently the oldest igneous rock identified in the Fennoscandian shield thus far. There is also additional, albeit indirect evidence for the existence of >3.0 Ga crust in eastern Finland; as shown by Sorjonen-Ward & Claoué-Long (1993), the Silvevaara tonalite in Ilomantsi contains xenocrystic zircons with ages >3.10 Ga. Peltonen et al. (2006) also reported ca. 3.55 Ga xenocrystic zircons from the kimberlite xenoliths from Kaavi and Kuopio areas, to the southwest of Kuhmo, thus suggesting that the exposed crust in the western part of the Karelian craton is, at least partly, underlain by crust of that age. It is, however, noteworthy that no zircons of this age have yet been recognised from either plutonic rocks or migmatites, nor from paragneisses in the Kuhmo terrain and Nurmes belt. This may be due to the limited amount of data available. Nevertheless, Nd isotopic data, together with U-Pb data on plutonic rocks suggest that if there are >3.0 Ga components present, they must be of rather limited extent (Paper I). In general, on the basis of Nd isotopic data, most felsic rocks from eastern Finland have crustal residence ages (T_{DM}) of 2.8–3.0 Ga (Huhma et al., 2007).

4.1.2. Poorly defined interval between 2.90–2.85 Ga

No plutonic rocks with ages of 2.90–2.85 Ga have been recorded from the Kuhmo terrain (*sensu* Paper IV) nor from the Nurmes Belt (*op. cit.*). Zircons dated from Nurmes paragneisses, however, do provide evidence for igneous sources of that age (Paper IV). The Ilomantsi terrain and Koitere complex (Fig. 1), are considered to be the most probable source area for the detrital material of the predominantly graywacke protoliths to these gneisses (Paper IV), which is consistent with the predominance of zircons of age 2.75–2.70 Ga. However, no igneous rocks with ages of 2.90–2.85 Ga have been reported from the Ilomantsi terrain either. The presence of 2.85–2.90 Ga zircons in the Nurmes paragneisses could imply derivation from the eastern part of the Karelian craton, where rocks of this age are exposed (for summary, see Slabunov et al. 2006a, b). Nevertheless, the significance of this apparent gap in magmatic processes in the Finnish Archaean between 2.90 and 2.85 Ga remains unclear.

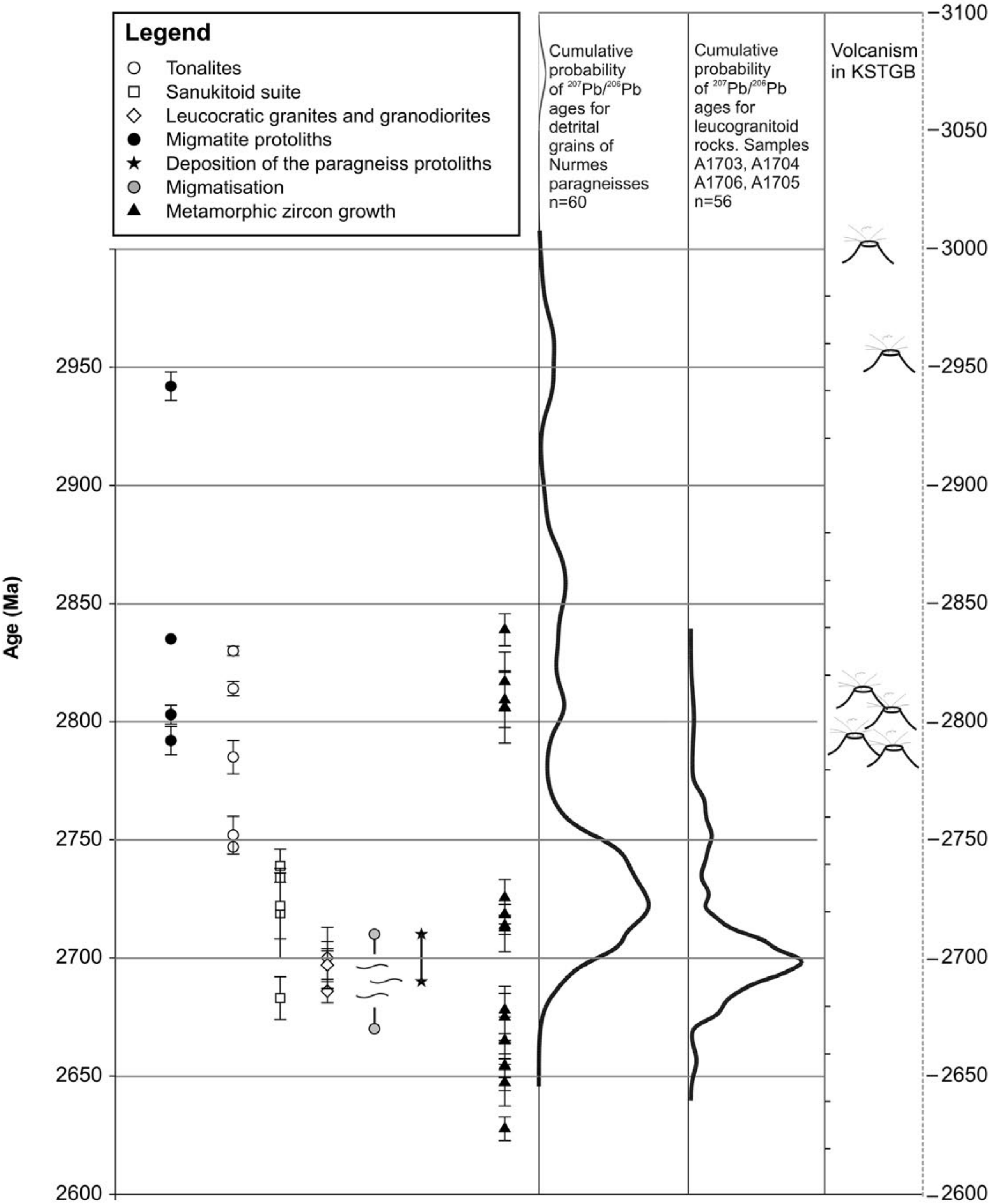

Fig. 2. Age compilation showing the U-Pb ages of non-migmatitic plutonic rocks, depositional ages of protoliths of Nurmes paragneisses, and protolith and approximate leucosome formation ages for the migmatites, as well as concordant Pb-Pb ages for metamorphic zircon domains from the Kuhmo terrain and Nurmes belt. Cumulative probabilities for the concordant and nearly concordant $^{207}Pb/^{206}Pb$ ages on the Nurmes paragneisses and leucogranitoid rocks are also shown. Error bars are at 2σ. Data and additional references are from Papers I, III, IV. References for major volcanic episodes are given in the caption of Figure 9 in Paper III. KSTGB refers to Kuhmo-Suomussalmi-Tipasjärvi greenstone belt.

4.1.3. *Intense period of crust formation at 2.85–2.68 Ga*

The oldest known non-migmatised plutonic rocks intruding the Kuhmo terrain and Nurmes belt are tonalites with ages of 2.83–2.81 Ga (Vaasjoki et al., 1999; Paper I). The majority of the zircons dated from migmatite protoliths of the Kuhmo terrain and the Vieki complex (*sensu* Paper IV) share rather similar ages (Paper III) (Fig. 2). In addition, there is a prominent clustering of ages for volcanic rocks from the Tipasjärvi-Kuhmo-Suomussalmi greensone belt at around 2.8 Ga (for references see caption of Figure 9 in Paper III). Because of the similar ages, it was considered that some of the migmatite mesosomes may represent migmatised equivalents of the greenstone belt rocks (Paper III). Tonalites and/or trondhjemites with similar ages have also been reported, e.g., from Koillismaa (Lauri et al., 2006), Suomujärvi (Evins et al., 2002) and Hisovaara, Russian Karelia (Bibikova et al., 2003). In addition, 2.84–2.81 Ga metamorphic zircon overgrowths were identified at Lylyvaara, east of the Kuhmo greenstone belt (Paper III) (Fig. 1). Crustal formation at 2.85–2.80 Ga is evidently one of the most significant events recorded in the Karelian craton, and accordingly, a geodynamic explanation needs to be sought.

The subsequent tonalitic magmatism in eastern Finland took place at 2.78 Ga and 2.75–2.74 Ga (e.g., Vaasjoki et al., 1999; Paper I) (Fig. 2). The trace element data on the 2.83–2.74 Ga tonalites suggest the presence of varying amounts of garnet in the residue (Paper II). However, one subtype of the 2.78 Ga Viitavaara tonalite (type II), does not necessarily require retention of garnet in the residue, as LREE/HREE fractionation is rather weak (Paper II). Sm-Nd isotopic analysis of the Viitavaara tonalite demonstrates initial ε_{Nd} value similar to depleted mantle (Paper I). Some of the Viitavaara samples correspond rather closely to low-Al TTD (cf. Drummond et al., 1996). Given these constraints, it is proposed that the Viitavaara tonalite magmas represented low-pressure partial melts of a mafic precursor and hence they are not necessarily analogous to adakitic magmatism (Paper II). It is noteworthy that a rhyolitic volcanic rock from Katerma, within the adjacent Kuhmo greenstone belt has yielded a U-Pb age of 2798±15 Ma (Hyppönen, 1983). This rhyolite may thus be coeval with the Viitavara tonalite. Whether the present close spatial association between these rocks is a result of post-emplacement tectonic processes is not, however, known.

The peraluminous 2.75 Ga Purnu tonalite, analogous to the Kuusamonkylä grey gneisses described by Martin (1987), shows relatively strong LREE/HREE fractionation, a feature that was interpreted as an indication of garnet in the residue (Martin, *op.cit*; Paper II). Tonalites with similar ages were reported by Vaasjoki et al. (1999) in the nearby Tipasjärvi greenstone belt and, similarly, ca. 2.75 Ga ages have been reported for tonalites in the Ilomantsi terrain (O´Brien et al., 1993; Sorjonen-Ward and Claoué-Long, 1993; Vaasjoki et al., 1993). Within error limits, the latter are apparently coeval with a meta-andesite from the adjacent Ilomantsi greenstone belt, although field relationships militate against the plutons being directly related to volcanism (Vaasjoki et al., 1993).

A distinct group of plutonic rocks, with geochemical characteristics appropriate for the sanukitoid suites, has been identified from both the Kuhmo terrain and the Nurmes belt. Moyen et al. (2001) first proposed (on the basis of the geochemical data from Querré, 1985) that the Arola granodiorite may be a member of this suite; later, more plutonic rocks with similar geochemical features were identified (Halla, 2005; Papers I, II). The sanukitoid suite in the Kuhmo terrain and Nurmes belt includes gabbros, quartz-diorites/diorites, and granodiorites having relatively high Mg/Fe and showing enrichment in LILE, together with elevated Cr and Ni. Typically, they are moderately to strongly enriched in LREE. These characteristics are often attributed to a metasomatised (enriched) mantle source component (e.g., Shirey & Hanson, 1984; Stern & Hanson, 1991; Stevenson et al., 1999; Smithies & Champion, 2000; Samsonov et al., 2004; Halla, 2005; Lobach-Zhuchenko et al., 2005; Papers I, II).

According to the present U-Pb age data, most of the plutons in Karelian domain belonging to the sanukitoid suites were emplaced within the time interval 2.74–2.70 Ga (Bibikova et al., 2005; Halla, 2005; Paper I). Some plutons could be as young as 2.68 Ga, but the interpretation of the U-Pb data of that specific pluton are not straightforward (Paper I). The general change in composition of plutonic rocks at 2.74 Ga is considered to reflect a change in tectonic processes, enhancing the contribution of an enriched mantle source component to the 2.74–2.70 Ga plutonic rocks (Papers I, II). Nevertheless, there is no clear consensus regarding the nature of the tectonic process that produced these magmas. Alternative interpretations include active subduction (e.g., Stern & Hanson, 1991), collision induced perturbances that led to the melting of a previously enriched mantle (Bibikova et al., 2005), plume-related uplift or delamination and decompression melting of metasomatised mantle (Kovalenko et al., 2005), or even emplacement in cratonic setting (Lobach-Zhuchenko et al., 2005).

Within the time-period 2.71–2.69 Ga, deposition of turbiditic greywackes, with mafic intercalations, took place in the Nurmes belt (Paper IV). These rocks were metamorphosed and deformed to gneisses and migmatites during Neoarchaean crustal reworking (Paper IV). U-Pb dating of zircon, together with Nd isotopic study of the mesosomes of the Nurmes paragneisses shows that a significant amount of 2.75–2.70 Ga detrital material is present in these rocks (Paper IV) (Fig. 2). Trace element characteristics are inconsistent with granites being a significant source component, but plutonic rocks belonging to the TTG association and sanukitoid suites may have been important source material. The associated amphibolites have compositions compatible with a depleted mantle origin and signify that basaltic material with MORB characteristics was involved (Paper IV). On the other hand, there is ample evidence for an enriched mantle source, as the Loso diorite that crosscuts the Nurmes-type paragneisses has sanukitoid characteristics (Papers II, IV). Given these constraints it appears that both enriched mantle (the source of magmas having sanukitoid affinity) and depleted mantle (amphibolites associated with paragneisses) reservoirs have contributed to crustal genesis between 2.71–2.69 Ga (Papers I, II, IV).

At 2.70–2.68 Ga, leucocratic granites and granodiorites (including leucogranites *s.s.*) were emplaced throughout eastern Finland (Paper I; Lauri et al., 2006) and also in adjacent Russian Karelia (e.g., Lobach-Zhuchenko et al., 2000). These granitoid rocks have a predominantly crustal signature, with a (probably minor) contribution from juvenile material (Paper I). Cumulative probability for concordant and nearly concordant $^{207}Pb/^{206}Pb$ age data on four leucocratic granitoid samples shows that these rocks contain inherited zircons with ages mostly <2.80 Ga (Fig. 2) (Paper I). An alternative interpretation is that Nurmes paragneiss material could be involved in the genesis of some plutons, but confirmation of this demands geochemical studies and more U-Pb age data. Apparently, the leucosome formation event in some of the migmatites of the Kuhmo terrain and in the Vieki complex was contemporaneous with these episodes (Paper III) (Fig. 2). Kontinen & Paavola (2006) suggested that the Neoarchaean orogenesis culminated in a continent-continent collision at 2.70 Ga, during which the Kuhmo–Ilomantsi and Iisalmi–Pudasjärvi crustal segments were brought together. This episode is closely temporally associated with the deposition of the Nurmes paragneiss protoliths, which likely occurred in a back arc or intra arc setting (Paper IV). If these interpretations are valid (cf. Sorjonen-Ward and Luukkonen, 2005), it appears that soon after deposition of the wackes, the Nurmes belt was deformed between the older crustal domains, with the former suture zone now buried beneath the Palaeoproterozoic Kainuu schist belt (Paper IV; see also Peltonen & Kontinen, 2004) (Fig. 1). Applying this model further would imply that the magmatism at 2.70–2.68 Ga and collision of the Kuhmo–Ilomantsi and Iisalmi–Pudasjärvi segments were more or less coeval and therefore, that these events may have been related. Additional heat for production of the leucocratic granitoid magmatism may have been derived from preceding (and probably partially coeval) sanukitoid-type magmatism (Paper I; Kovalenko et al., 2005). It thus seems that the major period of major crustal growth culminated at 2.70–2.68 Ga (Papers I, II, III, IV).

4.1.4. Metamorphism at 2.72–2.63 Ga

The age compilation resulting from the present study shows that metamorphic zircon growth took place between 2.72–2.63 Ga (Papers I, III, IV) (Fig. 2). Some of these overgrowths have ages similar to the latest granitoid magmatism, although most are between 2.68–2.63 Ga. While it is difficult to unequivocally assign precise age constraints on the duration of the migmatisation event, or events in eastern Finland, it appears likely that leucosome formation event took place between 2.72–2.67 Ga (Paper III). Thus, metamorphic zircon growth took place before and after leucosome formation and granitoid magmatism (Paper III). These metamorphic zircon ages concur with the 2.70–2.63 Ga granulite facies metamorphism in the Varpaisjärvi area (Iisalmi and Rautavaara terranes; Fig. 1) (Mänttäri & Hölttä, 2002). Moreover, based on the available age data it seems that after 2.67 Ga, there was only limited Archaean magmatism in eastern Finland. It is therefore reasonable to infer that all these crustal domains were juxtaposed by that time, forming part of a coherent craton (cf. Mänttäri & Hölttä, 2002; Sorjonen-Ward & Luukkonen, 2005; Kontinen & Paavola, 2006; Paper III) (Fig. 2).

4.2. Implications for craton correlation

Bleeker (2003) proposed that, rather than a single global-scale craton entity, there were probably at least three separate Archaean cratonic coalitions (i.e., Neoarchaean supercratons). Bleeker (*op.cit.*) considered that Karelian domain could have belonged to the same coalition as the Superior Province (Superia). One of the criteria in favour of a Superia connection is the timing of intense granitoid magmatism at ca. 2.7 Ga. In Karelian domain, it appears that 2.70–2.68 Ga leucocratic granitoid magmatism was dominant in eastern Finland and also in some parts of Russian Karelia (Slabunov et al., 2006a; Paper I and references therein). Another criterion for correlation with

Superia is the age of cratonisation between 2.68–2.63 Ga (Bleeker, 2003). Metamorphism in eastern Finland took place at ca. 2.72–2.63 Ga (Hölttä et al., 2000; Mänttäri & Hölttä, 2002; Lauri et al., 2006; Papers I, III, IV) and there also appears to have been an overall quiescent period of granitoid magmatism after 2.68 Ga. In addition, the zircon populations of the Nurmes paragneiss mesosomes and the depositional ages of the greywacke protoliths are remarkably similar to those of the main sedimentary belts in the Superior Province (Paper IV). These similarities support the concept that Karelian domain was located within the Superior supercraton (Papers I, IV). Before such correlations can be fully accepted, however, detailed comparative studies covering the whole Karelian domain and Superior Province should be carried out, underpinned by high-precision geochronology.

4.3. Future challenges

In recent years, understanding of the Archaean evolution of the Karelian craton has increased substantially. One of the reasons for this is the increased use of the SIMS technique, which has enabled more accurate identification of separate magmatic and metamorphic events (e.g., Hölttä et al., 2000; Mänttäri & Hölttä, 2002; Bibikova et al., 2005). There are still, however, many interesting and important problems that remain to be solved. With respect to the plutonic rocks under consideration in this study, Bibikova et al. (2005) demonstrated that the sanukitoids in Russian Karelia appear to form two separate arrays; the 2.71 Ga western array and the 2.74 Ga eastern array (Bibikova et al., *op.cit.*). In the Finnish Archaean, at least two plutons belonging to the sanukitoid suites are situated along the western margin of the Tipasjärvi-Kuhmo-Suomussalmi greenstone belt, namely the 2.74 Ga Arola granodiorite (Hyppönen, 1983; Papers I, II) and the 2.72 Ga Kaapinsalmi tonalite (Heilimo et al., 2007). This leads to several questions, such as whether or not it is purely coincidence that these two plutons, with sanukitoid suite characteristics, were emplaced in the contact zones between the greenstone belt and surrounding bedrock over a 20 Ma time interval? Perhaps it would be reasonable to perform combined SIMS U-Pb and detailed digital imagining (BSE and/or CL) studies on zircons from these plutons, even though conventional U-Pb analyses do not clearly indicate inheritance either of the samples. Bibikova et al. (2005) demonstrated that the zircons in the most felsic varieties of sanukitoids can have relict cores and this possibility would also be worth studying for the Arola and Kaapinsalmi plutons. Such investigations would also help better constrain the age relationships between the sanukitoid arrays in Russian Karelia and plutons in eastern Finland (cf. Heilimo et al., 2007). This would help resolve whether the plutons belonging to the sanukitoid suites in Karelia are related to two main separate tectonothermal events, rather than a continuous process, and how these magmatic rocks relate to one another.

Some, although probably only a minor proportion, of the ca. 2.70–2.68 Ga leucogranitoid magmatism is apparently not related to melting of pre-existing crust (Paper I). It would be interesting to establish the source for these rocks and the processes by which they formed, and whether they might be more voluminous than currently thought. Such a study would demand detailed geochemical characterisation combined with Sm-Nd and/or Lu-Hf isotope studies.

As increasing numbers of U-Pb SIMS age determinations on volcanic rocks are becoming available, classification and perhaps identification of new volcanic episodes are possible. Because at least some of the main plutonic episodes are known, this would enable more robust comparison between these events and processes. Combined geochemical characterisation and U-Pb geochronology on selected rock units would help constrain the relationships between the volcanic rocks within the greenstone belt and plutonic rocks surrounding them. This in turn would be crucial in understanding the relationship between the greenstone belts and surrounding bedrock.

5. CONCLUSIONS

The following principal conclusions, based on the published original papers (Papers I–IV), can be drawn:

1. U-Pb data on the migmatites indicate the existence of a sialic crust by 2.94 Ga, to the east of the Kuhmo greenstone belt, whereas the other dated mesosomes from the Kuhmo terrain and Vieki complex have protolith ages of 2.84–2.79 Ga (Paper III).
2. U-Pb age determinations and whole-rock geochemical data on non-migmatised plutonic rocks from the Kuhmo terrain and Nurmes belt (*sensu* Paper IV) confirm the concept of secular geochemical evolution. Based on the available age data, the main plutonic episodes are as follows: emplacement of tonalitic rocks at 2.83–2.75 Ga, main emplacement stage of plutons of sanukitoid affinity at 2.74–2.70 Ga, and emplacement of 2.70–2.68 Ga leucocratic granitoid rocks, which have predominantly crustal source characteristics (Papers I, II).
3. Geochemical characteristics of the tonalities are consistent with varying amounts of residual garnet in the source region (Paper II). Sanukitoid suites are considered indicative of a contribution from an enriched mantle source (Papers I, II).
4. The precursors of the Nurmes paragneisses and associated mafic intercalations were deposited between 2.71 Ga and 2.69 Ga. U-Pb studies on the detrital zircons reveal that ca. 2.75–2.70 Ga source material was predominant. Nd isotopic data for the intercalated amphibolites imply depleted mantle sources (Paper IV).
5. U-Pb data on leucosomes seem to indicate prolonged partial melting, over the time interval 2.72–2.67 Ga. This interpretation is, however, hampered by the scarcity of concordant U-Pb data and by zircon inheritance (Paper III).
6. U-Pb data on granitoid rocks and the Nurmes paragneisses indicate that metamorphism in the Kuhmo terrain and Nurmes belt took place at 2.72–2.70 Ga and 2.67–2.63 Ga (Papers I, III, IV).
7. The late stages of Archaean crustal evolution in eastern Finland show similarities with the Superior Province in terms of timing of late granite pulses, metamorphism, sediment deposition and detrital sediment populations. These features are considered to support the concept that the Karelian domain and Superior Provinces had close mutual proximity within the Neoarchaean craton coalition (Papers I, III, IV).

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Appendix I.

KKJ-4 and KKJ-3 (those marked with asterisk) coordinates for the U-Pb samples presented in Papers I, III, and IV.

Sample	**Northing**	**Easting**	**Data in Paper**
A1702	7151089	4462354	I
A1703	7104604	4449285	I
A1704	7153553	4494832	I
A1705	7120736	4445867	I
A1706	7146249	4435468	I
A1707	7151060	4450658	I
A1719	7117865	4468541	I
A79 & A80	7228900	4450450	III
A404 & A405	7150860	4483360	III
A1815 & A1816	7148757	4446587	III
A1765 & A1766	7027972	4494609	III
1-KUH-88	7108800	4475100	IV
1-NUR-88	7068880	4468540	IV
A1081*	7161640	3568400	IV
A331*	7135100	3563200	IV

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This thesis comprises a synopsis and four papers concerning U-Pb geochronology and geochemical evolution of Archaean rocks from the Kuhmo terrain and the Nurmes belt, eastern Finland. The U-Pb results on zircons from migmatites, non-migmatised plutonic rocks, and paragneisses show that the Archaean evolution of the crust extended over 300 Ma, culminating in reworking of the crust and metamorphism in the Neoarchaean.

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