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ISOTOPE GEOLOGY AND FENNOSCANDIAN LITHOSPHERE EVOLUTION

by
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The isotope laboratory at GTK has contributed enormously to geological research in Finland ever since its inception in the early sixties. The main analytical methods used have been U-Pb, Sm-Nd, Rb-Sr, Pb-Pb and light stable isotopes, and with the recent LA-MC-ICPMS instrument installation, the repertoire is increasing. Isotope research has contributed to many joint projects over a wide range of topics including modelling, mapping, mineral exploration, investigations related to nuclear waste disposal, hydrogeology and GTK consortium mapping projects abroad. Co-operation with universities has been important and isotope geology has had a role in numerous Ph.D. theses in Finland.

Building a full picture of the evolution of a piece of the Earth's crust requires a large amount of radiometric age and isotopic data that can only be supplied by a premiere isotope facility. Examples of the types of information the GTK isotope laboratory has produced include: 1. The oldest rocks so far discovered in Fennoscandia are the 3500 million years old Siurua gneisses, but signs of even older crust are evident in these rocks. 2. The main periods of crustal growth in Finland were related to collisional events at 2.8–2.7 Ga and ca. 1.9 Ga. Yet sediments produced over a wide region during the 1.9 Ga event contain abundant ca. 2.0 Ga zircons, for which there is no obvious source, suggesting that a major block of still unlocated crust must have existed somewhere nearby and supplied abundant detritus to proximal ocean basins ca. 1.9 billion years ago. 3. Before the breakup of the ancient Archean continental core, several pulses of mafic magmatism have been recognized between 2.44 Ga and 2 Ga, and these intrusions have proven to be particularly important as they contain some of the major ore bodies in Finland. These and other important results are briefly described in this paper to illustrate the importance of isotope geology in deciphering the geological history of the Fennoscandian Shield, and Finland in particular.

Keywords (GeoRef Thesaurus, AGI): lithosphere, crust, mantle, rocks, genesis, isotopes, absolute age, Precambrian, Finland

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INTRODUCTION

Radiogenic and stable isotopes are used in the Earth sciences as geochronometers and isotopic tracers to unravel geological and environmental processes. Achievements in isotope geology have had a major role in our understanding of the age and complex history of the 4.5-Ga-old Earth. In Finland, the isotope laboratory at GTK has contributed to this research since the early 1960s, and results obtained have provided the basis for modelling the Precambrian geological history of Finland and the Fennoscandian Shield (e.g. Bedrock Map of Finland, Korsman et al. 1997; Precambrian Geology of Finland, Lehtinen et al. 2005).

Since the laboratory is unique in Finland, extensive co-operation with scientists at GTK, the Universities and other institutions has been the main strategy from the very start. Because of this diversity of collaboration, isotope research has not just focused on a few types of problems, but instead has contributed to a wide range of projects including: modelling, mapping, mineral exploration, investigations related to nuclear waste disposal, hydrogeology and GTK consortium mapping projects abroad (Tanzania, Mozambique, Uganda). The contribution of isotope geology has been significant in numerous Ph.D. theses in Finland.

The final product of the research often is joint publications on a variety of geological subjects (see http://info.gsf.fi/fingeo/fingeo_eng.html). Published age determinations on approximately 1170 samples from Finland are available on the Internet in the GTK Active Map Explorer (http://geomaps2.gtk.fi /activemap/ , choose "published radiometric ages" data layer; also see the data layer description for a list of publications, which number around 220).

The main goal of this paper, after discussing laboratory history and methods, is to show the significance of isotope research in modelling the geological history of Finland and the Fennoscandian Shield. The section discussing the genesis and evolution of the lithosphere in Finland, together with the references, may be considered a compact and fairly comprehensive review of current isotope results on this topic.

HISTORY OF ISOTOPE GEOLOGY AT GTK

The first isotope studies on Finnish rock were already carried out more than fifty years ago, when Olavi Kouvo was as a visiting scientist in the USA. Collaborative work by Kouvo with leading experts in the then newly established field of radiometric age dating employing U-Pb, Th-Pb, Rb-Sr and K-Ar methods produced a fundamental (and at that time, controversial) change in the understanding of the age of the main crustal domains in Finland (Kouvo 1958, Wetherill et al. 1962, Kouvo & Tilton 1966). Upon his return to Finland, Kouvo was invited to establish a laboratory of isotope geology, which he did, at GTK in 1963. In these early days the laboratory built its own mass spectrometers and consumed huge numbers of person-hours hand picking large quantities (in today's terms) of pure mineral concentrates for analysis. It was soon realized that compared to other methods, the uranium-lead isotope system in the mineral zircon provided the most reliable age estimates for rocks, and was thus chosen as the principal tool. Since then, approximately 1600 samples have been analysed using this method.

Another early method utilized in the laboratory, common lead isotopes (mainly from sulphides), has provided significant information for determining the origin of ores and modelling crustal evolution (Vaasjoki 1981, Mänttäri 1995, Halla 2002, Peltonen et al. 2008). The Sm-Nd method was initiated at GTK in 1981 and is used for mineral isochron work and for constraining the long-term chemical evolution of the Earth's crust and mantle (Huhma 1986, Huhma et al. 1990, Rämö 1991). Today, the database consists of more than 2000 analyses. The stable isotope laboratory was established in 1985, and one of the main results has been the discovery of a large positive $\delta^{13}C$ anomaly in 2.2–2.1 Ga old carbonate sediments (Karhu 1993). Subsequently, stable isotopes have been used in hydrogeology (Kortelainen 2007) and studies on late Pleistocene atmospheric evolution (Arppe 2009).

METHODS AND INSTRUMENTATION

Currently, isotope geology at GTK concerns two main research programmes: 1) studies on the age, genesis and evolution of the crust, and 2) isotope hydrogeology. The laboratory employs a staff of 5 scientific and 5 technical persons, and is also frequented by visiting scientists. The conventional methods employed include U-Pb (on zircon, titanite, monazite, baddeleyite, etc.), Pb-Pb (sulphides, feldspars, whole rock), Sm-Nd (whole rock, pyroxene, plagioclase, garnet, etc.), Rb-Sr and stable isotopes (H, C, O). A commercial VG Sector 54 instrument for thermal ionization work has been in operation since 1990. Analyses for isotopic composition of hydrogen, carbon and oxygen are carried out on a Finnigan MAT 251 instrument installed in 1985. Participation in the joint Nordic project NORDSIM since 1995 has yielded outstanding results on deciphering a crustal evolution that is complicated by multiple deformational and metamorphic events. The NORDSIM facility joint operating agreement was recently renewed through 2014 following the successful upgrade of the CAMECA IMS 1270, which now provides a state-of-the-art instrument for the geoscience community.

In 2008, GTK and the Finnish universities established a joint laboratory, the Finnish Isotope Geosciences Laboratory (SIGL by its Finnish acronym), which is located at GTK together with the pre-existing isotope facilities. SIGL has been set up for the analysis of the isotopic composition of a broader range of elements and to have the capability to do this for nearly all types of materials. The lab features a Nu Instruments multiple-collector inductively coupled plasma mass spectrometer (LA-MC-ICPMS) that provides high precision isotopic measurements of elements in samples introduced as solutions (acid-dissolved rocks/minerals or waters) using the desolvating nebulizer or as solids (polished mounts or thin sections) using the New Wave 193 nm deep UV solid-state laser (Figure 1). The advantages of the system are its speed, versatility and extremely low detection limits.

Figure 1. Nu Instruments HR multicollector ICP-MS and New Wave 193ss laser installed at GTK Espoo January 2008.

Present SIGL Capabilities

So far, laser ablation techniques have mainly been applied to in situ U-Pb dating of zircon and monazite from grain mounts (Figure 2) or on thick sections. Hf isotope characterization of the zircon grains has also proven successful (e.g. Rutanen et al. 2010). Measurement of U isotopes from U minerals, e.g. uranophane, to date relatively young events in Finland has been tested with good results, but has so far only been applied to a few samples. Solution work has been concentrated on developing the U-series methodology for soil and carbonate samples. Uranium isotopes, along with Li, Mg, Pb and Sr are now routinely measured from surface and groundwater samples as part of the developing branch of water studies at GTK.

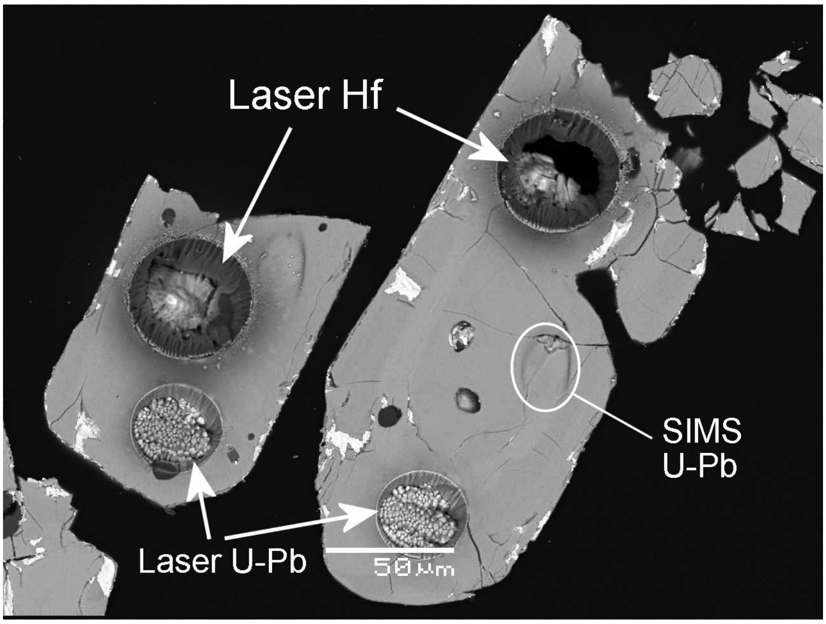

Figure 2. Backscattered electron image of zircon grains with Hf and U-Pb laser pits indicated.

Future Studies

Developments with the laser will concentrate on the capability to perform isotopic studies with high spatial resolution while measuring several isotopic systems on different or even the same minerals within a rock. This work will include U-Pb measurements of less commonly dated minerals, such as perovskite, titanite, baddeleyite, rutile and possibly ilmenite, depending on the U and common Pb content of the target minerals. Also included will be the measurement of Sr and Pb isotopes on spot analyses of feldspars, apatite, carbonates, perovskite and sulphides. In situ analyses of Fe, S and Cu in sulphides will also become increasingly important as the laboratory directs greater effort toward exploration and mining applications. U-series by laser (uranium minerals, apatite, carbonates) will also expand as the need for having the capability to date young events increases (e.g. determining the age of fracture fillings at the nuclear fuel storage facility).

We are convinced that working at a detailed scale with a set of complementary isotopic systems will be one of the most important directions for isotope research in the future. To facilitate the large amount of planned microsampling by laser, a unified coordinate transfer system has been developed that will make use of the powerful combination of mapping of mineral grain positions in rock thick sections by the MLA (Mineral Liberation Analyzer) at GTK Outokumpu, SEM imaging of the interesting grains to document zoning, and then direct isotope measurement by LA-MC-ICPMS. This system will reduce the work required in making preparations for many types of rocks (thick sections versus crushing, separation, hand-picking and mounting) while at the same time retaining spatial information regarding the target mineral-host mineral relationships in the rock. We anticipate this methodology will mark a major advance in understanding processes in crystallizing igneous systems and in systems with ore-bearing fluids.

On the solution side, the list of applications is continuously growing due to the versatility of the instrumentation. U-series solution work will continue to expand, including solutions from soils, carbonates, and other U-containing materials. Some examples of other planned projects include: isotopic analyses of Fe, Cu, Ni, S, for studying mantle-crust interactions and ore forming systems; monitoring the migration of redox sensitive elements (S, Fe, Cu, Zn, Cr, Ni, Mo, Hg) to map paleoenvironmental change and determine anthropogenic sources; Pb bioavailability studies using Pb isotopes as tracers; Sr isotopes of shellfish and mapping Sr inputs (from fertilizer) to closed basins (e.g. Baltic Sea); Si isotopes of foraminifera as a proxy for temperature change recorded in layered lake sediments.

ISOTOPE GEOLOGY AND EVOLUTION OF THE LITHOSPHERE IN FINLAND

The geologic history of the Fennoscandian shield is complex, and extensive collaboration between researchers working in the field and in laboratories is required to fully decipher the geologic record. In these studies isotopic methods play an indispensable role. The main goal of this section of the paper is to illustrate just how large a contribution isotope geology has made, particularly in terms of age dating of rocks. All GTK isotope-related projects have been initiated to study one or more of the following important themes: 1. mantle evolution, 2. crust-mantle interaction, 3. crustal age, origin and evolution and 4. metallogenesis.

The bedrock of Finland forms a part of the ancient Fennoscandian Shield, which is composed of rock units mostly formed between 3.2 and 1.6 billion years ago (Figure 3). This long geological history can be divided into four main periods of geological activity: 1. Archean, 2. Paleoproterozoic evolution preceding the major 1.9 Ga orogeny, 3. rocks related to the Paleoproterozoic 1.9 Ga orogeny, and 4. younger post-orogenic events.

1. Information on ***Archean (> 2.5 Ga)*** isotope systematics of the Fennoscandian Shield has increased significantly in recent years. This includes greenstone belts, paragneisses and granitoids, and involves both U-Pb dating (TIMS, SIMS, LA-ICPMS), and Sm-Nd and some Lu-Hf analyses for evaluating the crustal residence ages. In many of these studies, data from multiple isotopic systems are required in order to be able to look through Proterozoic metamorphic effects, which in some places are pervasive.

These studies have shown that the major crust-forming period in the Archean was ca. 2.8–2.7 Ga, and only a few remnants of older rocks have been preserved (Figure 3). The oldest rocks in the Fennoscandian Shield are ca. 3.5 Ga gneisses in Siurua, Pudasjärvi (Figure 4), where evidence of even older 3.7 Ga crust was obtained from small zircon cores (Figure 3, Mutanen & Huhma 2003, Lauri et al. in press). Signs of 3.5 Ga crust were also found in lower crustal xenoliths from the 0.5–0.6 Ga old kimberlites in Kaavi, eastern Finland (Peltonen et al. 2006). Some xenoliths yielded large ranges of U-Pb zircon ages from 3.5 to 1.8 Ga, but interestingly Proterozoic zircons were distinct grains, and not overgrowths on the Archean zircons.

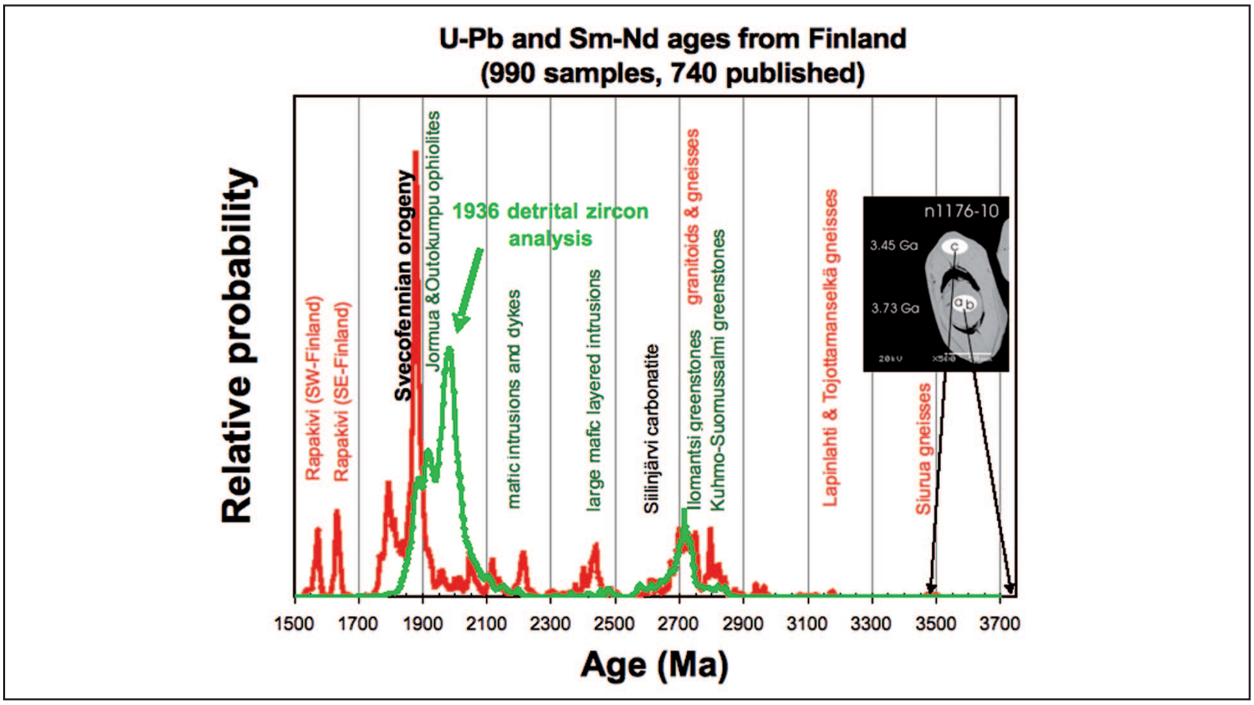

Figure 3. U-Pb and Sm-Nd ages from Finland. The red line shows primary rock ages and is based on results from 990 samples (from which data on 740 are published). The green line shows the age distribution of detrital zircons in Paleoproterozoic metasediments and is based on 1936 U-Pb analyses by SIMS (ca. 1000 published) and LA-MC-ICPMS (unpublished). Also shown is an image of ca. 3.5 Ga zircon from the oldest rock in Finland from Siurua with an older ca. 3.73 Ga core (Mutanen & Huhma 2003).

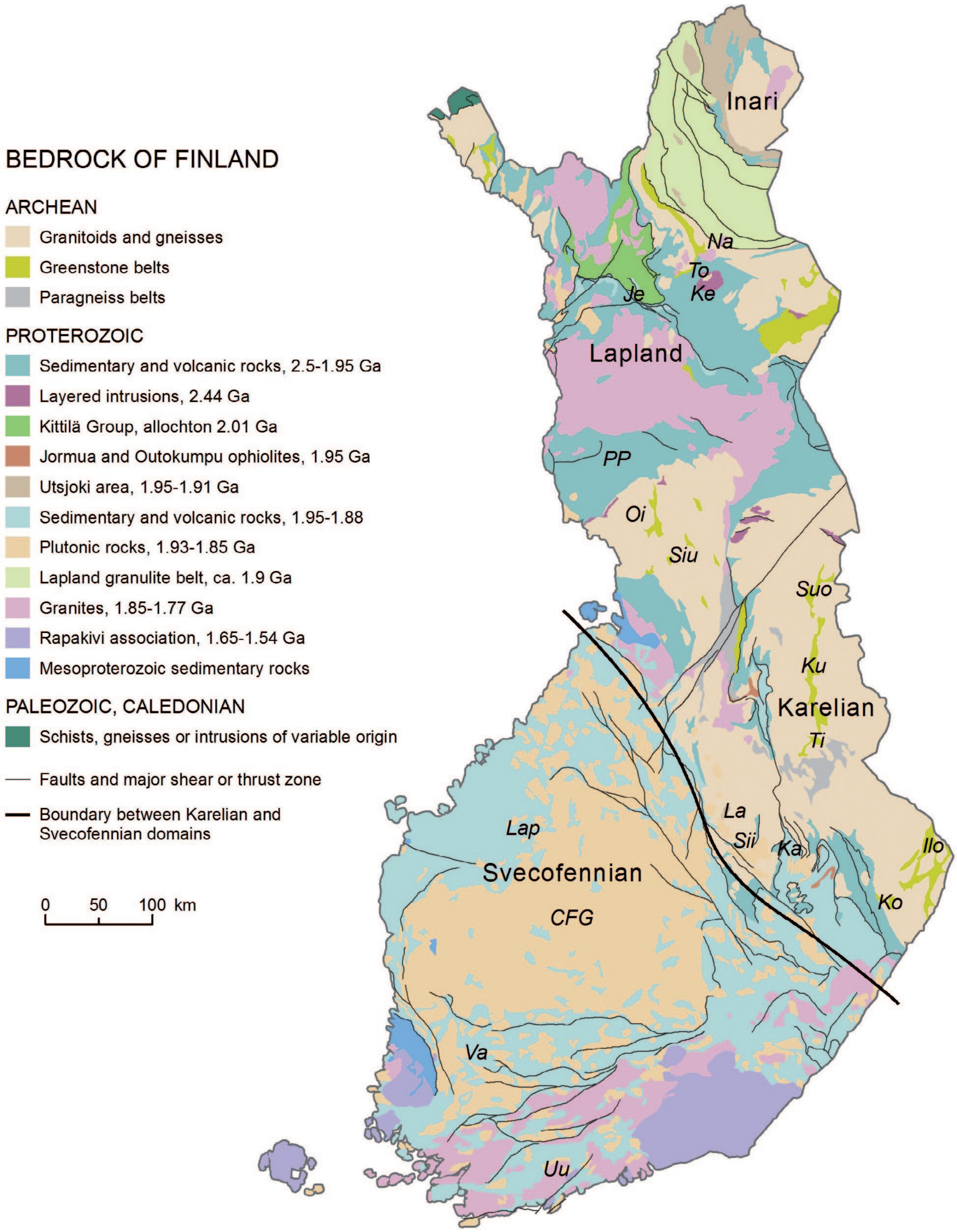

Figure 4. Geological map of Finland, modified from Korsman et al. (1997). Key from North to South: Na = 1.78 Ga Nattanen granite, reworked old crust; To = 3.2 Ga Tojottamanselkä gneiss; Ke = 2.06 Ga Keivitsa mafic intrusion; Je = 2.06 Ga Jeesiörova komatiites; PP = Paleoproterozoic Peräpohja Schist belt; Oi = Archean Oijärvi greenstone belt; Siu = 3.5 Ga Siurua gneisses, oldest crust in the EU; Suo/Ku/Ti/Ilo/Ko = Archean Suomussalmi/Kuhmo/Tipasjärvi/Ilomantsi/Kovero greenstone belt; La = 3.2 Ga Lapinlahti gneisses; Sii = 2.61 Ga Siilinjärvi carbonatite; Ka = 0.5–0.6 Ga Kaavi kimberlites; Lap = 70 Ma Lappajärvi impact crater; CFG = 1.87–1.88 Ga Central Finland granitoid area; Va = Vammala migmatite belt (1.87 Ga metamorphism); Uu = (West) Uusimaa migmatite belt (1.83–1.80 Ga metamorphism).

Most Archean gneisses (TTG) have ages of 2.83–2.78 Ga and 2.76–2.72 Ga, whereas leucogranitoids and leucosomes in migmatites are typically ca. 2.7 Ga (Hyppönen 1983, Käpyaho et al. 2006, 2007, Lauri et al. 2006, Luukkonen 1988, Mikkola et al. submitted, Vaasjoki et al. 1993, 1999*)*. Evidence of high-grade metamorphism at ca. 2.63 Ga is provided by U-Pb data on monazites and zircons as well as Sm-Nd analyses on garnet (Hölttä et al. 2000, Mänttäri & Hölttä 2002*)*.

U-Pb zircon ages from igneous rocks of the greenstone belts give the following results: 1) the Suomussalmi belt contains volcanic fragments of variable ages from 2.94 to 2.82 Ga, 2) the Kuhmo, Tipasjärvi and Oijärvi greenstone belts range from 2.83 to 2.80 Ga, 3) the Ilomantsi belt is predominantly ca. 2.75 Ga whereas 4) the Kovero belt (SW from Ilomantsi), in addition to containing 2.75 Ga material, also contains fragments of ca. 2.87 Ga felsic rocks (Vaasjoki et al 1993, 1999, Huhma et al. in prep*.*). These results suggest that greenstone belts register an extended fragmentary record of geological evolution.

The Sm-Nd results suggest that much of the crust in Kuhmo and Ilomantsi areas is relatively juvenile, whereas further north in Suomussalmi, rocks contain a larger component of older crustal material *(*O'Brien et al. 1993, Käpyaho et al. 2006, Mikkola et al. submitted, Huhma et al. in prep*)*. The oldest Sm-Nd and Lu-Hf model ages of 3.6–3.7 Ga have been obtained from the Siurua gneisses, consistent with their old zircon ages. The paragneisses have been considered as an important component in the Archean crust in Finland. Isotope studies have shown that they are in fact young in the context of Archean evolution. The age of deposition has been constrained close to 2.7 Ga, and much of the detritus was derived from only slightly older crust (Kontinen et al. 2007*)*.

2. The geological record of the pre-orogenic ***Paleoproterozoic (2.5–1.9 Ga)*** evolution is well preserved in parts of the Fennoscandian Shield, especially in Lapland where supracrustal and associated mafic plutonic rocks of this age are abundant. In contrast, the Karelian domain in eastern Finland contains only relatively small remnants of these formations. Isotope research has focused on the following three major topics: 1) the age and characterization of mafic magmatism, which provides information on mantle evolution and crust-mantle interaction; 2) the age, stratigraphy and characterization of supracrustal rocks, particularly in Lapland; and 3) C-isotope excursion in Paleoproterozoic carbonate sediments, which contributes to our knowledge of the evolution of the atmosphere.

Published and unpublished age results on 180 samples from the Karelian domain reveal major mafic igneous activity at 2.44, 2.22, 2.14–2.10 and 2.06 Ga (Figure 3). A few mafic dykes cutting the Archean crust at 2.3 and at 1.96 Ga are also evident. The 2.44 Ga rocks include also minor felsic lithologies and economically important large mafic layered intrusions. In fact, one of the laboratories' globally outstanding achievements was the first U-Pb dates from zircon and baddeleyite in mafic rocks, which were obtained from these 2.44 Ga layered intrusions (Kouvo 1977). Today, several 2.44 Ga intrusions are known throughout the Karelian domain in Northern Finland. An important rock association is the Kittilä Group in Lapland, which consists of ca. 2.015 Ga mafic and minor felsic juvenile rocks considered as an allochthonous ophiolite. In the epsilon-Nd vs. age diagram (Figure 5) these are represented by the (Vesmajärvi Fm) mafic rocks and felsic porphyries, which all have initial Nd isotopic compositions similar to depleted mantle and thus contain no contribution from older crustal material.

Another major volcanic unit in Lapland consists of the (Jeesiörova) komatiites, where in places primary clinopyroxene has survived through all later metamorphic events. Such samples provided the basis for Sm-Nd studies, which have yielded an age of ca. 2.06 Ga and an initial Nd isotopic composition close to depleted mantle (Figure 5). The diagram also shows, for instance, how the material of the 2.44 Ga layered intrusions (Penikat, Koitelainen, Akanvaara) and the 2.06 Ga Keivitsa intrusion are very distinct from coeval depleted mantle and require a large component from Archean LREE enriched lithosphere in their genesis.

A large number of the U-Pb age determinations mentioned above were published in 12 papers in a special volume on Lapland (Vaasjoki 2001), particularly Perttunen & Vaasjoki (2001), Rastas et al. (2001), Räsänen & Huhma (2001), Juopperi & Vaasjoki (2001), Manninen et al. (2001) and Mutanen & Huhma (2001). Other publications, many also containing Sm-Nd results, include those by Alapieti (1982), Huhma et al. (1990), Hanski et al. (1990, 1997, 2001a, 2001b, 2005, 2010), Hanski & Huhma (2005), Lauri & Mänttäri (2002), Lauri et al. (2006), and Niiranen et al. (2005, 2007). A large amount of unpublished results mentioned in Vuollo & Huhma (2005*)* will be published by Huhma et al. (in prep).

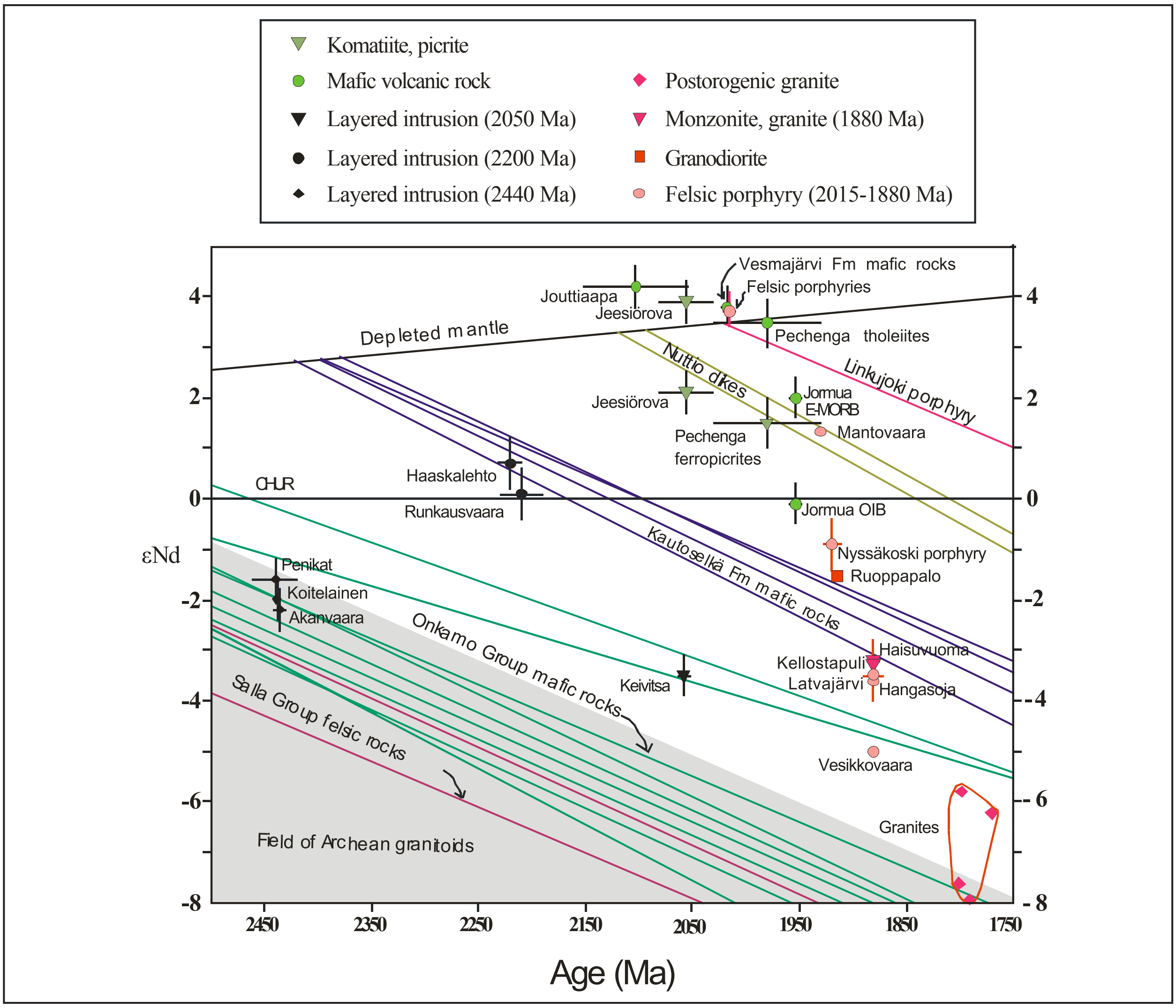

Figure 5. Nd-isotopic evolution diagram for Paleoproterozoic plutonic and volcanic rocks of northern Finland provides an example of the use of ^{147}Sm-^{143}Nd isotope system for studying the genesis of rocks (from Hanski & Huhma 2005, Figure 4.7.). The εNd on the Y-axis denotes the $^{143}Nd/^{144}Nd$ isotopic composition relative to chondrites (CHUR) and has been calculated from the measured $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios back to Proterozoic time. The ε-values are shown with symbols for rocks that have been dated by U-Pb or Sm-Nd method. Error bars are based on several analyses of each rock association. Evolution lines are shown for metavolcanic rocks lacking direct isotope dating. The main observation to be made from this diagram is that some rocks have origins in depleted mantle (e.g. Jouttiaapa basalts) or have very short crustal prehistories (e.g. 2.015 Ga felsic porphyries), whereas others represent essentially recycled old crustal material (e.g. 1.8 Ga granites). Not all names on the diagram are explained in the text, but may be of interest to some readers; further information is available in Hanski & Huhma (2005). Evolution of depleted upper mantle is after DePaolo (1981). CHUR refers to chondritic uniform reservoir and equals to the evolution of Bulk Earth.

The discovery of a large positive $\delta^{13}C$ isotope anomaly in 2.2–2.1 Ga Paleoproterozoic carbonate sedimentary rocks has been one of the important results from the GTK isotope studies (Karhu 1993). Elevated $\delta^{13}C$ values up to +10 exist globally and have been explained by an abnormally high rate of organic carbon deposition, which generated a high rate of O_2 production (Karhu 1993, Karhu & Holland 1996). Recently, improved time constraints have been obtained by SIMS dating on zircon in pyroclastic rocks from the Peräpohja Schist Belt, giving an age of 2106 ± 8 Ma (the Hirsimaa Formation). This closely approximates the end of the carbon isotope excursion at a time when the marine $\delta^{13}C$ values were at 4–6‰ (Karhu et al. 2007). This is supported by the 2.06 Ga ages obtained from the Pechenga supracrustal rocks overlying the high delta-C carbonate metasediments (NW Russia, Melezhik et al. 2007).

3. The ***Paleoproterozoic orogeny (ca. 1.95–1.8 Ga)*** represents a major crust forming event that contributed to a large part of Fennoscandia and is a significant component globally. Isotope research includes the following topics.

1) Early phases, particularly the (Jormua and Outokumpu) ophiolites.
2) Provenance and age of deposition of the metasediments within Svecofennian, Upper Kalevian and Lapland granulite belt.

3) U-Pb age and origin of igneous rocks, particularly Sm-Nd characterization of the juvenile vs. recycling of older LREE enriched lithospheric (crustal) material in the genesis with emphasis on the Svecofennian and Karelian boundary zone.
4) Timing of tectonic and metamorphic evolution and late igneous phases.

Summarizing all the studies on these topics is beyond the scope of this paper, but a brief summary of a few selected items is included here.

The age of the 1.95 Ga ophiolites is now well constrained and isotopic evidence strongly suggests that the Jormua ophiolite represents a remnant of an Early Proterozoic seafloor that mainly consisted of Archean subcontinental lithospheric mantle (Kontinen 1987, Peltonen et al. 1996, 1998, 2003, 2008).

The bulk of the Svecofennian and Upper Kalevian metasediments were deposited ca. 1.92 Ga ago and are mixtures of predominantly Proterozoic mantle sources with minor Archean components, also shown in the Sm-Nd data (Huhma 1987, Huhma et al. 1991, Claesson et al. 1993, Lahtinen et al. 2002, 2009, 2010, Rutland et al. 2004, Bergman et al. 2008). The isotope characteristics of the migmatitic metapelites of the Lapland granulite belt broadly share these features (Tuisku & Huhma 2006). All these Proterozoic metasediments contain abundant detritus from ca. 2 Ga source rocks, for which there is no known source (Figure 3). Some metasediments also occur in higher stratigraphic levels and are younger than 1.87 Ga.

The oldest rocks in the ***Svecofennian*** domain are ca. 1.93 Ga gneisses and volcanics with initial Nd-epsilon close to +3 and are thus juvenile new crust (Figure 6). The main suites of the mafic and felsic igneous lithologies were formed at 1.90–1.87 Ga ago, and have initial Nd-epsilon values of -1 to +3 (Huhma 1986, Patchett & Kouvo 1986, Lahtinen & Huhma 1997, Vaasjoki & Huhma 1999, Rämö et al. 2001, Vaasjoki et al. 2003, Kurhila et al. 2005, Makkonen & Huhma 2007). This shows that many of these rocks have their ultimate origin in depleted mantle with only a slight input of older crustal material. Lower epsilon values in some rocks suggest the involvement of older crustal material in their genesis. Co-operation with Estonian colleagues has revealed that similar crust continues further south into the Baltic countries under the Paleozoic cover (Puura & Huhma 1993, Puura et al. 2004). Distinct domains within the Svecofennian crust are evident from the lead isotope data on galenas and suggest fundamental variations in source characteristics (Vaasjoki 1981, Huhma 1986). In Northern Finland, the arc-related magmas of the Lapland granulite belt have initial Nd-epsilon close to zero and were intruded into the sediments at 1.92–1.90 Ga ago (Meriläinen 1976, Tuisku & Huhma 2006). Based on Sm-Nd and U-Pb studies it is evident that even more juvenile 1.9 Ga crust exists in the Utsjoki area between the Archean Inari domain and the Lapland granulite belt (Figures 4 and 6, Huhma unpublished).

The contribution of older LREE-enriched lithosphere (crust) in the genesis of 1.9–1.8 Ga rocks is generally high in the ***Karelian*** domain, where some granites may represent largely reworked Archean crust (Figures 5 and 6) (e.g. Huhma 1986, Ruotoistenmäki et al. 2001, Ahtonen et al. 2007, Heilimo et al. 2009).

The isotope studies employing U-Pb on monazite, titanite, zircon and columbite together with Sm-Nd on garnet show that two major high grade metamorphic episodes are evident in the Svecofennian domain, ca. 1.88–1.87 Ga e.g. in the Vammala migmatite belt and ca. 1.83–1.80 Ga further south in the West Uusimaa belt. In the Lapland granulite belt the U-Pb on monazite and zircon together with Sm-Nd on garnet constrain the high-grade metamorphism from peak conditions at ca. 1.9 Ga to subsequent decompression and cooling at 1.87 Ga. The 1.8 Ga event is well shown in many places throughout the Shield by abundant isotopic data, suggesting a major thermal peak and crustal reworking to produce granites. Some mantle-derived mafic rocks were also emplaced at ca. 1.8 Ga ago.

Papers providing isotope data on the timing of these tectonic and metamorphic evolution and late igneous phases include Hopgood et al. (1983), Korsman et al. (1984), Suominen (1991), Kontinen et al. (1992), Mouri et al. (1999, 2005), Alviola et al. (2001), Väisänen et al. (2002), Ehlers et al. (2004), Skyttä et al. (2005, 2006), Skyttä & Mänttäri (2008), Mänttäri et al. (2007), Pajunen et al. (2008a,b), Torvela et al. (2008) and Saalmann et al. (2009).

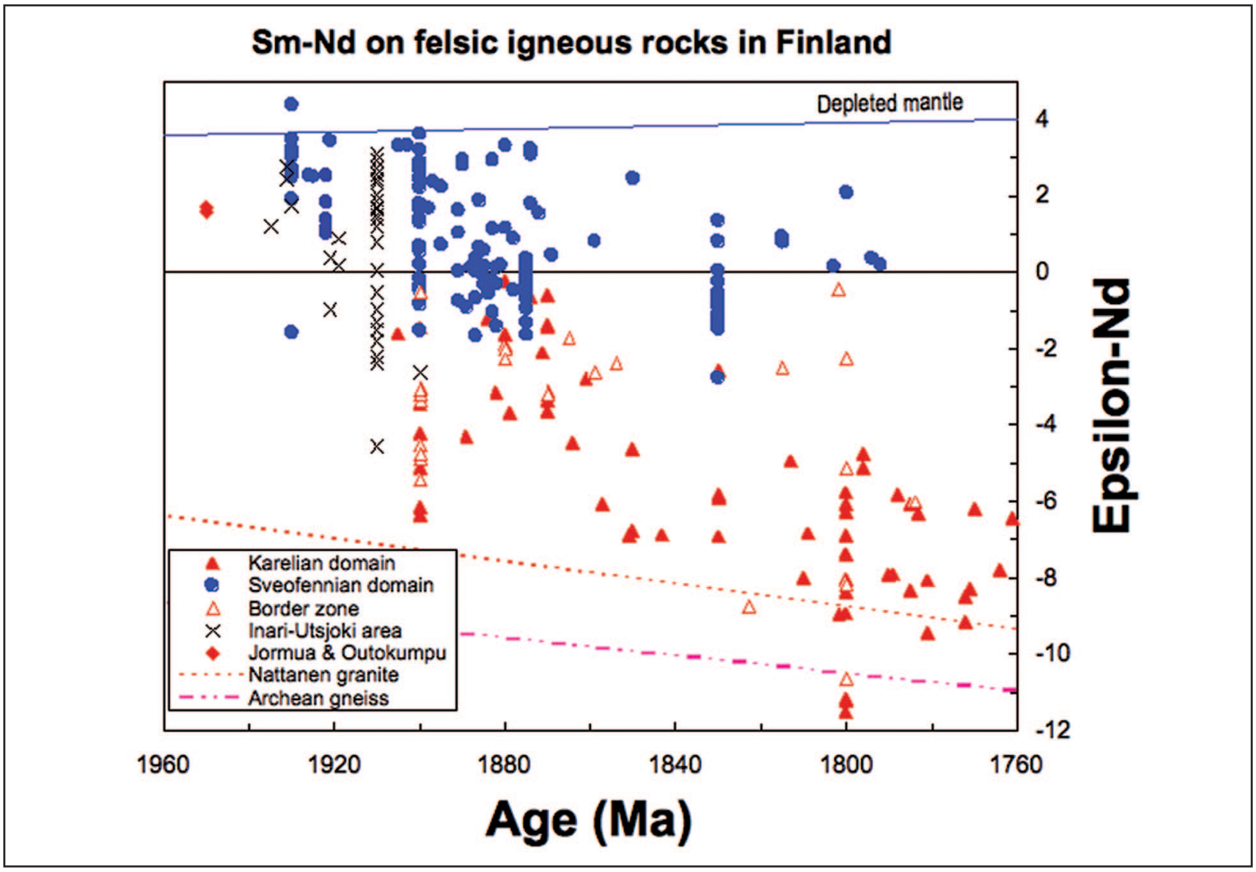

Figure 6. Initial Nd isotopic composition (epsilon-Nd) for 1.76–1.96 Ga felsic igneous rocks in Finland. Ages are U-Pb ages or estimated from the geological context at 1.8 Ga, 1.83 Ga (migmatite belt in S Finland), 1.87 Ga (Central Finland granitoids), 1.9 Ga, and 1.91 Ga (Lapland granulite & Utsjoki area). Note that a slight change in age will not affect the overall picture; see e.g. the evolution line for Nattanen granite or typical Ne-oarchean gneiss. (Data from references in the text and unpublished, n = 270).

4. Isotope studies on the ***post-orogenic crustal lithologies and evolution*** include:

1) rapakivi granites, which consist of two main age groups at 1.64 and 1.57 Ga (Vaasjoki 1977, Rämö 1991, Rämö et al. 1996),
2) 1.26 Ga (postjotnian) dolerites (Suominen 1991) and 1.2 Ga lamproites (O'Brien et al. 2007),
3) 0.5–0.6 Ga kimberlites hosting scientifically important mantle and crustal xenoliths (Peltonen et al. 1999, 2002, 2006, Hölttä et al. 2000b, Peltonen & Mänttäri 2001, O'Brien & Tyni 1999),
4) late veins and shear zones, e.g. ca. 0.4 Ga fluorite-calcite-galena veins (Alm et al. 2005) and fault breccias (Mänttäri et al. 2007), and
5) impact structures (e.g. Lappajärvi at ca. 70 Ma, Mänttäri & Koivisto 2001).

CONCLUSIONS

Since the early 1960s, analyses based on traditional isotope systems such as U-Pb, Sm-Nd, Pb-Pb and $\delta^{13}C$ have been used at GTK to produce geochronological and isotopic database, which provides the cornerstones for building a comprehensive story of the geological history. It may be concluded that the contribution of isotope geology has been enormous for the current understanding of the geological evolution of Finland and the Fennoscandian Shield.

Recent equipment added to the laboratory will continue expanding the existing database. GTK will also focus on the analytical development of non-traditional heavy stable isotopes in a wider field of applications involving mineral exploration, hydrogeology and other environmental issues.

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