Late Svecofennian leucogranites of southern Finland

Chronicles of an orogenic collapse

MATTI KURHILA

ACADEMIC DISSERTATION
To be presented, with the permission of the Faculty of Sciences of the University of Helsinki, for public examination in Small Festival Hall, University main building, on 25 March 2011, at 12 noon.

DEPARTMENT OF GEOSCIENCES AND GEOGRAPHY A8 / HELSINKI 2011

Cover photo: Layered leucogranite at Veikkola

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ISSN 1798-7911
ISBN 978-952-10-6311-4 (pbk.)
ISBN 978-952-10-6312-1 (PDF)
http://ethesis.helsinki.fi

Helsinki University Print
Helsinki 2011

Kurhila M., 2011. *Late Svecofennian leucogranites of southern Finland – Chronicles of an orogenic collapse*. Helsinki University Press. Helsinki. 23 pages and 5 figures.

Abstract

Leucogranite magmatism occurred in southern Finland during the later stages of the Paleoproterozoic Svecofennian orogeny. The leucogranites are considered to have formed from pre-existing crustal rocks that have undergone anatexis in the extensional stage of the orogeny, following continental collision and resultant crustal thickening.

The leucogranites have been studied in the field using petrographic and mineralogical methods, elemental and isotope geochemistry on whole rocks and minerals, and U-Pb geochronology. On outcrop scale, these granites typically form heterogeneous, layered, sheet-like bodies that migmatize their country rocks. All of the leucogranites are peraluminous and rich in SiO_2, but otherwise display significant geochemical variation. Their Nd isotope composition ranges from fairly juvenile to very unradiogenic, and the Hf isotope composition of their zircon shows a varying degree of mixing in the source, the zircon populations becoming more heterogeneous and generally less radiogenic towards the east.

The leucogranites have been dated using U-Pb isotopic analyses, utilizing thermal ionization mass spectrometry, secondary ion mass spectrometry, and laser ablation multicollector ICP mass spectrometry on zircon and monazite. The results show that the granites were emplaced between 1.85 Ga and 1.79 Ga, which is a considerably longer period than has traditionally been perceived for these rocks. The rocks tend to become younger towards the east. Single crystal data also display a wide array of inherited zircons, especially in the eastern part of the leucogranite belt. The most common inherited age groups are ~2.8–2.5 Ga, ~2.1–2.1 Ga, and ~1.9 Ga. Magmatic zircon and monazite usually record similar ages for any one sample.

Thermobarometric calculations indicate that the leucogranites in the Veikkola area of south-central Finland were formed from relatively low-temperature melts, and emplaced at 17-25 km depth, i.e. at mid-crustal level. It is likely that these conditions apply to the Svecofennian leucogranites in general. Large differences in the Hf and Nd isotope compositions, emplacement ages, and distributions of inherited zircon ages show that these granites were formed from different types of source rocks, which probably included both sedimentary and igneous rocks.

Acknowledgements

I wish to express my gratitude to Prof. Tapani Rämö, who was the principal supervisor of this work, and had enough faith in me to hire me in the research project without our knowing one another in advance. Also, Dr Mikko Nironen acted as co-supervisor and constantly kept my spirit up along the way. My other co-authors Dr Irmeli Mänttäri and Prof. Tom Andersen and the late Docent Matti Vaasjoki helped me in numerous ways for which they are acknowledged. As for the funding of my work, I would like to thank the following institutions and people: the Academy of Finland (project 54088), the Finnish Graduate School in Geology and its head Prof. Veli-Pekka Salonen, the Finnish-Norwegian Cultural Foundation, and the Rector of the University of Helsinki.

I am indebted to the reviewers of this work, Profs Marlina Elburg and Alvar Soesoo, whose suggestions greatly improved this study. This work could not have been carried out without the staff of the laboratories for isotope geology and mineralogy at the Geological Survey of Finland (GTK), of whom I would especially like to thank Docent Hannu Huhma, Matti Karhunen, Tuula Hokkanen, Marita Niemelä, Arto Pulkkinen, Lasse Heikkinen, Leena Järvinen, Mirja Saarinen, Dr Jukka Marmo, Dr Marja Lehtonen, Lassi Pakkanen and Bo Johanson. Also, the staff at the Nordsim laboratory in Stockholm deserves my deepest gratitude, particularly Dr Martin Whitehouse, Dr Lev Ilyinsky, Kerstin Lindén, Bodil Kajrup, Dr Chris Kirkland and Dr Yaron Be'eri. Prof. Tom Andersen and Siri Simonsen at Oslo University contributed significantly to the laser ablation analyses, for which they are duly thanked.

My colleagues, both past and present, at the University of Helsinki whom I would like to thank include Pasi Heikkilä, Dr Sari Lukkari, Dr Paula Kosunen, Dr Laura Lauri, Akseli Torppa, Dr Brent Elliott, Outi Hyttinen, Esa Heilimo, Dr Mika Räisänen, Riku Raitala, Tero Taipale, Kirsi Larjamo, Dr Tero Niiranen, Dr Laura Arppe, Aku Heinonen, Frauke Kubischta, Habte Asnakew, Mikko Haaramo, Dr Seija Kultti, Dr Anu Kaakinen, Jussi Heinonen, Ilona Romu and many others. Kirsi-Marja Äyräs, Helena Korkka, Dr Mia Kotilainen, Kristina Löyttyjärvi and Tuija Vaahtojärvi have provided unfailing support in office and laboratories.

At the GTK, I have greatly benefitted from discussions with Dr Asko Käpyaho, Tuija Elminen, Dr Pietari Skyttä, Docent Pentti Hölttä, Prof. Raimo Lahtinen, Dr Kari Kinnunen and Markku Lehtinen, among others. The geology team at the Finnish Museum of Natural History, in particular Dr Jaana Halla and Docent Arto Luttinen, deserve special thanks for their friendship and continued support, as do my geologist friends Anja Arkonsuo, Jyrki Bergström and Jouni Rautiainen.

A lot of non-geologist friends helped me to keep things in perspective, for which I would like to thank them. One of them, David Hackston, kindly helped me to improve the English language of this work. Finally, I want to thank my parents Pekka and Pallas Kurhila for everything they have done to ease my path. I also wish to thank my siblings Prof. Salla Kurhila and Dr Jaakko Kurhila, whose examples encouraged me to pursue an academic career.

Contents

List of original publications

This thesis is based on the following publications:

I Kurhila, M., Vaasjoki, M., Mänttäri, I., Rämö, T., Nironen, M., 2005. U–Pb ages and Nd isotope characteristics of the lateorogenic, migmatizing microcline granites in southwestern Finland. Bulletin of the Geological Society of Finland 77, 105–128.

II Kurhila, M., Mänttäri, I., Vaasjoki, M., Rämö, O.T., Nironen, M. U-Pb geochronology of the late Svecofennian Leucogranites of Southern Finland. Manuscript submitted to Precambrian Research on November 29, 2010.

III Nironen, M., Kurhila, M., 2008. The Veikkola granite area in southern Finland: emplacement of a 1.83–1.82 Ga plutonic sequence in an extensional regime. Bulletin of the Geological Society of Finland 80, 39–68.

IV Kurhila, M., Andersen, T., Rämö, O.T., 2010. Diverse sources of crustal granitic magma: Lu-Hf isotope data on zircon in three Paleoproterozoic leucogranites of southern Finland. Lithos 115, 263–271.

The publications are henceforth referred to in the text by their roman numerals.

The research project was initiated by O.T. Rämö and M. Nironen and funded by the Academyof Finland (Project 54088). O.T. Rämö and M. Nironen planned the outline of the study, which was later modified by M. Kurhila., I. Mänttäri and M. Vaasjoki.

M. Kurhila's (M.K.) contribution to the papers was as follows:

I: M.K. did the field work and sampling together with M. Vaasjoki, O.T. Rämö and M. Nironen. M.K. completed all sample preparations, except for crushing the U-Pb samples. M.K. did the geochemical isotope purification for all U-Pb and Sm-Nd ID-TIMS analyses. He also hand-picked the zircons for SIMS analyses and performed these analyses jointly with M. Vaasjoki. M.K. assisted O.T. Rämö in the Sm-Nd isotope analyses. M.K. interpreted the U-Pb data together with I.Mänttäri and M.Vaasjoki, and the Nd data with O.T. Rämö. M.K. assumed main responsibility for writing the manuscript, with modifications added by the co-authors.

II: M.K. did the field work and sampling together with M. Vaasjoki, O.T. Rämö and M. Nironen. M.K. did all the sample preparation, hand-picking, geochemical purification and ID-TIMS analytical work. M.K. did the SIMS analyses jointly with M. Vaasjoki. M.K. interpreted the data with I. Mänttäri. M.K. assumed the main responsibility for writing the manuscript, with commentary from the other authors.

III: M.K. did the field work and sampling together with M. Nironen. M.K.'s main contribution to the analytical part consisted in mineral chemistry and in providing thermobarometrical calculations. M.K. assumed the main responsibility for writing the mineral chemistry section of the manuscript, and the discussion and conclusions were written jointly with M. Nironen, who finalized the work.

IV: Field work and sample preparations for the Laser ablation ICP-MS analyses were done previously by M.K. for papers I and II. The analytical work was done by M.K. jointly with T. Andersen. M.K. assisted O.T. Rämö in sample preparation and geochemical separation for the Sm-Nd isotopic work. M.K. wrote the manuscript, which was then edited by the co-authors.

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1 Introduction

In collisional orogenies, different types of granitoid magmatism usually take place in successive stages of collision, crustal shortening and thickening, orogenic collapse, and subsequent stabilization of the crust. In the Paleoproterozoic Svecofennian domain of southern and central Finland, four groups of granitoid rocks have been identified (Sederholm, 1926; Eskola, 1932). Simonen (1971) labelled these groups synorogenic, late-orogenic, postorogenic, and anorogenic, from oldest to youngest. The synorogenic granitoids range from tonalities and granodiorites to pure granites that usually form distinct intrusions. They are metaluminous to peraluminous and commonly show arc-type geochemical affinities (e.g. Nironen, 2005). The late-orogenic granites are mostly heterogeneous, flat-lying sheets that commonly grade into migmatites and are exclusively peraluminous, high-silica leucogranites with crustal isotopic signatures (ibid.). Post-orogenic granites are typically dikes or sharply crosscutting minor plutons, consisting of shoshonitic, high-temperature A-type granitoids (Eklund et al., 1998). This work deals with the late-orogenic granites of southern Finland that have been ascribed to the extensional, i.e. the collapse stage of the Svecofennian orogeny (Korja & Heikkinen, 2005; Skyttä & Mänttäri, 2008).

In a complex cratonic system such as the Svecofennian orogen of southern Finland (Fig. 1), which consists of several individual terranes (Korsman et al., 1997), the interrelationships of plutonic rocks and their respective tectonic settings are often obscure. In recent years, the Svecofennian orogeny has been subdivided into several, relatively short tectonic events that affected various parts of the present Fennoscandian shield at different times (cf. Lahtinen et al., 2005, 2008; Korja et al., 2006). New models feature several microcontinents that were accreted on to the Archean Karelian craton from ~1.95 Ga onwards. In the first stages, large amounts of new crustal material were differentiated from a juvenile (long-term LREE-depleted) mantle source (Huhma, 1986). Subsequently, according to Lahtinen et al. (2005), a microcontinent (“Keitele”) accreted to the Primitive arc complex (cf. Korsman et al., 1997) from the west and, finally, the Bergslagen microcontinent collided with the amalgamated crustal blocks from the south. The present study focuses on felsic intrusive rocks formed in the aftermath of the latter collision in southern Finland.

Compared to younger (mid-Proterozoic) rapakivi granites (Rämö & Haapala, 1995 and references therein) and the volumetrically minor postorogenic (~1.8 Ga) granites (e.g. Eklund et al., 1998; Konopelko & Eklund, 2003; Andersson et al., 2006) of the domain, the late Svecofennian leucogranites have been relatively little studied. Yet the late-orogenic granites cover a considerable geographic area. This is also true in northern Finland, where the late-orogenic mostly leucogranitic Central Lapland granitoid complex covers a vast area (Airo & Ahtonen, 1999; Väänänen, 2004; Nironen, 2005), but still remains among the least studied lithologic units of the Fennoscandian shield. Although these leucogranites in both northern and southern Finland constitute a significant proportion of the exposed crystalline bedrock, volumetrically they can be considered less substantial, because the intrusions are generally found as flat-lying sheets (Ehlers et al., 1993; Selonen et al., 1996; Nironen et al., 2006; Patison et al., 2006; Stålfors & Ehlers, 2006).

The Arc complex of southern Finland (cf. Korsman et al., 1997) was accreted on to the previously assembled collage of Palaeoproterozoic and Archaean blocks at about 1.87 Ga (e.g. Lahtinen et al., 2005; Korsman et al., 1999; Nironen, 1997; see also Huhma, 1986). The crust was thickened and remains anomalously thick today (up to 60 km; Korsman et al., 1999). The leucogranite magmatism occurred after the collision that led to the orogenic collapse stage. Whether the exact tectonic regime involved primarily transpressional or extensional forces remains a subject of ongoing debate (Stålfors & Ehlers, 2006; Korja & Heikkinen, 2005; Lindh, 2005).

The primary aim of this work is to attain a comprehensive handle on the chronology of the leucogranitic magmatism of southern Finland utilizing U-Pb isotopic methods on zircon and monazite. In addition, elemental whole-rock geochemistry, mineral chemistry, and radiogenic isotope geochemistry (the Sm-Nd and Lu-Hf systems) are used to gain a better understanding of the origin of these granites.

2 Review of the original papers

2.1 Paper I

Paper I concentrates on the radiogenic isotopes of the late-orogenic granites of southwestern Finland. The main scope of the paper is U-Pb geochronology, and the dated samples are also analyzed for Sm-Nd isotope composition. Four late Svecofennian granite samples have been dated using secondary ion mass spectrometry (SIMS) and five more using conventional thermal ionization mass spectrometry (TIMS). Analysis revealed that the leucogranites of southwestern Finland were emplaced between 1.85 Ga and 1.82 Ga. The zircon in these granites is very uranium-rich and is therefore often metamict, resulting in very discordant U-Pb isotopic analysis results. The apparent inherited cores found using the scanning electron microscope often display an age similar to that of the rims, thus promoting the idea of a resetting of the U-Pb isotopic systematics, something which probably occurred during the partial melting of the source rocks of these granites.

The unequivocal age of over 1.85 Ga for the eastern part of the Veikkola granite in south-central Finland is a novel result and quite a surprising discovery, given that these granites have been traditionally considered to be between 1.84 and 1.82 Ga old (Korsman et al., 1997; Johannes et al., 2003). Moreover, one noticeable feature in most of these granites is the contemporaneity of their monazite and zircon. Thus, monazite can be used as a proxy of the emplacement age for these leucogranites in the event of zircon data being either absent or of poor quality. A prominent exception here is the Oripää granite in western Finland; this granite includes two zircon populations, ~1.87 and ~1.85 Ga, whereas monazite has a concordia age of ~1.80 Ga. The discrepancy in the ages and obscurity of the zircon morphology and age results prevents any unambiguous determination of the emplacement age for this particular granite.

Whole-rock Nd isotope composition was determined for the late-orogenic granites and one synorogenic granodiorite adjacent to the Oripää granite that has a conspicuously

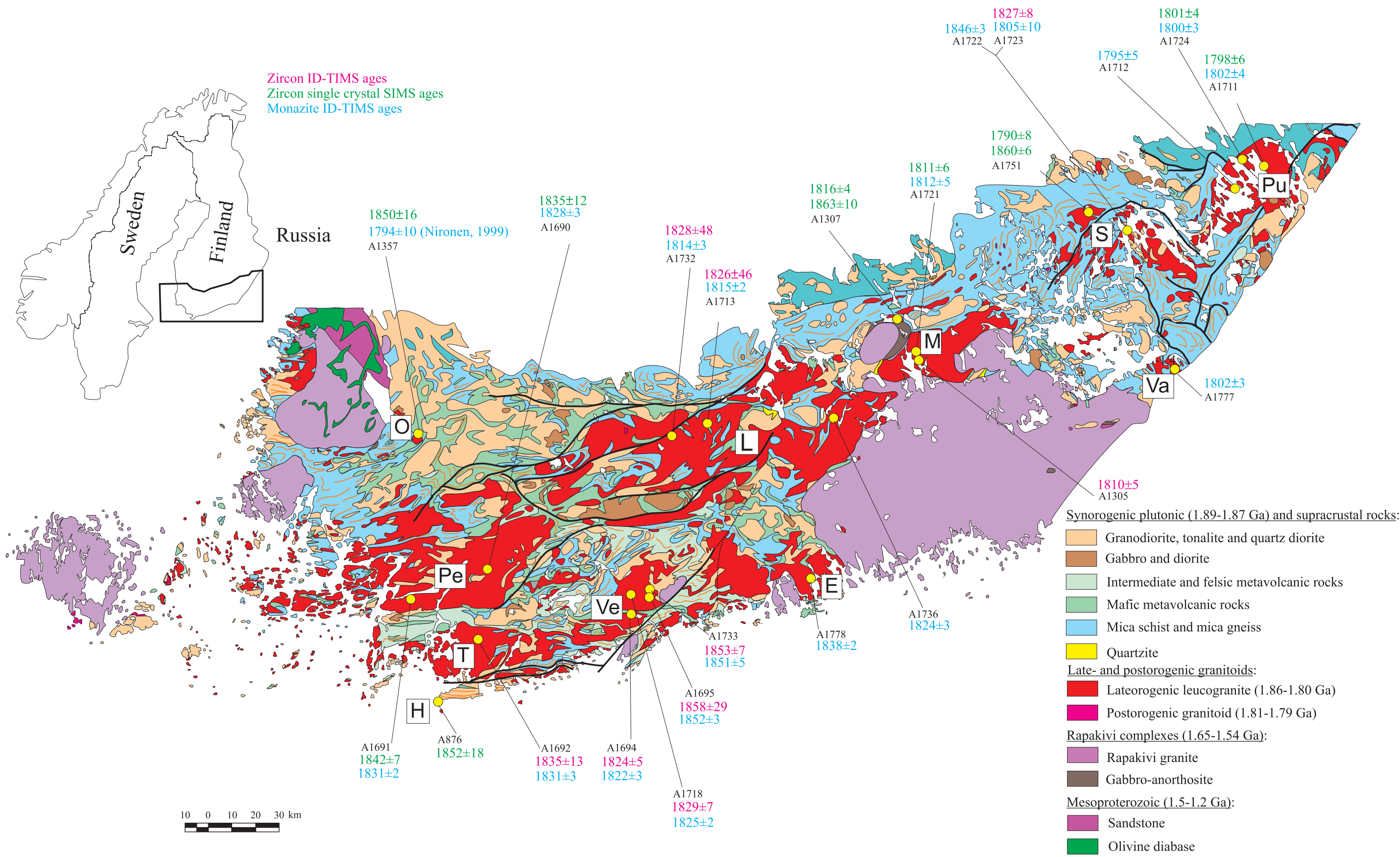

Figure 1. The bedrock of southern Finland according to Korsman et al. (1997). The inset shows the location of the area within Finland. Locations of the U-Pb isotopic age samples are marked and the relevant age results are indicated. Key to leucogranite units: E = Epoo, H = Hanko, L = Lahti, M =Mäntyharju, O = Oripää, Pe = Perniö, Pu = Puruvesi, S = Sulkava, T = Tenhola, Va = Valkamo, Ve= Veikkola. Data from Papers I and II.

radiogenic Nd isotope composition (initial ε_{Nd} value of +2.5). There is a trend towards more radiogenic compositions moving from the south (ε_{Nd} -1.1) to the north (ε_{Nd} +2.5). The number of inherited U-Pb age results in zircon is generally quite small and does not correlate with the Nd isotope composition of the respective samples.

2.2 Paper II

Paper II deals with the U-Pb zircon and monazite geochronology of the late-orogenic granites in the central and eastern parts of the granite zone. In light of the U-Pb isotopic data from Paper I, geochronological aspects concerning the whole of southern Finland (i.e. the Arc complex of southern Finland) are discussed. Contrary to the granites in southwestern Finland, those in the eastern part of the zone commonly have substantial levels of inherited zircon. The inherited ages range from Archean to Paleoproterozoic, and also encompass the youngest synorogenic stages of the Svecofennian orogeny, i.e. 1.88-1.87 Ga.

SIMS and TIMS U-Pb isotopic data on fifteen (5 SIMS, 10 TIMS) samples show that the granites are progressively younger towards the east. The amount and age distribution of inherited zircon vary considerably, as do the emplacement ages themselves. The ages of the leucogranites in this study fall between ~1.84 and ~1.79 Ga, i.e., it widens the traditionally perceived age range of 1.84–1.82 Ga (cf. Korsman et al., 1997) even further. A special case among the late Svecofennian leucogranites is the Puruvesi granite area right next to the Russian border at the eastern end of the zone (Fig. 1). This area consists of two distinct granite types forming a concentric batholith; the central type is grey, relatively biotite-rich, porphyritic, homogeneous, and has garnet only as an accessory mineral. The marginal phase is very leucocratic, has abundant gneissose inclusions, is garnet-rich, and has substantial grain-size variations. Their zircon and monazite ages are, however, identical. Both have similar single zircon age patterns where, in addition to the 1.80 Ga main population, most zircon core domains are 2.0 Ga and Archean.

The youngest of all the late-orogenic granites studied here, the Keittomäki granite in Sulkava in eastern Finland (Fig. 1), was emplaced as late as 1.79 Ga. It is thus ~20 Ma younger than the A-type Pirilä granodiorite some 30 km to the north (Vaasjoki & Sakko, 1988), which is thought to represent a later, postorogenic magmatic stage and a deeper, enriched lithospheric mantle source (Eklund et al., 1998). Hence, the different orogenic stages overlap considerably in time across the belt of the late Svecofennian leucogranites of southern Finland.

In many of the granites studied, inherited zircon ages correspond to those of typical Svecofennian detrital zircons, suggesting that the source rocks of these granites were sedimentary. However, in some cases, such as the Keittomäki granite, inheritance patterns are quite different, with only one or a few prominent inherited age groups, thus suggesting that these zircons are of igneous origin. Despite overall petrographic similarities, there is thus positive evidence to support the claim that the source rocks of the leucogranites have included both sedimentary and igneous units.

2.3 Paper III

Paper III deals with a relatively restricted leucogranite unit in the Veikkola area located at the south-central part of the Arc complex of southern Finland (Fig. 1). Four separate stages of leucogranitic magmatism are identified, and the paper also provides an extensive descrption of a more mafic, enderbitic rock with intrusive contacts with the granites. The four granites are, in descending order of the emplacement ages: the layered, medium to coarse-grained Nuuksio granite; the petrographically similar Haapajärvi granite; the porphyritic Evitskog granite; and the even-grained Kylmälä granite. All four granites have similar mineral compositions with biotite and garnet as the only mafic silicates. Each of them also contains leucocratic veins or layers. The age range between these adjacent granite bodies is ~25-30 Ma – astonishingly wide. These granites were studied for their structural features, geochemistry, mineral chemistry, and thermobarometry. In addition the surrounding migmatite leucosomes were sampled in order to examine whether they could represent the magmatic precursors of the granites or the felsic veins that cut the leucogranites. The compositional differences found in garnet and the fact that the granites record higher pressures show that the migmatites are not likely to be the immediate source of the granites. The granites have rather varying major and minor element contents relative to their limited SiO_2 range, but their respective REE patterns are fairly uniform. Compared with experimental data from various source rock candidates, it is obvious that both sedimentary (e.g. metagreywacke) and metaigneous (biotite gneiss) sources could have produced matching melts via a process of anatexis.

The thermometric results of the mineral chemical analyses from the granites are somewhat suspect, as the petrographic study revealed some signs of retrograde reactions. In addition, calculated zircon saturation temperatures do not agree very well with reactions. However, all the acquired temperature results are low (less than 800 °C), which is plausible, given the leucocratic composition of the rocks. Barometric study indicates crystallization at ~17–25 km, with the oldest granite having the deepest origin. The layering present in the granites was probably formed as a result of deformation post-dating the emplacement. On the basis of structural evidence, the pyroxene-bearing enderbite is considered coeval with the youngest granite phases and marks the only reported incidence of mafic magmatism related to the leucogranites. However, the enderbite cannot have formed from the same source rocks as the granites and its origin remains unclear.

2.4 Paper IV

For Paper IV, the U-Pb and Lu-Hf isotope composition of zircons were analyzed using laser ablation MC-ICP-MS from three leucogranite intrusions: one from southwestern Finland (Perniö) and two from southeastern Finland (Jaani granite from the Mäntyharju area and the central phase of the Puruvesi granite, Fig. 1). Whole-rock Sm-Nd isotopic analyses were also performed on the same rocks. Results indicate that these three granites are markedly different in terms of their age, Hf isotope composition of zircon, and their whole-rock Nd isotopes. While the two former granites have close to chondritic εNd values, the latter is strongly unradiogenic, with an initial ε_{Nd} value of -6.4 (see also Huhma, 1986), indicating a strong Archean contribution to the source. This difference is also reflected in the Hf isotopic composition of the zircon: in the whole, the Puruvesi sample is much less radiogenic compared with the other two. The Kistolanperä sample, representing the Perniö granite, has quite a homogeneous zircon Hf composition and age, but the Puruvesi and Jaani samples have abundant inherited zircon, where typically the inherited grains have significantly more unradiogenic Hf. The age results have large errors compared to SIMS analyses of the same granites (Papers I and II), but nevertheless display similar patterns. Because of the uniform nature of zircon in the Perniö granite, it has been suggested that this rock represents partial melts from primarily igneous rocks. For the other two granites, the large spread of Hf isotopic compositions, inherited ages and a strongly unradiogenic Nd isotope composition (the latter found only in the Puruvesi granite) are indicative of a metasedimentary source with a major Archean component. When the distribution of inherited ages is compared with available detrital zircon ages within the Svecofennian domain, the inheritance patterns coincide quite well, further supporting a sedimentary source for these granites.

3 Composition of the late-orogenic leucogranites of southern Finland

3.1 Petrography and typology

Leucogranites are commonly regarded as partial melts of pre-existing crust (e.g. Thompson, 1996; Patiño Douce, 1999), and their mineral and geochemical composition reflects this origin. The late Svecofennian leucogranites of southern Finland typically migmatize their country-rocks, and it is for this reason that the margins of the granites cannot be precisely defined. They may also form homogeneous plutons or sheet-like intrusions in certain places. In outcrop scale, the leucogranites tend to be quite heterogeneous in composition. They are leucocratic, medium to coarse-grained and typically layered, i.e. with coarser, lighter bands alternating with finer and darker ones. The scale of the layering is typically of the order of decimeters. A preferred orientation may or may not be present; both porphyritic and equigranular textures are also common.

The mineralogical composition of the late Svecofennian leucogranites of southern Finland is characteristic of peraluminous granites. Microcline is the dominant feldspar, with quartz and zoned plagioclase being the next most abundant phases. These granites mostly contain two micas, while garnet is commonly present as a main mineral. Cordierite and sillimanite, however, are rarely found. Apatite, monazite, and zircon are the most abundant accessory minerals. Rutile, magnetite, anatase, and uraninite are rare.

Whole-rock geochemistry indicates that these granites are not invariably S-type sensu stricto (Paper III; Rämö et al., 2005). Although they are peraluminous, their A/CNK is not always above 1.1. Moreover, they frequently contain more Na_2O than K_2O. However, their mineral composition is consistent with S-type characteristics with prominent garnet, muscovite, cordierite, and monazite as accessory phases. The late-orogenic granites are restricted to rather high SiO_2 percentage (≥ 70 wt. %) and have biotite and garnet as the only mafic silicates. Because the discriminating factors are arbitrary to a certain extent, while the term itself implies genetic connotations, the concept of S-type granite is dismissed from the Svecofennian leucogranites in this work.

3.2 Radiogenic isotope composition

From the Nd isotope data available, it is evident that, as expected, the late-orogenic granites are not directly mantle-derived, but rather their source rocks were themselves recycled older crustal material. On the whole, the initial ε_{Nd} values of these granites are close to zero. The Nd isotopic compositions of the granites in the western part of the belt tend to get slightly more radiogenic from south to north (Fig. 2). The +2.5 initial value of the Oripää granite in western Finland is the highest among the leucogranites (Paper I). The Puruvesi granite, which is located near the contact to the Archean craton in eastern Finland, displays strongly negative initial ε_{Nd} values (Paper IV; Huhma, 1986), reflecting material input from Archean source rocks. Depleted mantle model ages (DePaolo, 1981) are in the range of 1.95–2.2 Ga for the leucogranites, except for the Puruvesi batholith, for which they cluster at about ~2.5 Ga.

Hf isotopes of zircon comply with the whole-rock Nd data. Overall, the Puruvesi granite has the least radiogenic zircon compared with those of the Jaani and Perniö granites (Paper IV). The median values of the ε_{Hf} values of zircon in the Perniö and the Jaani granites are similar, but the Jaani granite has a few distinctly unradiogenic zircons, whereas the Perniö granite is rather homogeneous. The Puruvesi granite also has a group of very unradiogenic zircons, most of which display inherited ages (Fig. 3). It should be noted in this context that the apparent core domains, coeval with the rims in some zircons of the Perniö granite described in Paper I, are not inherited in terms of their Hf isotope composition, which implies homogeneous Hf isotope composition for the entire zircon population in this granite.

4 Age of the late Svecofennian magmatism

In Fig. 1, the U-Pb ages obtained in this study are marked on the map of southern Finland, while Fig. 4 shows these ages projected on to an east-west striking line. It is evident that the ages are generally younger in the east. It is perhaps due to the fact that most previous studies into the ages of these rocks concentrated on the western half of the belt (Suominen, 1991; Huhma, 1986; Hopgood et al., 1983) that the notion of 1.84-1.82 Ga age for these granites has emerged. In the present study, however, the age range is established to be at least ~60 Ma, from ≥1850 Ma to ~1790 Ma, during which magmatism has been virtually continuous (Fig. 4). This seems rather a long time for the prevalence of leucogranitic magmatism, compared to many other orogens of Archean (e.g. Käpyaho et al., 2006; Moyen et al., 2003), Paleozoic (e.g. Schaltegger & Corfu, 1992; Valle Aguado et al., 2005), and Cenozoic (e.g. Yang et al., 2009; Keay et al., 2001) age. Moreover,

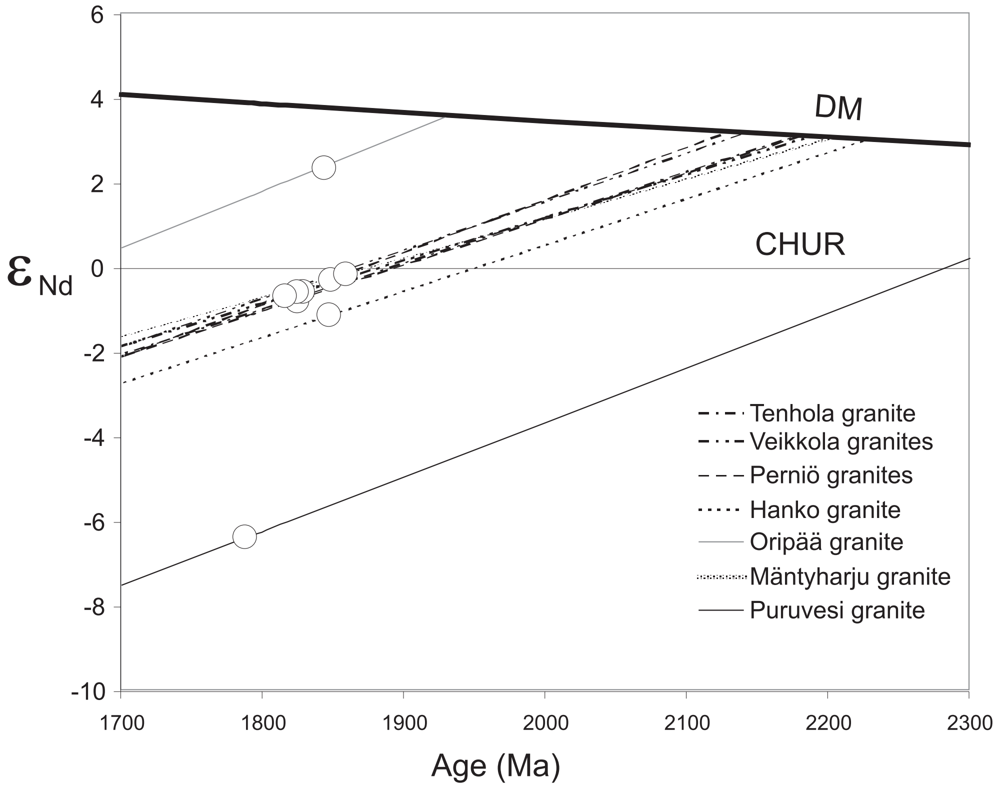

Figure 2. Whole-rock Nd isotope composition of the late-orogenic leucogranites of southern Finland shown in an ε_{Nd} vs. age diagram. DM = depleted mantle (DePaolo, 1981), CHUR = Chondritic Uniform Reservoir (DePaolo & Wasserburg, 1976). Data from Papers I and IV.

the absolute ages of these granites overlap with both the earlier synorogenic stage and subsequent postorogenic stage (Paper II). It is therefore evident – and quite striking – that different tectonic regimes prevailed simultaneously in different parts of the Svecofennian domain.

A prominent feature of the late Svecofennian leucogranites is the presence of coeval monazite and zircon. This is not uncommon in leucogranites elsewhere (cf. Rubatto et al., 2006; Dias et al., 1998). Generally, monazite is less resistant to high-temperature geologic processes than zircon – in high-grade metamorphism it is easily recrystallized (Crowley & Ghent, 1999; Rubatto et al., 2001). Because of this tendency, monazite seldom retains inherited cores with rims that formed later. Therefore, monazite U-Pb age results are frequently concordant, while multi-crystal zircon fractions give discordant and heterogeneous results using the ID-TIMS method (Papers I and II). Accordingly, when no contrasting zircon data existed, monazite ages were used to constrain the emplacement ages of the leucogranites.

Using SIMS, inherited zircon ages in the leucogranites were detected. The granites with most inherited zircon are the Puruvesi granite and the intrusions of the Mäntyharju granite area, namely the Kaisavuori and Jaani granites. The inheritance patterns of these granites differ somewhat: in the Mäntyharju

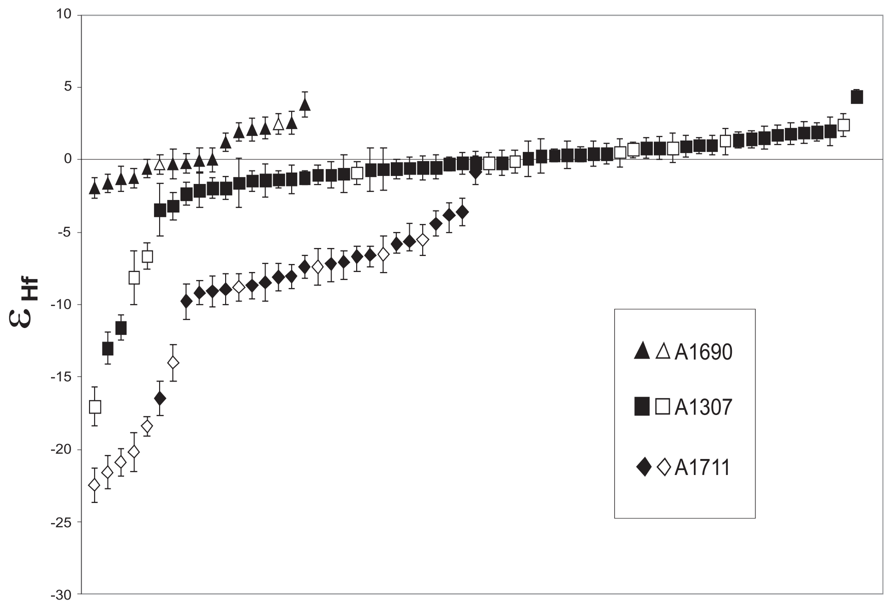

Figure 3. Individual zircon Hf isotope compositions (initial ε_{Hf} values) of the Perniö (sample A1690), Mäntyharju (sample A1307) and Puruvesi (central phase; sample A1711) leucogranites. Open symbols denote inherited zircons, but all values are calculated to the emplacement ages. Vertical bars are 2 sigma errors. Data from paper IV.

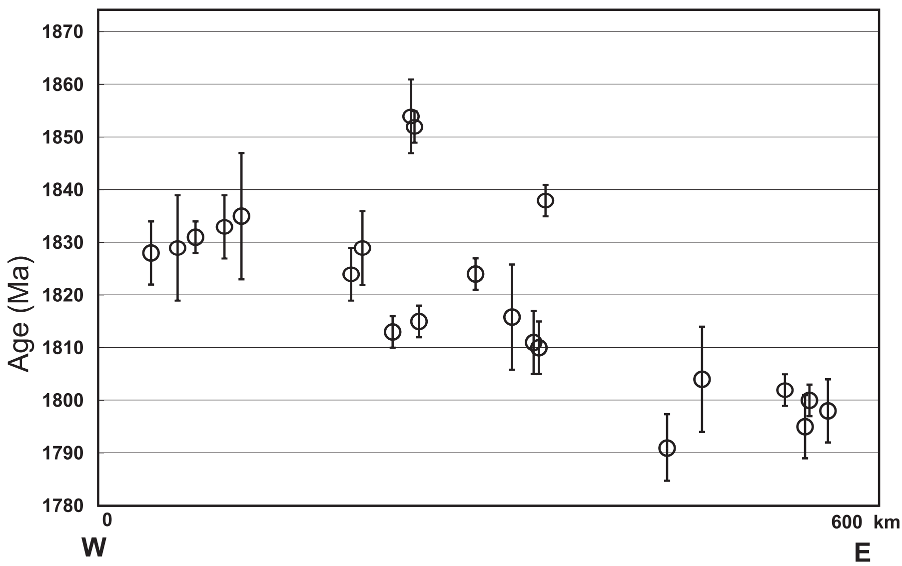

Figure 4. U-Pb ages of leucogranites from the sites indicated in Fig. 1, plotted along a W-E axis across the granite belt. Vertical bars correspond to 2-sigma errors.

area the most prominent inherited age groups are 2.8–2.5 Ga, 2.0–2.1 Ga, ~1.90 Ga, and 1.86 Ga, the two youngest of which represent the Svecofennian orogeny (Vaasjoki, 1996; Korsman et al., 1999; Väisänen, 2002; Lahtinen et al., 2005). In Puruvesi, only one Svecofennian zircon grain was encountered, and most of the inherited ages are Archean or ~2.0 Ga. This difference in the relative distributions of inherited ages in the two areas is understood to stem from different source rocks.

Nd model ages do not follow the same pattern as U-Pb isotopic ages, as neither the emplacement ages nor the amount of inherited zircon correlate with the whole-rock Nd isotope compositions (Papers I, II, IV). On the other hand, Hf isotope compositions are less radiogenic in inherited zircon grains than in the igneous ones within any one sample, following the U-Pb age distribution. However, igneous zircons of similar ages across different samples display great variation in their Hf isotope compositions (Fig. 4), thus supporting the idea of different types of source rocks.

5 Tectonic questions

5.1 Transport and emplacement

Brown (1994) has stated that the process of the generation of felsic magmas within the continental crust is relatively well understood. However, the question of potential heat sources for melting has been debated extensively (e.g. Petford et al., 2000; Kukkonen & Lauri, 2009; Brown, 2010). It is widely established that temperatures high enough to cause large-scale dehydration melting in lower/middle crust are difficult to achieve solely by radiogenic heat production in a thickened crust (Thompson & Connolly, 1995; Skjerlie et al., 1993). However, the percentage of melt required to produce leucogranites is smaller and may well be achieved, at least on a local scale, via a process such as that outlined above (cf. Kukkonen & Lauri, 2009).

Recently, the mechanisms of magma transport have been the subject of much debate. Diapirism has been rejected as a magma ascent mechanism within the middle crust (e.g. Petford et al., 2000; Vigneresse, 2004), and melt-filled fracture networks have been proposed as the probable mechanism (Solar et al., 1998; Weinberg, 1999; Vanderhaeghe, 2009). Bons et al. (2010) have recently argued thata sustained fracture network of continuous melt flow is mechanically unlikely to form. Instead they propose a stepwise melt accumulation process whereby batches of melt accumulate locally. The significant geochemical differences within the leucogranite belt of southern Finland are consistent with the model expounded by Bons et al. (2010).

The large age difference observed in adjacent leucogranite bodies in the Veikkola area (Papers I and III) is difficult to explain using a simple tectonic model. Barometric calculations indicate a deeper origin for the oldest granite in the area. The strain rate was possibly higher in the initial stage of the orogenic collapse. This would have allowed the first leucogranite melts to crystallize at a deeper level (cf. Rey et al., 2009). Higher strain rate also affects the percentage of melt needed for transport (Urtson & Soesoo, 2009), meaning that smaller melt volumes would be able to leave their sources.

5.2 Crustal evolution

The presently accepted model of the Svecofennian crustal evolution of southern Finland involves a continental arc (the Arc complex of southern Finland) colliding with the previously accreted Primitive arc complex and the Arc complex of western Finland (Fig. 5; Korsman et al., 1999, Lahtinen et al., 2005). This collision took place at ~1.89–1.87 Ga and resulted in crustal thickening and shortening. During the collision, convergence-related magmatism produced calc-alkaline granitoids and more mafic plutonic rocks, as well as volcanic rocks, the emplacement of which had ceased by 1.87 Ga (Vaasjoki, 1996). As a result of this thickening, the crust became isostatically unstable, and a collapse stage ensued. This involved the detachment of the middle and upper crust (Korja & Heikkinen, 2008). Crustal anatexis, triggered by radiogenic heat (Kukkonen & Lauri, 2009) and/or thinning-induced mafic underplating (Korsman et al., 1999), then produced the leucogranites. Shoshonitic postorogenic granites originating from deeper levels intruded into the older crustal units.

Within the Svecofennian domain of Finland, the late-orogenic leucogranites are largely confined to the Arc complex of southern Finland (Fig. 1). This may stem from different prevailing tectonic environments. The Arc complex of western Finland was accreted to the Primitive arc complex before its amalgamation to the Archean craton, and relatively little crustal shortening took place. The Arc complex of southern Finland, on the other hand, collided with the previously assembled blocks, resulting in crustal shortening and extensive stacking (Lahtinen et al., 2005), both required for leucogranite magmatism (Crawford & Windley, 1990).

The apparent progress of leucogranite magmatism from west to east has not been taken into account in tectonic models

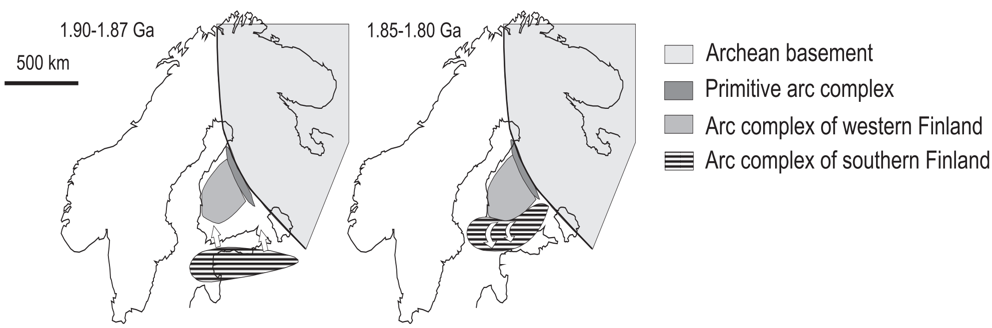

Figure 5. A schematic model of the collision of the Arc complex of southern Finland with the previously accreted blocks. The docking process was governed by a counterclockwise rotational extension, and this may account for the progress of leucogranite magmatism from west to east in southern Finland. Modified after Lahtinen et al. (2005).

presented for southern Finland, yet a decreasing trend of U-Pb ages can be clearly seen (Fig. 4). As the synorogenic rocks are coeval throughout the area (Vaasjoki, 1996), but the late-orogenic leucogranites indicate a distinctly longer period of emplacement, the nature of lithospheric movement must have changed. Lateral extension proceeding towards the east would result in the counterclockwise movement of the colliding block (i.e. Arc complex of southern Finland; Fig. 5). This "rotation" is in agreement with the generally dextral nature of shearing observed along the boundaries and within the Arc complex of southern Finland (e.g. Väisänen, 2002; Torvela, 2007; Saalmann et al., 2010). Local deviations from the trend might reflect differences in the exhumation level, as the barometry results indicate pressure variations for the leucogranite intrusions. Given the very large study area and the consequent sparsity of dating sites, the possibility that the whole age pattern is a sampling artifact cannot be ruled out. More research would be warranted to establish a geochronologically detailed model of Svecofennian orogeny in Finland.

6 Conclusions

The Paleoproterozoic late Svecofennian leucogranites form a ~600 km long E-W trending belt across southernmost Finland. They crop out as heterogeneous, discontinuous plutons that frequently grade into migmatites. Biotite and garnet are their principal mafic minerals. Associated mafic magmatism is extremely rare and is all but completely absent in most localities.

The leucogranites are peraluminous, but geochemically variable, both in terms of major and trace element concentrations. Also, their whole-rock Nd and zircon Hf isotope compositions vary greatly, from slightly superchondritic to strongly subchondritic. Overall, there is a trend towards more juvenile Nd isotope compositions from south to north, save for the Puruvesi granite close to the Archean cratonic margin, which has much less radiogenic Nd and Hf isotope compositions.

In the Veikkola area of south-central Finland, leucogranites were emplaced at ~17–25 km depths, possibly by the assembly of local melt batches from a deeper source. Their emplacement ages vary from 1.85 Ga to 1.82 Ga. Diminishing strain rates during the course of the orogenic collapse may have contributed to the differences in ages and emplacement levels of the granites in this area. The granites were probably derived by dehydration melting from heterogeneous, greywacke-dominated rocks.

The leucogranites of southern Finland were emplaced between 1.85 Ga and 1.79 Ga and arose from the partial melts of older crustal rocks. This ~60 Ma time span is much wider than has traditionally been assigned to these granites. Even on a global scale, periods of continuous leucogranite magmatism lasting this long are rare. The large spread of ages suggests that the orogenic collapse advanced across the Arc complex of southern Finland from west to east.

The ages of the late Svecofennian leucogranites of southern Finland overlap the syn- and postorogenic stages of the traditional Svecofennian orogeny. Thus the three orogenic stages cannot be separated by absolute ages. Rather, different conditions prevailed simultaneously in various localities within the Svecofennian domain, resulting in different types of orogenic magmatism during any given time frame across southern Finland.

Almost all of the leucogranites studied contain abundant monazite in addition to zircon. In most cases, igneous zircons and monazites of individual samples record similar ages, and therefore monazite can safely be used to estimate the emplacement ages of these granites.

Zircon inheritance is rare in the leucogranites of the western part of the belt, but commonplace in the east. Inherited zircons fall into three age groups: 2.8–2.5 Ga, 2.1–2.0 Ga, and ~1.9 Ga. These ages are common in Svecofennian detrital zircons, and hence support a metasedimentary origin for these granites. The differences in the inheritance patterns reflect the nature and origin of the source rocks. The sources of the late-orogenic leucogranites included both sedimentary and igneous rocks.

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