Bergslagen etapp 1

Provenance of Svecofennian sedimentary rocks in Bergslagen and surrounding areas

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Cover: Sampling at Inlandsvägen in Orsa Finnmark. The insets show the youngest zircon (Eskörönningen, 1,679 ± 21 Ma, above) and the oldest Archaean zircon (Torrvarpsund, 3,459 ± 25 Ma, below) in the analysed samples.
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CONTENT

ABSTRACT

In autumn 2017, 29 samples for provenance studies were collected from Svecofennian sedimentary rocks at 28 different sample sites in Bergslagen and surrounding areas in Sweden. Of these, 24 samples had a sufficient amount of zircon grains, and U–Pb dates of 2,203 zircon grains were thus obtained using *Laser ablation inductively coupled plasma mass spectrometry* (LA-ICP-MS) at the Geological Survey of Denmark and Greenland (GEUS).

Most of the samples in this project have their maximum zircon populations in the 50 million years intervals 1,850–1,899 and 1,900–1,949 Ma, respectively. This implies that most of the detrital zircons in these areas show dates that are close to or lie within the assumed time span for the deposition of the Svecofennian sedimentary sequences in Bergslagen. This, in turn, indicates that the sedimentary material originates from relatively proximal Svecokarelian intrusive and Svecofennian volcanic rocks from the Fennoscandian Shield.

However, in the arenites and arkoses of the Närkesberg formation in the Närkesberg–Hjortkvarn area, the 1st order peaks occur in the 2,000–2,049 (Siggetorp–Laggarfall and Linnerud–Stensätter) or in the upper part of the 1,950–1,999 Ma interval. This indicates sediment supply from a ≥ 2.0 Ga continent. The absence of zircons overprinted by younger metamorphic events in the rocks of this area either indicates that the zircons emanated from a continent that has not been affected by Svecokarelian metamorphism at the time of erosion and probably also at the time of sediment transport, or, that a metamorphic overprint was not recorded in the zircons. It seems likely, that the sedimentary rocks of the Närkesberg formation were derived from a border area between the Fennoscandian and Ukrainian Shields.

The analysed samples in this study show only a few or no zircon dates in the age range 2.5–2.2 Ga. This is in agreement with results of earlier provenance studies in Sweden and Finland.

The youngest zircon populations occur in the highly metamorphic rocks in the Gävle area, which also show the lowest number of zircons with U/Th ratios below 5, indicating that these rocks have been affected by one or more high temperature metamorphic events overprinting the detrital zircons.

Most of the Archaean zircons occur in samples from the southwestern, central western and northwestern parts of the study area, whereas few or no Archaean zircons were found in the central and southeastern parts.

Geochemical discrimination diagrams for tectonic setting, provenance and mineral composition show equivocal results, but those which are based on major elements show a distinct discrimination of samples between the southern and the northern part of the investigated area.

SAMMANFATTNING

Hösten 2017 samlades 29 prover för proveniensstudier in från svekofenniska metasedimentära bergarter på 28 olika platser i Bergslagen med omgivning i Sverige. Av dessa hade 24 stycken tillräckligt många zirkonkorn, och på dem har 2 203 zirkonanalyser gjorts med *Laser ablation inductively coupled plasma mass spectrometry* (LA-ICP-MS) på De nationale geologiske undersøgelser for Danmark og Grønland (GEUS) i Köpenhamn.

De flesta proverna i det här projektet har sina maximala zirkonpopulationer i 50 miljoner års intervallerna 1 850–1 899 respektive 1 900–1 949 Ma. Detta innebär att de flesta detritiska zirkoner i de här områdena har åldrar som ligger nära eller i det antagna tidsintervallet för avsättningen av de svekofenniska sedimentära sekvenserna i Bergslagen. Detta antyder i sin tur att sedimentmaterialet härstammar från relativt närbelägna svekokarelska intrusivbergarter och svekofenniska vulkaniter av den fennoskandiska skölden.

I areniterna och arkoserna i Närkesbergsformationen i Närkesberg–Hjortkvarnområdet förekommer emellertid topparna av första ordningen i intervallet 2 000–2 049 Ma (Siggetorp–Laggarfall och Linnerud–Stensätter) eller i den övre delen av intervallet 1 950–1 999 Ma. Detta tyder på sedimenttillförsel från en mer än två miljarder år gammal kontinent. Frånvaron av zirkoner överpräglade av yngre metamorfa händelser i bergarterna i det här området antyder antingen att de härstammar från en kontinent som inte hade påverkats av svekokarelsk metamorfos vid tidpunkten för erosion och antagligen också sedimenttransport, eller att en metamorf påverkan inte återspeglas i de här zirkonerna. Det verkar därför troligt att de sedimentära bergarterna i Närkesbergsformationen härstammar från ett gränsområde mellan de fennoskandiska och ukrainska sköldarna.

De analyserade proverna i denna studie visar endast några få eller inga zirkonåldrar alls i åldersintervallet 2,5–2,2 miljarder år, vilket är i överensstämmelse med resultaten från tidigare proveniensstudier i Sverige och Finland.

De yngsta zirkonpopulationerna förekommer i de högmetamorfa bergarterna i Gävleområdet. Här finns också det lägsta antalet zirkoner som har en U/Th-kvot under 5. Detta tyder troligen på att de här bergarterna utsatts för en eller flera metamorfa händelser som överpräglade de detritiska zirkonerna.

De flesta zirkonerna med arkeiska åldrar förekommer i prover från de sydvästra, centralavästra och nordvästra delarna av projektområdet, medan endast få eller inga arkeiska zirkoner alls har hittats i de centrala och sydöstra delarna.

Geokemiska diskrimineringsdiagram för tektonisk miljö, proveniens och mineralsammansättning visar något olika resultat, men de som är baserade på huvudelementen visar att proverna från den södra delen av projektområdet skiljer sig från dem från den norra delen.

INTRODUCTION

Bergslagen in eastern central Sweden (Stephens et al. 2009, Stephens & Jansson 2020; Fig. 1a, b, c) is one of four major ore-provinces in Sweden, of which three currently are producing. The other provinces are Northern Norrbotten (Bergman et al. 2001; Bergman 2018), the Skellefte district (Allen et al. 1996b; Kathol & Weihed 2005) and the Caledonian orogen (Zachrisson 1986, Roberts & Stephens 2000). In Bergslagen, extensive mining activity has taken place since the Middle Ages. Bergslagen is a not clearly defined area and covers all or parts of the historical provinces Värmland, Dalarna, Hälsingland, Gästrikland, Närke, Västmanland, Uppland, Södermanland and Östergötland (Fig. 1c).

Geologically, the Bergslagen area is situated predominantly in the southwestern part of the Svecokarelian orogen in the Fennoscandian Shield (Stephens et al. 2009, Stephens & Jansson 2020). The bedrock is dominated by Palaeoproterozoic rocks, formed or reworked by Svecokarelian orogenic processes between 1.96 and 1.75 Ga; in the western part of the area, these rocks are also affected by Sveconorwegian deformation and metamorphism. Subordinately occur minor volumes of 1.7 Ga old volcanic and sedimentary rocks (Dala porphyries and Digerberg sedimentary rocks; Hjelmqvist 1966, Lundqvist & Persson 1999, Nyström 2004), siliciclastic sedimentary and basaltic rocks of Jotnian age in the Gävle area (Bergman et al. 2005, Delin & Söderman 2005a, b) and fault-bounded remnants of an undeformed Lower Palaeozoic sedimentary cover in the Siljan impact structure (Wickman 1988, Henkel & Pesonen 1992) and in southern Närke (Nielsen & Schovsbo 2006, Stephens et al. 2009).

The Palaeoproterozoic bedrock consists of felsic volcanic rocks, deposited at c. 1.91–1.89 Ga which are interlayered by shallow water limestones and to different degrees deformed and metamorphosed siliciclastic sedimentary rocks (Stephens & Jansson 2020). The latter metasedimentary rocks, which are the scope of this report, are lying stratigraphically beneath, intercalated with and stratigraphically above the volcanic sequence (Stephens & Jansson 2020). All these supracrustal rocks are intruded by a dominantly calc-alkaline c. 1.91–1.87 Ga plutonic suite (Stephens & Jansson 2020) and 1.85–1.75 Ga intrusive rocks (Allen et al. 1996a; Stephens et al. 2007, 2009).

The Palaeoproterozoic metasedimentary rocks make up a significant part of the supracrustal rocks in Bergslagen and surrounding areas. They are metamorphosed to different degrees and comprise rocks with well-preserved primary structures as well as strongly altered, in parts migmatised, varieties. They belong to the Svecofennian supracrustal rocks in the western part of the Fennoscandian Shield (Stephens et al. 2009).

Most of these metasedimentary rocks were deposited, deformed and metamorphosed under the Svecokarelian orogeny. However, in the westernmost parts of the study area, rock sequences of the same age have additionally been affected by the Sveconorwegian orogeny. Since all described rocks in the following are metamorphosed, the prefix 'meta' has been omitted for the sake of simplicity.

Palaeoproterozoic sedimentary rocks in Finland and Sweden have previously been subject to provenance studies. Two samples from a study by Claesson et al. (1993), are from the present area. Bergman et al. (2008) analysed detrital zircons from a quartzite of the uppermost formation of the Hamrånge group in the central-eastern part of the study area. Stephens & Andersson (2015) dated detrital zircon crystals in paragneisses from Uppland and the lake Mälaren area. In addition, provenance studies have been done on the 1,882–1,850 Ma quartzites of the Västervik area (Sultan et al. 2005) and the Jotnian Dala sandstone in Dalarna (Lundmark & Lamminen 2016).

This report presents the results from a subproject within the 'Bergslagen etapp 1' project. It must be considered as a technical report with only a limited amount of more detailed studies and interpretations. Thus, we encourage that further studies should be carried out on the obtained geochronological, geochemical and petrological data for the entire area or for one or several of the subareas. A preliminary report in Swedish about the sampling was presented by Kathol (2018).

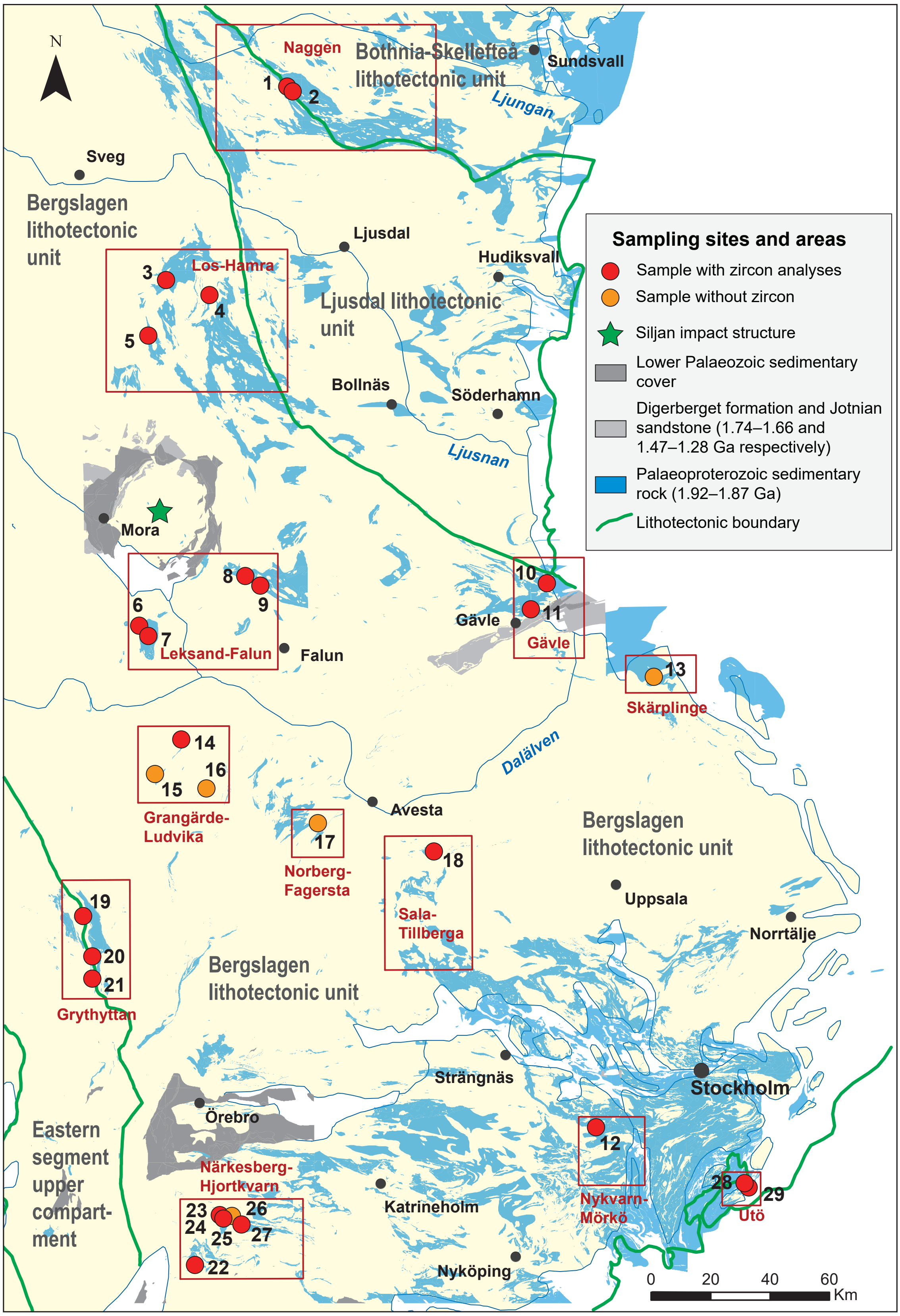


Figure 1a. Sedimentary rocks of different generations in Bergslagen and surrounding areas. Sample sites and areas in the Palaeoproterozoic, 1.92–1.87 Ga sedimentary rocks are marked with circles and red rectangles, respectively. Numbers at the sample sites refer to the first column in table 2.

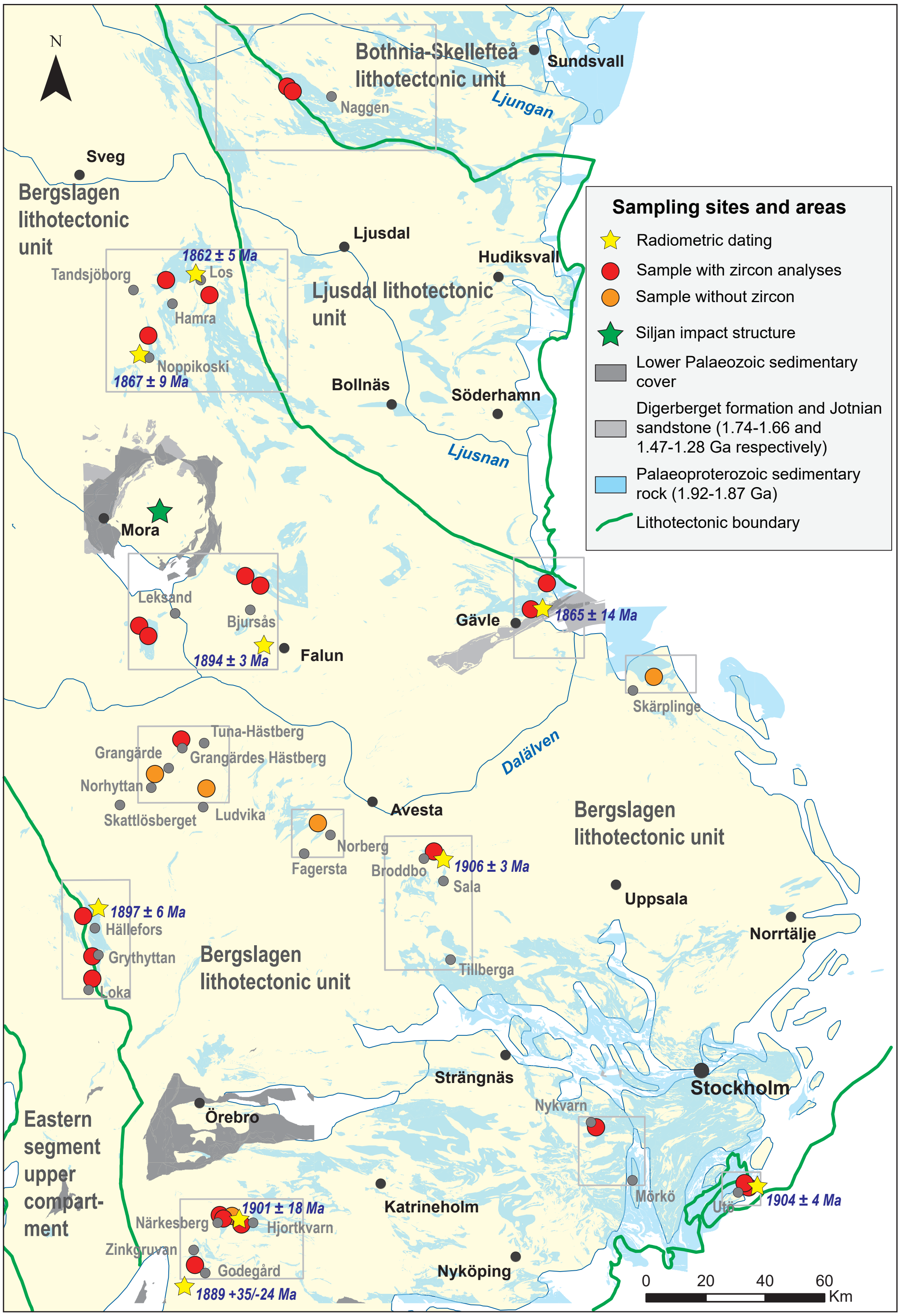


Figure 1b. Bergslagen and surrounding areas with sites for radiometric datings, relevant for this study, and localities named in the text (in grey).

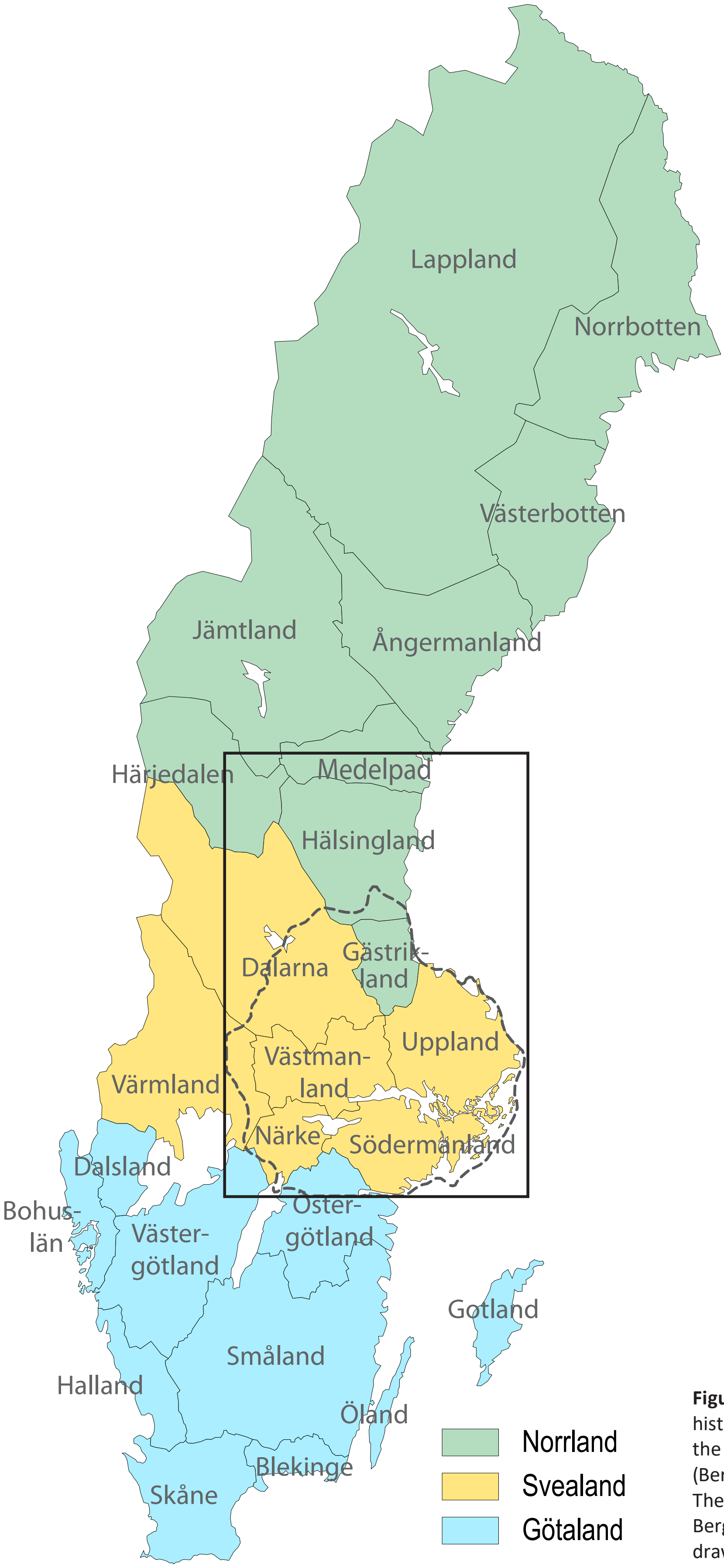


Figure 1c. Map showing the historical provinces in Sweden and the location of the study area (Bergslagen and surrounding areas). The historical mining district of Bergslagen is marked by a roughly drawn dark grey, dashed line.

SELECTION OF SAMPLING SITES AND METHODS

The first author, Benno Kathol, spent two weeks in the autumn of 2017 to collect rock samples for provenance studies of Palaeoproterozoic Svecofennian sedimentary rocks in Bergslagen and surrounding areas. The study area extends from Naggen west of Sundsvall in the north to Hjortkvarn in the south, and from Grythyttan in the west to the island of Utö in the east (Fig. 1a, b).

In this study area, from now on called Bergslagen area or Bergslagen and surrounding areas, 14 subareas with Svecofennian sedimentary bedrock were selected in a first step for investigation. In each subarea, several suitable sampling sites were selected using bedrock maps of the Geological Survey of Sweden (SGU), the SGU bedrock observation database (swe: *halldb*) for rock properties, and the real estate map (swe: *fastighetskartan*) to ensure the accessibility of the sampling sites.

In total, 29 samples were collected at 28 different sample sites in twelve of the preliminary fourteen chosen subareas (Fig. 1a). In this selection, it is considered that the metamorphic grade should be relatively low, though there were made some exceptions in the Gävle and the Nykvarn–Mörkö area. In addition, the grain size was considered, and, which with the exception for the Grythyttan shale, has been fine sand or coarser.

Furthermore, map sheet descriptions and relevant literature have been utilized, especially to obtain information about the stratigraphic position within, and differences in stratigraphic positions between, certain areas. Sampling localities were selected to cover the largest possible range of the sedimentary sequences.

At each sampling site, separate samples for zircon U–Pb dating, whole rock lithogeochemical analysis and for preparation of thin sections were taken. Documentation of the sample sites were made according to the structure of the halldb-database of the SGU, and photographs were acquired from the samples and the sample sites.

The zircon U–Pb dating of the samples were carried out by Simon Hansen Serre & Tonny B. Thomsen at the Geological Survey of Denmark and Greenland (GEUS) by *Laser ablation inductively coupled plasma mass spectrometry* (LA-ICP-MS). Presentation of the results in tables and stacked diagrams was done by Tonny B. Thomsen.

ANALYTICAL METHODS: LASER ABLATION ICP-MS ANALYSIS

Zircon U-Pb geochronology was carried out on mineral separates embedded in epoxy mounts by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Geological Survey of Denmark and Greenland (GEUS). A NWR213 frequency-quintupled solid state Nd:YAG laser system from Elemental Scientific Lasers (ESI) mounted with a two-volume TV2 ablation cell was coupled to an ELEMENT 2 double-focusing single-collector magnetic sector-field ICPMS from Thermo-Fisher Scientific. The mass spectrometer was equipped with a Fassel type quartz torch shielded with a grounded Pt electrode and a quartz bonnet. Operating conditions and data acquisition parameters are listed in Table 1.

To ensure stable laser output energy, a laser warm-up time of at least 15 minutes were applied before operation, providing stable laser power and flat ablation craters by a "resonator-flat" laser beam. The mass spectrometer was run for at least one hour before analyses to stabilize the background signal. Prior to loading, samples and standards were carefully cleaned with ethanol to remove surface contamination. After insertion, the ablation cell was flushed with helium gas to minimize the gas blank level. The ablated material was swept by the helium carrier gas and mixed with argon gas c. 0.5 m before introduction into the plasma in the interface region of the mass spectrometer.

Just before the beginning of analysis, the ICP-MS was optimised at dry plasma conditions through continuous linear ablation of the GJ-1 zircon standard. The signal-to-noise ratio for

Table 1. LA-ICP-MS operating conditions and data acquisition parameters.

Laser system	**New Wave Research NWR213 solid state Nd:YAG laser with aperture imaging**
Laser wavelength	213 nm (Nd:YAG)
Laser mode	Q-switched (Nd:YAG)
Nominal pulse width	4 ns (Nd:YAG)
Repetition rate	10 Hz
Spot sizes (diameter)	20 or 25 µm
Incident pulse energy	0.05 mJ per pulse (at 25 µm beam size; 60%)
Energy density on sample	9.5-10.8 J/cm^2 (homogenized energy distribution)
Ablation cell	TV2 with custom sample holder
Ablation cell gas flow rates	850–920 ml/min He
Tubing for gas flow	Tygon S3 B44-3 and S-50 HL
Laser beam focus	Fixed at sample surface
ICP-MS	**Thermo-Fisher Scientific ELEMENT 2 double-focusing magnetic sector-field ICP-MS**
Interface cones	Ni sampler and skimmer cone
Detector type	single-collector discrete dynode electron multiplier
Detector mode	cross-calibrated pulse counting and analogue
Detector vacuum	10^{-7} mbar (during analysis)
Argon gas flow rates (l/min):	
Plasma	16
Auxiliary	0.85
Sample	0.940–0.995
RF power	1470 W
Lenses (V):	
Extraction	-2000
Focus	-1050 to -1075
X-Deflection	4.39
Y-Deflection	-3.41
Shape	111
SEM potential	2300 V
Data acquisition parameters	
Isotopes measured (sampling time in brackets)	^{202}Hg (10), Mass 204 (^{204}Hg + ^{204}Pb)(20), ^{206}Pb (10), ^{207}Pb (50), ^{208}Pb (10), ^{232}Th (10), ^{238}U (20)
Settling times	1 ms
Search and integration window	4%
Samples per peak	100
Aquisition mode	Time resolved analysis
Scan type	E-scan
Detection mode	Both
Integration type	Average
Mass resolution	300 (low resolution)
Oxide production rate	Tuned to ≤ 0.2% UO_2 ($^{254}UO_2/^{238}U$)
Analysis duration	30 s. blank, 30 s. ablation and 35 s. washout.
Data processing	
Software	Iolite vers. 2.5 (Hellstrom et al. 2008) including VizualAge DRS (Petrus & Kamber 2012)
External standardization	GJ-1 (with Harvard 91500 and Plesovice zircons for age control)
Internal standard isotope	^{238}U

the heavy mass range of interest (i.e. from ^{202}Hg to ^{238}U), emphasizing on ^{238}U and ^{206}Pb, was maximized, while at the same time opting for low element-oxide production level by minimising the $^{254}UO_2/^{238}U$ ratio. To minimize instrumental drift a standard-sample-standard analysis protocol was followed, bracketing eight sample analyses by three measurements of the standard GJ-1 zircon (Jackson et al. 2004). The standard zircons, Harvard 91500 (Wiedenbeck et al. 1995, 2004) and Plesovice (Slama et al. 2008) were inserted for quality control of the standard analyses, yielding an internal precision of <3% (2 S.E.) and an average age accuracy within 3% deviation from reference values.

Data were acquired from single spot analysis of 20 or 25 µm depending on the general grain sizes in the sample. Analyses were run with a nominal laser fluence of ~10 J/cm^2 and a repetition rate of 10 Hz. Total acquisition time for single analysis was c. 1.5 minutes, including 30 seconds background measurement followed by laser ablation for 30 seconds and washout for 35 seconds. Factory-supplied software was used for the acquisition of the transient data, obtained through automated running mode of pre-set analytical locations. Data reduction was performed off-line through the software Iolite v. 2.5 (Hellstrom et al. 2008, Paton et al. 2011), using the Iolite-integral VizualAge data reduction scheme (DRS) routine (Petrus & Kamber 2012), which includes a correction routine for down-hole isotopic fractionation (Paton et al. 2010), and provides routines for data that require correction for common Pb.

Spot analysis locations were selected on basis of the "best spot location", i.e. where there are a minimum number of inclusions, cracks or other impurities (optimally there are none), and preferably where zoning is controllable or visible (at least in 2D flat surface perspective). Also, other parameters as e.g. thickness of the grain that benefits optimal conditions for the analysis were considered.

Depending on the number of zircon analyses and the number of age populations that occur in a given rock sample, statistics then provide an estimate of the age proportions that (hopefully) are representative of the rock. There is always a possibility for some bias and variation, especially if there are many different input age populations.

The results of the analyses are presented in stacked diagrams for each sampling area. The diagrams show combined 1,500–3,500 Ma binned frequency histograms and probability density distribution plots (PDP) as described by Thomsen et al. (2006). They also show calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using coupled $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ age pairs. A fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% were used.

SAMPLING AREAS, ROCK TYPES AND RESULTS FROM ZIRCON ANALYSES

Most of the sample sites are situated in the Bergslagen lithotectonic unit (Stephens & Jansson 2020), exceptions are those in the Naggen area in the north (Fig. 1a). The sites in the Naggen area are lying just north of the border between the Ljusdal and the Bothnia-Skellefteå lithotectonic units (Stephens & Bergman 2020) and the sites at Grythyttan are lying in the Bergslagen lithotectonic unit, but close to the border to the upper compartment of the Eastern segment of the Sveconorwegian orogen (Stephens et al. 2020).

Description of the sampled rocks in this chapter is mainly based on field observations. Determination of grain sizes were obtained from thin section, when available. Relevant information from previous mapping and literature was also used. A compilation of data for all samples is given in Table 2.

Table 2. Sample list in order of description below with sample ID, analysis type (At), sample name, rock type, sampling area and stratigraphic unit. Analysis type: Z = zircon analysis, C = geochemical analysis, C* = geochemical analysis not used in the plots of the geochemical diagrams, T = thin section. Coordinates are given in the reference system SWEREF99 TM.

No	Sample	At	Sample name	N	E	Rock type	Area	Stratigraphic unit
1	KBK170016A	ZC	Nylandet västra	6907292	538845	Arkosic arenite	Naggen	Naggen group
2	KBK170017A	ZCT	Nylandet östra	6906821	539532	Arkosic arenite	Naggen	Naggen group
3	KBK170011A	ZCT	Värmlandsströmmen	6843218	497781	Quartz arenite	Los–Hamra	Los formation
4	KBK170012A	ZCT	Karlsberg	6838321	512142	Quartz arenite	Los–Hamra	Los formation
5	KBK170013A	ZCT	Vässmasmägg	6824853	491770	Quartzite	Los–Hamra	Los formation
6	KBK170015A	ZCT	Skallskog	6727565	489181	Arenite	Leksand–Falun	Leksand formation
7	KBK170014A	ZCT	Balkbodarna	6724615	491642	Arenite	Leksand–Falun	Leksand formation
8	KBK170010A	ZCT	Fänrikbo	6744231	524435	Dense quartzite	Leksand–Falun	Ärtknubben formation
9	KBK170009A	ZC	Fjällgrycksbo	6740962	529193	Dense quartzite	Leksand–Falun	Ärtknubben formation
10	KBK170019A	ZC	Eskörönningen	6741910	624490	Gneissose quartzite–quartz arenite	Gävle	
11	KBK170018A	ZCT	Persbacka	6733040	618922	Gneissose quartzite–quartz arenite	Gävle	
12	KBK170021A	ZCT	Udden	6559820	640941	Paragneiss	Nykvarn–Mörkö	
13	KBK170020A	CT	Barknåre	6710300	660166	Arenite to quartz arenite	Skärplinge	
14	KBK170008A	ZC	Lindbastmora	6689220	502933	Quartz arenite	Grangärde–Ludvika	
15	KBK170006A	CT	Södra Gåstjärnen	6678152	493850	Greywacke	Grangärde–Ludvika	
16	KBK170007A	C*	Håksberg mine	6673448	511177	Intermediate volcaniclastic rock	Grangärde–Ludvika	
17	KBK170002A	C*T	Solfallet	6661770	548370	Mafic volcanic rock	Norberg–Fagersta	Igeltjärn formation
18	KBK170001A	ZCT	Nötbo-Broddbo	6652242	587058	Quartz arenite	Sala–Tillberga	Larsbo formation
19	KBK170003A	ZC	Lill-Sången	6630602	470258	Arenite	Grythyttan	Torrvarpen formation
20	KBK170004A	ZCT	Torrvarpsund	6616730	473282	Slate	Grythyttan	Torrvarpen formation
21	KBK170005A	ZCT	Yxhammarshöjden	6609763	473155	Quartzite	Grythyttan	Torrvarpen formation
22	KBK170022A	ZCT	Grissjötorp	6513731	507471	Greywacke	Närkesberg–Hjortkvarn	Vintergölen formation
23	KBK170023A	ZC	Siggetorp–Laggarfall	6530485	515673	Layered arkosic arenite	Närkesberg–Hjortkvarn	Närkesberg formation
24	KBK170023B	ZCT	Siggetorp–Laggarfall	6530485	515673	Massive arkosic arenite	Närkesberg–Hjortkvarn	Närkesberg formation
25	KBK170024A	ZCT	Linnerud–Stensäter	6529500	516869	Arenite	Närkesberg–Hjortkvarn	Närkesberg formation
26	KBK170025A	C	Ångsågen	6530264	519730	Arenite	Närkesberg–Hjortkvarn	Närkesberg formation
27	KBK170026A	ZCT	Lilla Fågelhult	6527322	522829	Arenite	Närkesberg–Hjortkvarn	Närkesberg formation
28	KBK170028A	ZCT	Rävstavik västra	6540491	691909	Greywacke	Utö	
29	KBK170027A	ZC	Rävstavik östra	6540387	692066	Arenite	Utö	

Of the collected 29 samples, three had no zircons and in two the number of analysed grains (either 10 or 20 with each 10 analysed spots) was too low for a statistic approach. Consequently, these five samples were disregarded in the provenance analyses. However, they are used in the chemical diagrams.

On the remaining 24 samples, 2,203 zircon U–Pb analyses were acquired, of which 493 were corrected for common lead content. Of the total number of analyses, 2,186 analyses place within the 90–110% concordance interval relative to the Concordia (100%) on a Wetherill (1956) diagram, which was used for interpretation in this study. From these 2,186 analyses, four groups of percentage ranges were selected to classify the content of every 50 million years (50 m.y.) interval and in that way to characterise the results for every particular sample. The percentage ranges, < 2%, >= 2% – < 8%, >= 8% – < 18% and >= 18% were defined using a fracture method (singularity analysis method; frequency anomalies) as described in Zhu & Cheng (2019). A summary of the analyses is given in Appendix 1.

Naggen

The sampled rocktype in the Naggen area in the north has been referred to as Naggen arkose by Delin & Aaro (1994). It occurs in an open synclinal structure on top of surrounding greywackes, i.e., it forms the uppermost part of the sedimentary sequence in the Naggen area. Lundegårdh (1960) described the rocks in the Naggen area under the name Naggen group as ruditic and arenitic with commonly well-preserved primary sedimentary structures. The degree of metamorphic alteration in the sedimentary rocks of the Naggen area increases strongly towards the east where migmatites prevail (Lundegårdh 1967, Albrecht 2011). According to Lundegårdh (1960, 1967) these rocks were formed by frost weathering in a cool climate with subsequent deposition by strong currents such as rivers. Lundqvist (1987) and Lundqvist et al. (1990) considered that the formation of the Naggen arkose, and other arenites and arkoses in southern Norrland, required an Archaean or Proterozoic granitic basement in the southwest of the Naggen area to be exposed to erosion. However, such a basement could not be identified in the region.

In the Naggen area, two samples (Nylandet västra and Nylandet östra) were taken of a massive, recrystallised, light grey-brown and moderately sorted arkosic arenite with a grain size of silt to medium sand (Fig. 2). Both samples represent approximately the same stratigraphic level. Further sampling of different stratigraphic horizons was originally planned, but was, due to lack of time and ongoing moose hunting in the area, not carried out.

At Nylandet västra, 49 zircon U–Pb dates were obtained, all are within the 90–110% concordia interval, and none required correction for common lead. The U/Th ratios vary between 1.6 and 37.0, and 49% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). More than 20% of the zircons show dates that fall in the age interval 1,850–1,899 Ma with a maximum probability peak at 1,871 Ma and about 30% in the interval 1,950–1,999 Ma with a maximum at 1,980 Ma. About 8% of the analysed zircons have dates in the intervals 1,900–1,949, 2,000–2,049 and 2,650–2,699 Ma each. The youngest zircon was dated to 1,841 Ma and the oldest to 2,895 Ma. About 16.3% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,678 Ma (Fig. 3).

At Nylandet östra, 124 zircon U–Pb dates were obtained, all are within the 90–110% concordia interval, and only two analyses required correction for common lead. The U/Th ratios vary between 1.2 and 34.0 with a single outlier at 434.0, and 60% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). More than 20%

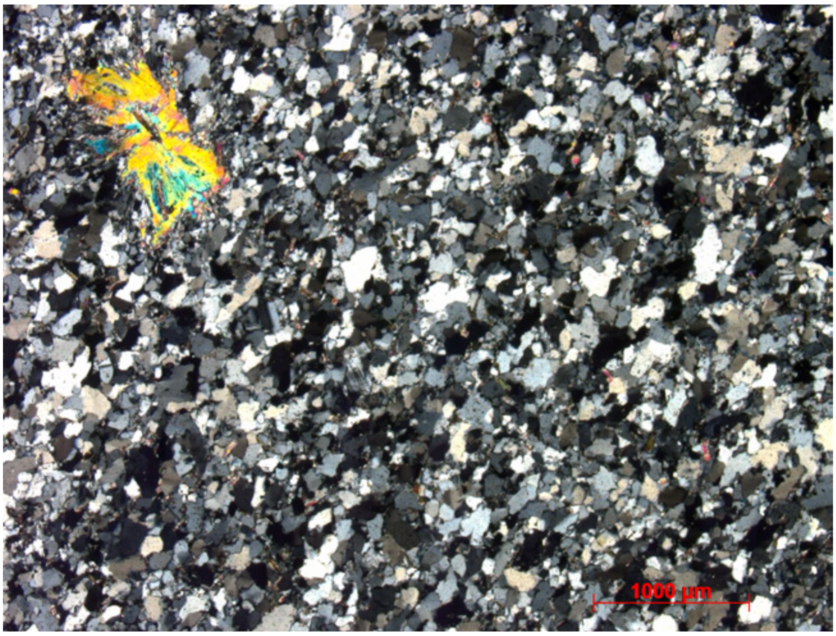


Figure 2. Moderately sorted arkosic arenite from Nylandet östra, about 12 km west of the village Naggen. Crossed nicols. (6906821/ 539532). Photomicrograph: Benno Kathol.

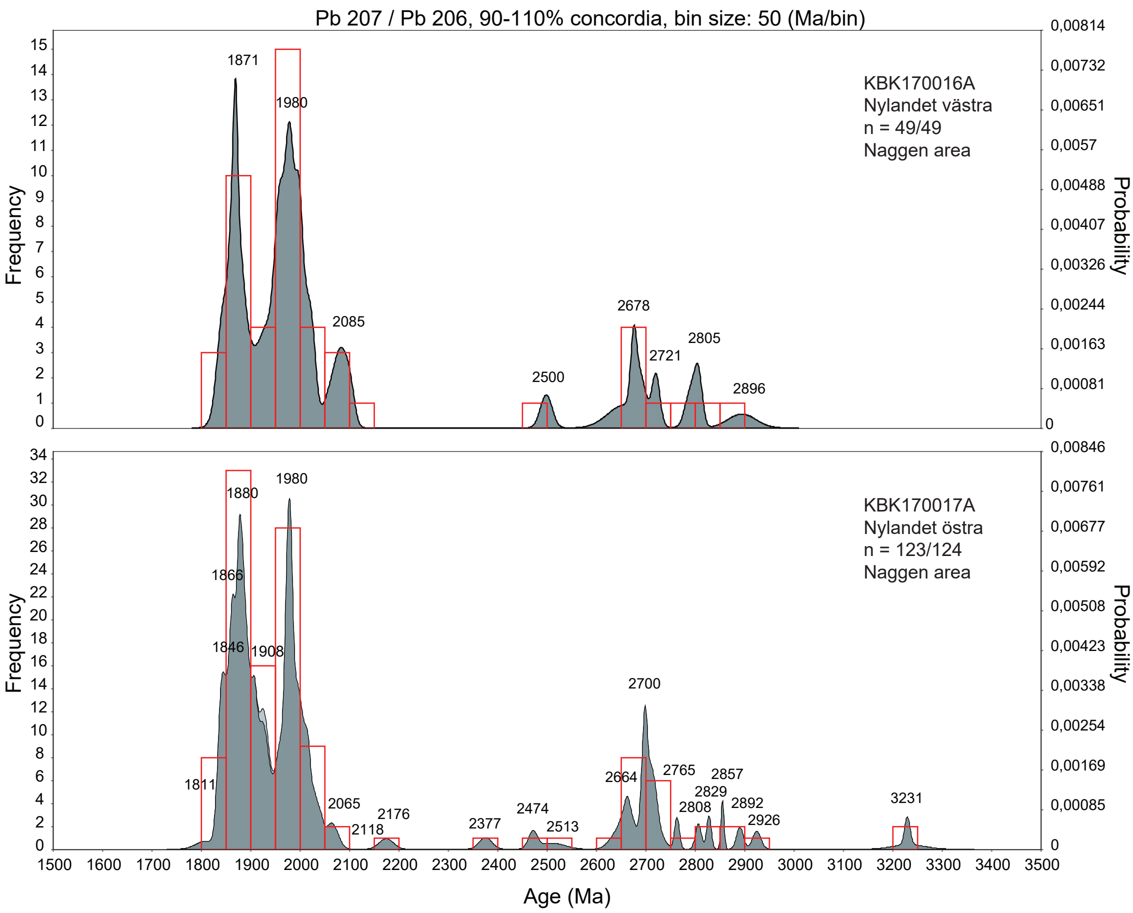


Figure 3. Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Naggen area with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./ bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.

of the zircons have dates that fall in the age intervals 1,850–1,899 Ma with a maximum probability peak at 1,880 Ma, and 1,950–1,999 Ma with a maximum peak at 1,980 Ma, respectively. Almost 14% of the zircons have dates in the interval 1,900–1,949 Ma. The youngest zircon was dated to 1,808 Ma and the oldest to 3,233 Ma. About 19.4% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,700 Ma (Fig. 3).

The results from the two samples in the Naggen area support that parts of the, by Lundqvist et al. (1990) postulated, granitic Archaean or Proterozoic basement exposed in the southwest of the Naggen area are of Archaean age. However, the samples from the Naggen area show a quartzose sedimentary provenance signature (see Fig. 38 in section *Lithogeochemical analyses*), which could be due to erosion and resedimentation of the Archaean basement rocks, predating the final emplacement in the Naggen area.

Los–Hamra

The sedimentary rocks in the Los–Hamra area occur in a syncline with argillitic rocks and layers of arenite in the lowermost part, overlain by quartzite and quartz arenite followed by rhyolite and basalt at the top in the core of the syncline (Lundqvist 1968, 1987; Delin & Aaro 2000). This supracrustal sequence is named the *Los Formation* by Lundqvist (1968). The rhyolite was dated at Ryggskog, about 3 km northwest of Los and yielded an age of 1,862 ± 5 Ma (Delin & Persson 1999) giving a minimum age for the sedimentary sequence in the area of Värmlandsströmmen. The metamorphic grade in the argillitic rocks varies from greenschist facies to upper amphibolite facies. The rocks are deformed to gneisses, and partial melting formed metatexitic structures in these gneisses.

A sample of a layered, light brownish grey, poorly sorted quartz arenite with grain size very fine to coarse sand was collected in the vicinity of the Värmlandsströmmen rapids in the Voxnan river (Fig. 4a, b). The sample site is located in an arenitic intercalation in the dominantly argillitic part of the sedimentary sequence. At this locality, the arenite is overlying the lowermost part of the argillite sequence. This implies that the sample originates from the lower to middle part of the above-mentioned syncline, that is, the lower to middle part of the Los formation. Close to this locality, Claesson et al. (1993) collected a sample for a provenance U–Pb detrital zircon study. The zircon dates in their sample are in the age range 1.89–1.82 Ga and no Archaean zircons were observed.

The second sample in the Los–Hamra area was collected at Karlsberg south of Los from a layered grey quartz arenite with a grain size of fine to coarse sand and showing muscovite and sericite on the bedding planes (Fig. 5a, b). This rock belongs to the unit of quartzite and quartz arenite which is overlain by rhyolite and consequently occurs in the uppermost part of the sedimentary sequence of the Los formation.

The third sample, a massive, grey, poorly sorted quartzite with grain sizes between silt and fine sand (Fig. 6a, b) was collected close to Vässmasmägg at the Inlandsvägen road. The sample site is located in an occurrence of quartz arenite and arenite which lies between Noppikoski and Tandsjöborg. This occurrence is overlain by a locally eutaxitic rhyolite (Lundqvist 1987), which has been dated to 1,867 ± 9 Ma at Noppikoski by Welin (1987), and which yields a minimum age for the sampled quartzite from Vässmasmägg. Together with the dating at Ryggskog (Delin & Persson 1999), this age places the rhyolite in the uppermost part of the Los formation at c. 1.86 Ga and can therefore also be considered as a minimum age for the other two sampled rocks of the Los–Hamra area.

Figure 4a. Layered quartz arenite from Värmlandsströmmen, about 7.5 km north of Hamra. (6843218/497781). Photo: Benno Kathol.

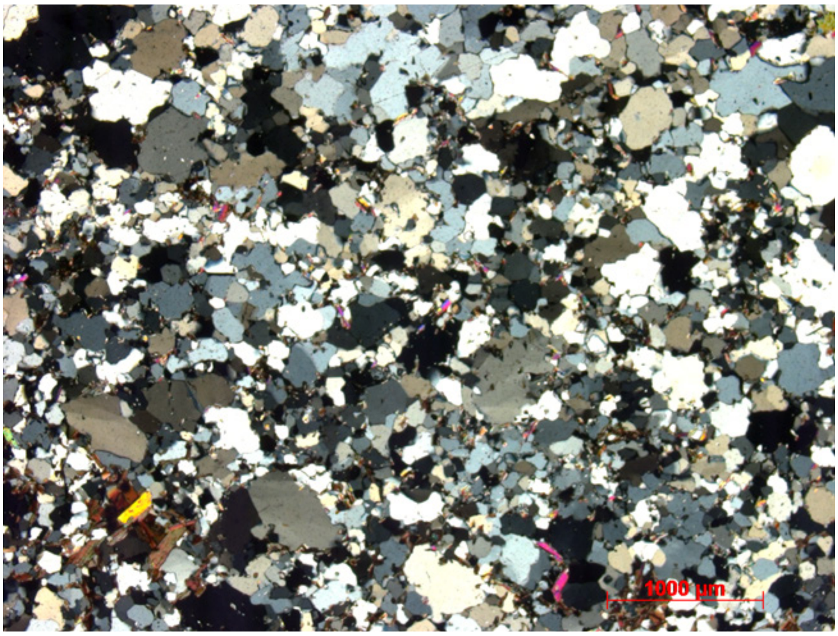


Figure 4b. Poorly sorted quartz arenite from Värmlandsströmmen, about 7.5 km north of Hamra. Crossed nicols. (6843218/97781). Microphotograph: Benno Kathol.

At Värmlandsströmmen, 116 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, 51 analyses required correction for common lead. The U/Th ratios vary between 1.5 and 42.8, and 55% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 43% of the zircons show dates that fall in the age interval 1,850–1,899 Ma with a maximum probability peak at 1,879 Ma. About 11 and 16% of the analysed zircons show dates in the intervals 1,900–1,949 and 1,950–1,999 Ma, with peaks at 1,931 and 1,981 Ma, respectively. The youngest zircon was dated to 1,831 Ma and the oldest to 2,963 Ma. About 11.2% of the zircons are of Archaean age, and the Archaean zircons show a maximum at around 2,688 Ma (Fig. 7).

Figure 5a. Layered quartz arenite from Karlsberg, about 6.5 km south-south-east of Los. (6838321/ 512142). Photo: Benno Kathol.

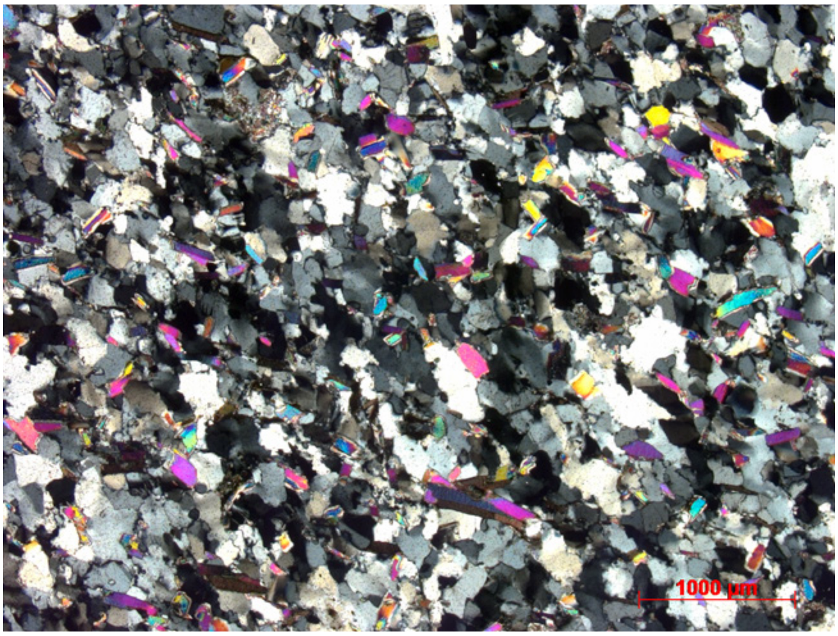


Figure 5b. Muscovite- and sericite-bearing quartz arenite from Karlsberg, about 6.5 km south-south-east of Los. Crossed nicols. (6838321/ 512142). Micro-photograph: Benno Kathol.

At Karlsberg, 116 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, 34 analyses required correction for common lead. The U/Th ratios vary between 1.0 and 45.5, and 55% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 34% of the analysed zircons have dates in the age interval 1,850–1,899 Ma and about 21% in the interval 1,900–1,949 Ma with maximum probability peaks at 1,870 and 1,940 Ma, respectively. Almost 13% of the zircons show dates in the interval 1,950–1,999 Ma. The youngest zircon was dated to 1,793 Ma and the oldest to 3,099 Ma. About 19.0% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,721 Ma (Fig. 7).

Figure 6a. Massive quartzite from Vässmasmägg, about 7 km north of Noppikoski. (6824853/ 491770). Photo: Benno Kathol.

Figure 6b. Poorly sorted quartzite from Vässmasmägg, about 7 km north of Noppikoski. (6824853/ 491770). Microphotograph: Benno Kathol.

At Vässmasmägg, 115 zircon U–Pb dates were obtained, all are within the 90–110% concordia interval and 33 analyses required correction for common lead. The U/Th ratios vary between 1.2 and 34.1, and 58% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). Almost 30% of the analysed zircons show dates that fall in the age interval 1,850–1,899 Ma with a maximum probability peak at 1,882 Ma. About 11, 17 and 15%, respectively of the zircons have dates in the intervals 1,900–1,949, 1,950–1,999 and 2,000–2,049 Ma, with peaks at 1,943, 1,993 and 2,026 Ma. The youngest zircon was dated to 1,820 Ma and the oldest to 2,854 Ma. About 13.9% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,686 Ma (Fig. 7).

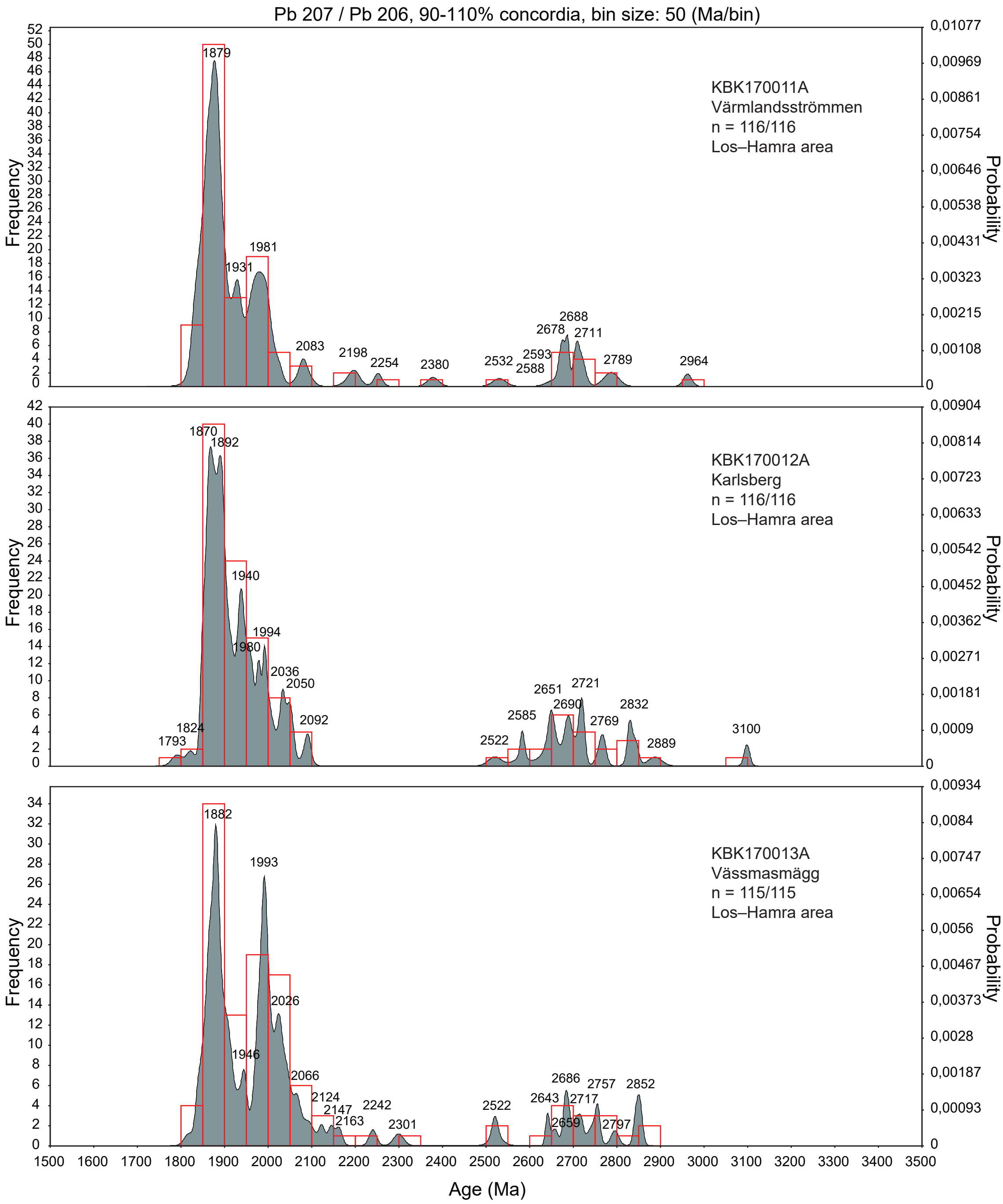


Figure 7. Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Los–Hamra area with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.

The signature of the Proterozoic zircons from the Los–Hamra area with dominating peaks at 1,879, 1,870 and 1,882 Ma (Fig. 7) are consistent with the age range 1.89–1.82 Ga, obtained by Claesson et al. (1993) at Värmlandsströmmen. However, in all three samples from the Los–Hamra area, considerable amounts of Archaean zircons occur, which contrasts with the result of Claesson et al. (1993). It is speculated if these zircons can be assigned to the same Archaean basement as described for the arkoses from Naggen. Also, in the Los–Hamra area, the sampled rocks show a quartzose sedimentary provenance signature (Fig. 38), which could be due to erosion and resedimentation of Archaean basement rocks, predating the final emplacement in the area.

Dates from Värmlandsströmmen younger than the minimum age of 1,862 Ma, provided by the rhyolite dating at Ryggskog (Delin & Persson 1999) show a mean U/Th ratio of 9.5 (n=19) which is somewhat higher than the mean U/Th ratio of 5.6 (n=97) for the analyses showing ages above 1,862 Ma. At Karlsberg, the U/Th ratios have a mean value of 5.4 (n=11) for the analyses below 1,862 Ma and of 5.9 (n=105) for those above. The confining age at Vässmasmägg is given by the age of 1,867 ± 9 Ma of the rhyolite from Noppikoski (Welin 1987). Here, there are mean U/Th values of 11.2 (n=13) for analyses below 1,867 Ma and of 5.0 (n=102) for those above.

These mean U/Th ratio values might indicate metamorphic influence of the zircons with ages below the minimum age in the samples from Värmlandsströmmen and especially from Vässmasmägg. In the sample from Karlsberg, no such difference is indicated by the mean values of the zircon populations below and above 1,862 Ma.

Leksand–Falun

Southwest of Leksand, there is a sequence of quartz arenite with intercalations of conglomerate which by Kresten & Aaro (1987a) has been referred to as the Leksand formation, and which, according to the authors, overlays the volcanic sequence in the Leksand–Falun area. At Skallskog, in the northwestern, upper part of the sedimentary sequence of the Leksand formation, a sample was collected from a layered, recrystallised, dark grey, poorly sorted arenite with a grain size of silt to medium sand (Fig. 8a, b). Another sample was taken in the eastern, lower part of the Leksand formation, south of Balkbodarna, in a massive, recrystallised, grey, moderately sorted quartz arenite with a grain size of silt to coarse sand (Fig. 9a, b).

A sedimentary sequence north of Bjursås has been divided by Kresten & Aaro (1987b) into greywackes and schists of the Marnäs formation and the overlying Ärtknubben formation, mainly consisting of quartzites. Both formations occur stratigraphically below the volcanic rocks of the Leksand–Falun area. However, it must be mentioned that the boundary between the volcanic and sedimentary rocks is indicated on the map as a normal fault with the volcanic rocks in the downthrown block. At each of the localities Fänrikbo and Fjällgrycksbo, north of Falun, a sample of a massive recrystallised, brittle, light grey, dense or fine-grained quartzite was collected (Fig. 10a, b), containing disseminated sulphide minerals. At Fjällgrycksbo there are also intrusions of massive, medium- to coarse-grained, red granite in the quartzite. The quartzite belongs to the Ärtknubben formation, thus representing the uppermost part of the sedimentary sequence that is overlain by the volcanic sequence in this area (Kresten & Aaro 1987b).

At Skallskog, 108 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, 11 analyses required correction for common lead. The U/Th ratios vary between 0.8 and 83.0, and 55% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 31% of the analysed zircons have dates that fall in the age interval 1,850–1,899 Ma with a maximum probability peak at 1,879 Ma. About 18, 12 and 11% of the analysed zircons have dates in the intervals 1,800–1,849, 1,900–1,949 and 1,950–1,999 Ma, with peaks at 1,837 Ma in the first and 1,983 Ma in the last interval. The youngest zircon was dated to 1,735 Ma and the oldest to 3,277 Ma. About 13.0% of the zircons are of Archaean age, and the Archaean zircons show maxima at 2,636 and 2,740 Ma, respectively (Fig. 11).

Figure 8a. Layered arenite from Skallskog, about 12.5 km west-southwest of Leksand (6727565/ 489181). Photo: Benno Kathol.

Figure 8b. Poorly sorted arenite from Skallskog, about 12.5 km west-southwest of Leksand (6727565/ 489181). Crossed nicols. Photo: Benno Kathol.

At Balkbodarna, 81 zircon U–Pb dates were obtained, all dates occur within the 90–110% concordia interval, and 10 analyses required correction for common lead. The U/Th ratios vary between 1.5 and 52.0 with a single outlier at 196.9, and 41% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 47% of the analysed zircons show dates in the age interval 1,850–1,899 Ma with a maximum probability peak at 1,882 Ma. About 17 and 12% of the analysed zircons have dates in the intervals 1,800–1,849 and 1,900–1,949 Ma, with a peak at 1,943 Ma in the latter interval. The youngest zircon was dated to 1,764 Ma and the oldest to 2,771 Ma. There are only three zircons are of Archaean age (2.5%), and the they show a maximum at 2,729 Ma (Fig. 11).

At Fänrikbo, 114 zircon U–Pb dates were obtained, and all dates occur within the 90–110% concordia interval, 21 analyses required correction for common lead. The U/Th ratios vary

Figure 9a. Massive quartz arenite from Balkbodarna, about 12 m southwest of Leksand (6724615/ 491642). Photo: Benno Kathol.

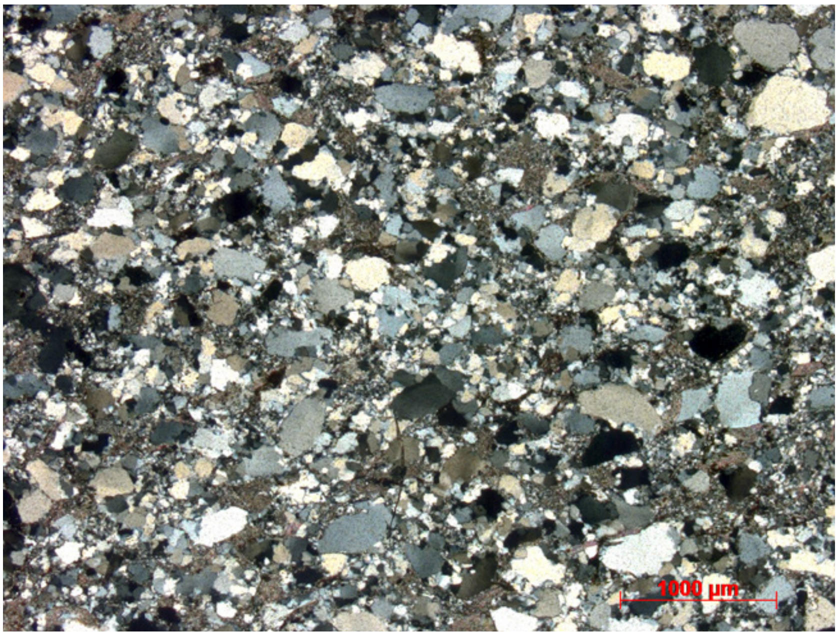


Figure 9b. Moderately sorted quartz arenite from Balkbodarna, about 12 m southwest of Leksand (6724615/ 491642). Crossed nicols. Photo: Benno Kathol.

between 1.1 and 58.1, and 47% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 19% of the analysed zircons show dates that fall in the age interval 1,800–1,849 Ma and about 35% in the interval 1,850–1,899 Ma with maximum probability peaks at 1,805 and 1,865 Ma, respectively. About 11% of the analysed zircons have dates in the interval 1,900–1,949 Ma. The youngest zircon was dated to 1,678 Ma and the oldest to 3,217 Ma. About 14.0% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,624 Ma (Fig. 11).

At Fjällgrycksbo, 108 zircon U–Pb dates were obtained, and 103 of them are within the 90–110% concordia interval, 46 analyses required correction for common lead. The U/Th ratios vary between 1.2 and 74.0, and 26% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 35% of the analysed zircons show dates in the age interval

1,800–1,849 Ma and about 21% in the interval 1,850–1,899 Ma with maximum probability peaks at 1,842 and 1,867 Ma, respectively. About 17% of the zircons have dates in the interval 1,900–1,949 Ma. The youngest zircon was dated to 1,772 Ma and the oldest to 2,967 Ma. About 8.7% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,696 Ma (Fig. 11).

Figure 10a. Massive dense quartzite from Fänrikbo, about 10 km north of Bjursås (6744231/524435). Photo: Benno Kathol.

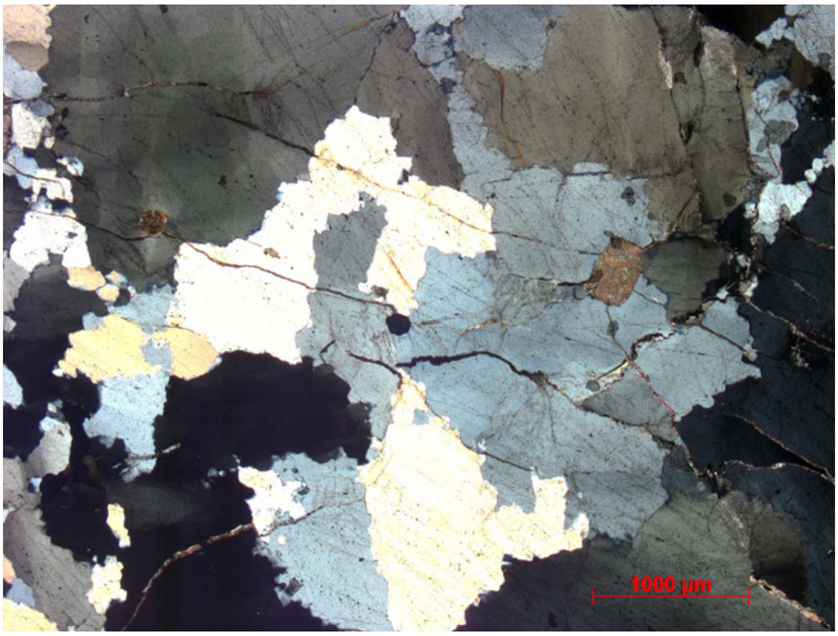
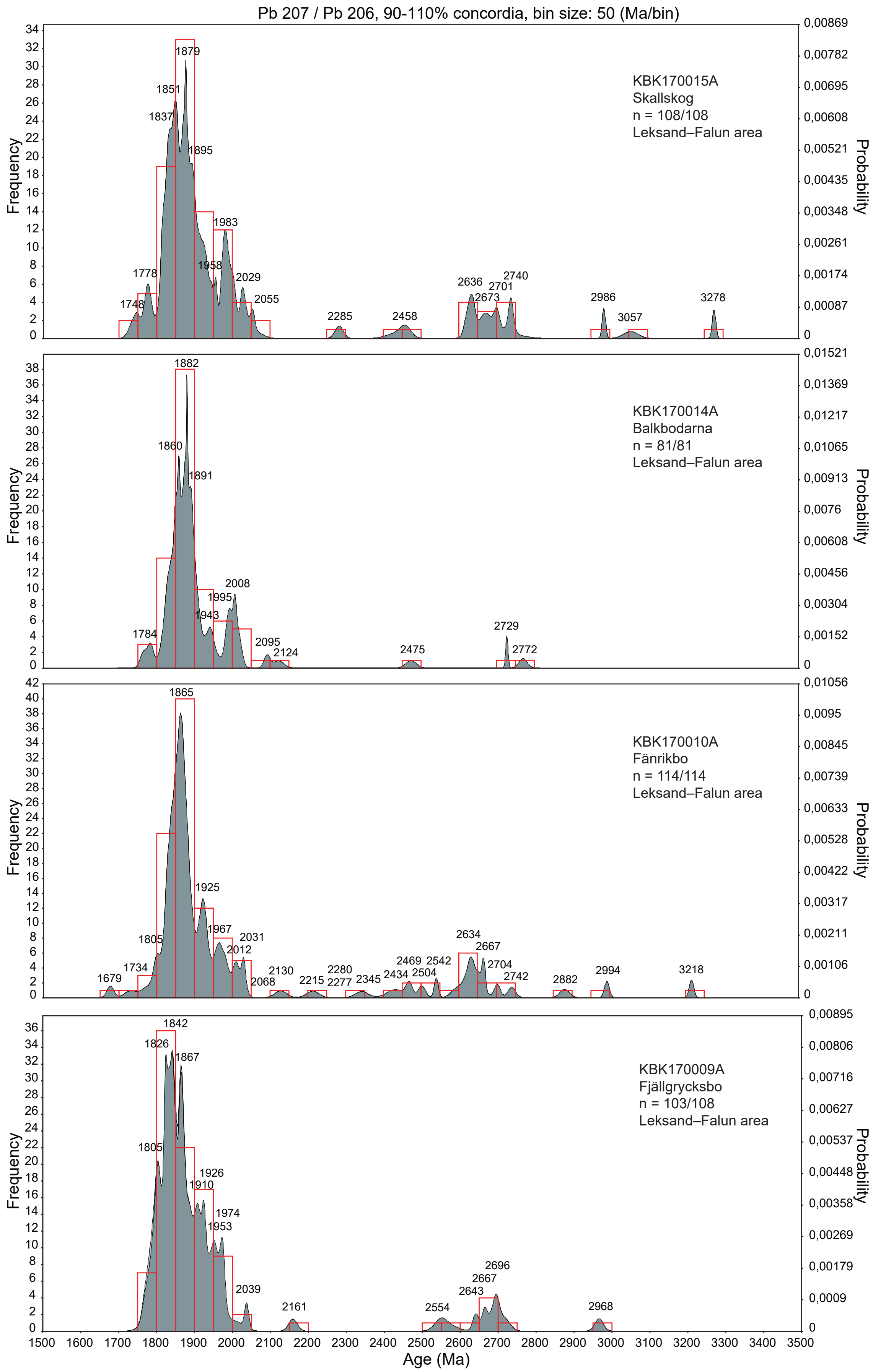


Figure 10b. Massive dense quartzite from Fänrikbo, about 10 km north of Bjursås (6744231/524435). Crossed nicols. Microphotograph: Benno Kathol.

▶ **Figure 11.** Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Leksand–Falun area with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.


Pb 207 / Pb 206, 90-110% concordia, bin size: 50 (Ma/bin)
KBK170015A
Skallskog
n = 108/108
Leksand–Falun area
KBK170014A
Balkbodarna
n = 81/81
Leksand–Falun area
KBK170010A
Fänrikbo
n = 114/114
Leksand–Falun area
KBK170009A
Fjällgrycksbo
n = 103/108
Leksand–Falun area
Frequency
Probability
Age (Ma)

There is no proof for different time intervals for the deposition of the Leksand and the Ärtknubben formations (see Fig. 31a in section *Summary and interpretation of all analysed samples*). Regarding the classified 50 m.y. intervals in figure 31b in section *Summary and interpretation of all analysed samples*, the samples from both formations show high percentage of dates in the age interval 1,850–1,899 Ma. The two samples from the Ärtknubben formation, underlying the volcanic sequence, also show a high percentage of dates in the interval 1,800–1,849 Ma, which is slightly different for the samples from the overlying Leksand formation. The latter have only one maximum percentage interval each in the time span 1,850–1,899 Ma, but percentages of almost 18% in the interval 1,800–1,849 Ma (see Fig. 31b in section *Summary and interpretation of all analysed samples*).

No radiometric dating of the volcanic rock sequences in contact with either the Leksand formation or the Marnäs and Ärtknubben formations, which could directly be used as maximum or minimum age, is available. However, a rhyolite from an isolated occurrence of volcanic rocks around Falun (Falun inlier) in the southeastern part of the Leksand–Falun area has been dated at 1,894 ± 3 Ma by Kampmann et al. (2016). This figure could possibly be used to separate the Leksand and Ärtknubben formations in time but is has not been taken into consideration in figure 31a in section *Summary and interpretation of all analysed samples*, because the Falun inlier is not in direct contact to either formation. But it can be stated that the two samples from the underlying Ärtknubben formation, show higher mean U/Pb ratios for analyses below 1,894 Ma (7.9, n=64 for Fänrikbo and especially 13.7, n=65 for Fjällgrycksbo), than for analyses above 1,894 Ma (6.1, n=50 for Fänrikbo and 7.0, n=38 for Fjällgrycksbo). This probably indicates that the lower ages, if taking 1,894 Ma as a minimum age, are due to younger metamorphic events.

However, even in the two samples from the overlying Leksand formation, where 1,894 Ma could be considered as a maximum age for the lowermost part of the sequence, more than half of the zircons have dates younger than 1,894 Ma. These zircons also have lower mean U/Th ratios (6.8, n=50 for Balkbodarna and 6.9, n=56 for Skallskog) than those with dates above 1,894 Ma (14.1, n=38 for Balkbodarna and 8.6, n=52 for Skallskog), which excludes metamorphic influence as the only explanation for the high amount of young zircons. The sample site at Balkbodarna lies in the middle and that at Skallskog in the upper, youngest part of the Leksand formation. These stratigraphic positions would allow input of zircon material from rocks younger than 1,894 Ma. That scenario would indicate that the deposition of the sedimentary Leksand formation prevailed over a longer time.

Summing up the signatures of the zircon analyses of the Leksand–Falun area, and considering the stratigraphic positions of the Leksand and the Ärtknubben formations according to Kresten & Aaro (1987b), the former overlying the volcanic sequence in the area and the latter on top of the underlying sedimentary rocks, it can be concluded that the time span for the deposition of the entire volcanic sequence must have been very short. This is consistent with the results from Kampmann et al. (2016), who postulate a time span of less than 10 Ma for the deposition of the entire volcanic sequence in the Falun area.

If this short time span cannot be accepted, the stratigraphic scheme of Kresten & Aaro (1987b) or the role of the normal fault at the boundary between the Marnäs and Ärtknubben formations on one hand and the overlying volcanic rocks on the other must be reinvestigated.

A low amount of Archaean zircons in the sample from Balkbodarna in the middle part of the Leksand formation, compared to an amount of 13% Archaean zircons in the Skallskog sample from the upper part of the formation, might indicate variable exposure of rocks of different ages in the provenance area during the depostion of the Leksand formation (Figs. 11, 35b in section *Archaean zircons*).

Gävle and Nykvarn–Mörkö

Both sample localities in the Gävle area occur within a rock sequence that has been marked as veined and locally migmatitic metagreywacke and meta-argillite on the bedrock map by Bergman et al. (2005). A minimum age for the metasedimentary sequence in the Gävle area is provided by the dating of an intrusive metagranodiorite, which west of Engesberg gave an age of 1,865 ± 14 Ma (Bergman et al. 2005). The Persbacka sampling locality is situated about 3.8 km southwest, and that of Eskörönningen about 7.5 km north-northeast of the dating locality.

South of Eskörönningen, northeast of Gävle, a foliated, gneissose and veined, dark grey quartzite to quartz arenite has been sampled. The rock is recrystallised and the observed grain size of fine to medium sand is not interpreted as the primary grain size. It contains garnet and up to 1 mm sized biotite flakes.

The Persbacka sampling site is located at the northern end of a 250 m long road cut of the old E4 north of Gävle. The rock is a foliated, gneissose and veined, grey quartzite to quartz arenite. The grain size is medium to very coarse sand which due to recrystallisation probably not is the original size. The rock contains up to 1 cm size garnets (Fig. 12a, b).

The sampling area Nykvarn–Mörkö is located in the western part of a larger area with sedimentary rocks in southeastern Bergslagen, which, with the exception of the Gävle sampling area, exhibit signs of higher metamorphic grade than those of the other areas described in this study. The sedimentary rocks of the Nykvarn–Mörkö area are altered to paragneisses and metatexites. At Udden, southeast of Nykvarn, a sample was collected of a foliated, recrystallised, dark grey, unveined paragneiss which consists of about 50% of quartz and 50% of biotite (Fig. 13a, b). The quartz grains have a grain size of fine to medium sand and the biotite flakes have lengths up to three millimetres. However, it is uncertain whether these are original grain sizes or if the rock is recrystallised.

At Eskörönningen, 94 zircon U–Pb dates were obtained, and 93 dates are within the 90–110% concordia interval, 24 analyses required correction for common lead. The U/Th ratios vary between 3.2 and 163.0 with a single outlier at 740.0, and only 10% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 30% of the analysed zircons have dates that fall in the age interval 1,750–1,799 Ma, about 29% in the interval 1,800–1,849 Ma and 23% in the 1,850–1,899 Ma interval. Maximum probability peaks lie at 1,756, 1,819 and 1,895 Ma. About 17% of the zircons have dates in the interval 1,700–1,749 Ma, with a peak at 1,733 Ma. The youngest 'concordant' zircon, also youngest in this this study, is dated to 1,679 Ma and the oldest to 1,895 Ma. Archaean zircons have not been found in this sample (Fig. 14).

At Persbacka, 115 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, 35 analyses required correction for common lead. The U/Th ratios vary between 1.7 and 310.0 with a well-balanced distribution even of the values above 100, and 17% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 18% of the analysed zircons have dates that fall in the age interval 1,750–1,799 Ma, about 34% in the interval 1,800–1,849 Ma and 23% in the 1,850–1,899 Ma interval. Maximum probability peaks occur at 1,783, 1,822 and 1,887 Ma. Age intervals with 8.00 to 17.99% of the analysed zircons have not been determined. The youngest 'concordant' zircon is dated to 1,769 Ma and the oldest to 2,810 Ma. Only five Archaean zircons have been observed which is 4.3% of the total amount of zircons and the analysed dates occur quite equally distributed in the 50 m.y. intervals between 2,500 and 2,849 Ma (Fig. 14).

At Udden, only 19 zircon U–Pb dates were obtained which possibly is a too low number for a reliable statistical approach. The zircon dates are within the 90–110% concordia interval, none

Figure 12a. Gneissose quartz arenite from a road cut at the old E4 road, east of Persbacka, about 5 km north-northeast of Gävle (6733040/618922). Photo: Benno Kathol.

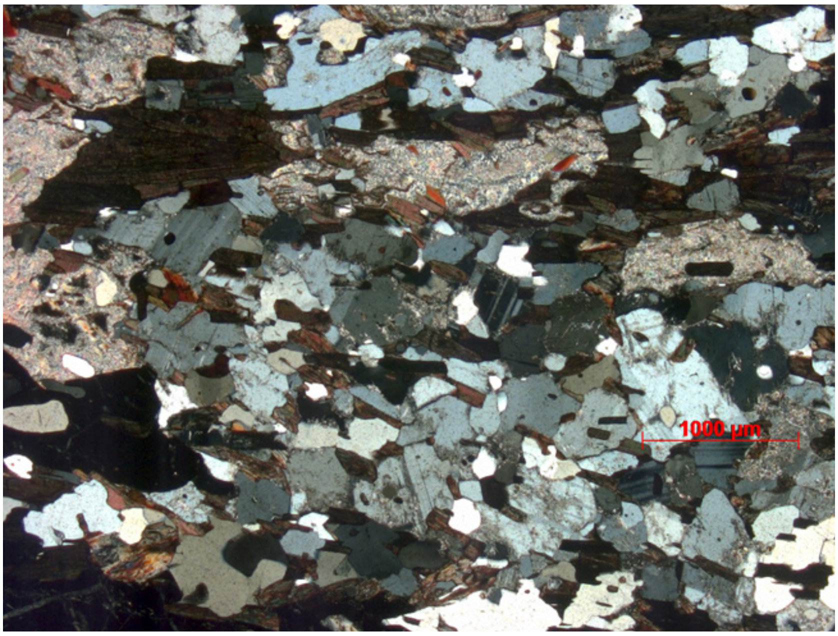


Figure 12b. Gneissose quartz arenite from a road cut at the old E4 road, east of Persbacka, about 5 km north-northeast of Gävle (6733040/618922). Crossed nicols. Microphotograph: Benno Kathol.

required correction for common lead. The U/Th ratios vary between 1.8 and 31.1, and 42% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 21% of the zircons have dates that fall in the age intervals 1,850–1,899 and 1,950–1,999 Ma each. Associated maximum probability peaks lie at 1,896 and 1,972 Ma respectively. Almost 16% of the zircons have dates in the interval 2,000–2,049, c. 11% each fall in the intervals 1,800–1,849, 1,900–1,049 and 2,150–2,199 Ma. The youngest zircon was dated to 1,832 Ma and the oldest to 2,458 Ma. None of the zircons is of Archaean age (Fig. 14).

In the high-grade rocks in the Gävle area, about 90% of the analysed zircons at Eskörönningen and 83% at Persbacka show U/Th ratios above 5.0, which clearly indicate that most of the zircons are influenced by metamorphic events, younger than the age of the metagranodio-

Figure 13a. Paragneiss, consisting of about 50% quartz and 50% biotite from Udden, about 3.4 km southeast of Nykvarn (6559820/640941). Photo: Benno Kathol.

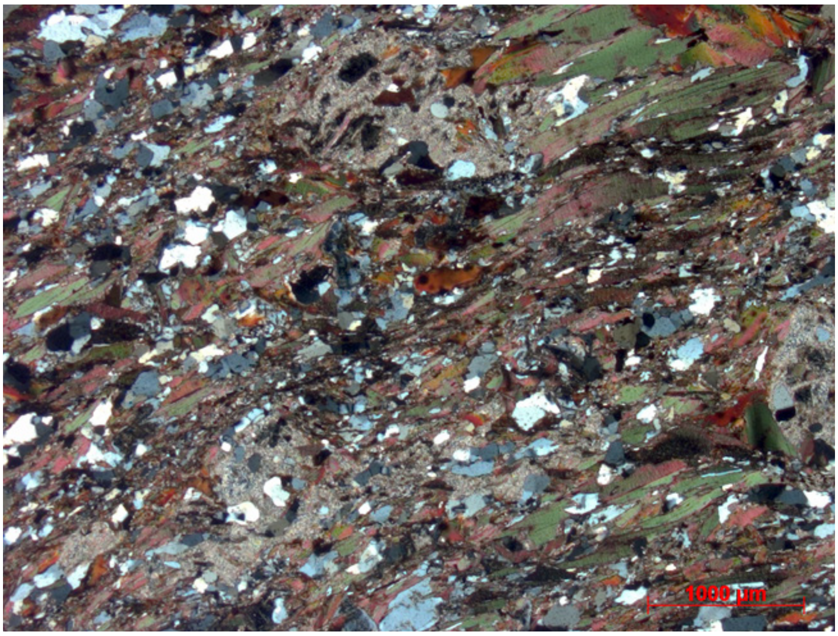


Figure 13b. Paragneiss, consisting of about 50% quartz and 50% biotite from Udden, about 3.4 km southeast of Nykvarn (6559820/640941). Crossed nicols. Microphotograph: Benno Kathol.

rite, dated west of Engesberg to 1,865 ± 14 Ma (Bergman et al. 2005). In the Eskörönningen and Persbacka samples, the analysed zircons with dates below the minimum age of 1,865 Ma have very high mean U/Th ratios of 37.0 (n=82) and 78.0 (n=71), respectively, which also suggests clear metamorphic overprint in these rocks.

At Eskörönningen, metamorphic events as young as 1,700–1,750 Ma are indicated by the dates of the youngest zircon population and associated U/Th ratios. Similar features should be expected in the equally high-grade rocks from Udden in the Nykvarn–Mörkö area. Here, the number of probably metamorphic zircons is less, but still 58% (n=11) of the analysed zircons show U/Th ratios above 5.0. However, there is no dating of an intrusive or overlying magmatic rock which could give a minimum or maximum depositional age.

The proportion of Archaean input within these high-grade rocks is very sparse with Archaean zircons occurring only in the sample from Persbacka. If this is due to the grade of metamorphism or the position of these sample areas in eastern and southeastern Bergslagen (see Fig. 35b in section *Archaean zircons*) is unclear. Another striking feature is that the analysed dates from Eskörönningen are confined to a relatively narrow time interval of 1.7–1.9 Ma, compared to most of the other samples.

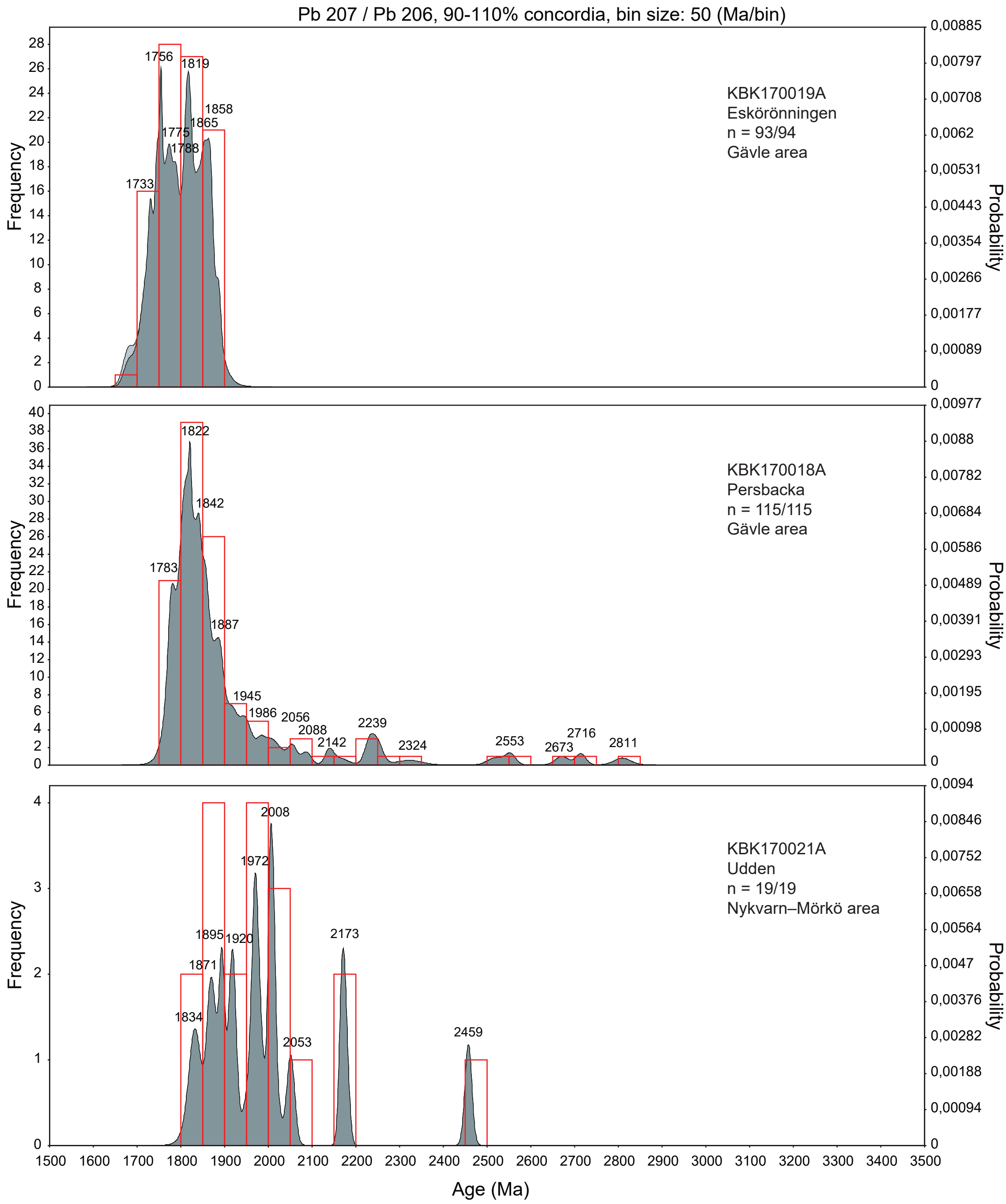


Figure 14. Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Gävle and Nykvarn–Mörkö areas with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.

Skärplinge

To the east of Skärplinge, there is a synform consisting of lowermost dacite–rhyolite and greywacke followed by quartz arenite in its central, upper part; the latter was sampled in a flat, platy outcrop at Barknåre. The rock in the outcrop is a layered and folded, recrystallised, dark grey arenite to quartz arenite with a grain size of very fine to medium sand (Fig. 15a, b). In places, the rock contains thin quartz-feldspar veins that are oriented either parallel or perpendicular to the bedding. In the latter case they are folded. The outcrop consists mostly of pegmatite. In the sample from Barknåre, 10 zircon grains were extracted but not analysed. However, a lithogeochemical analysis was done, and the result has been used in the geochemical diagrams.

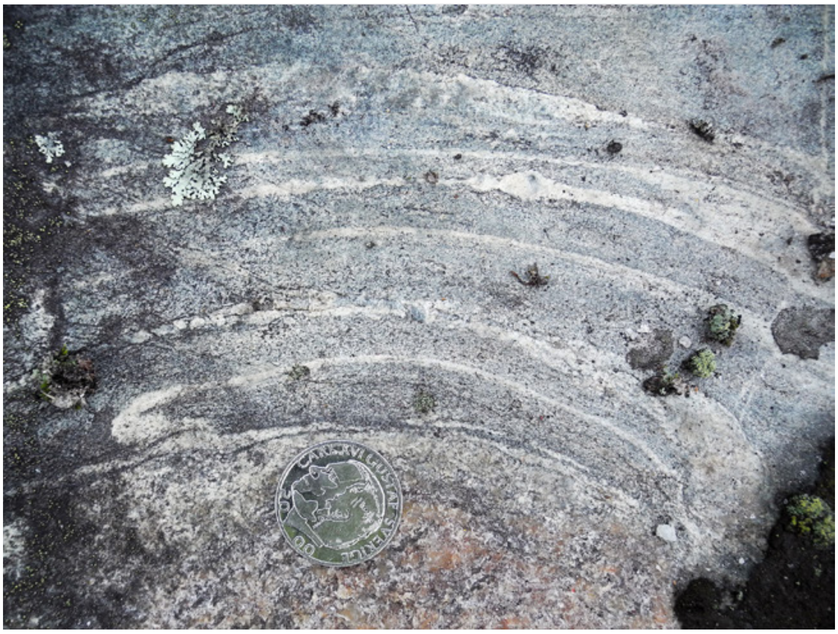


Figure 15a. Layered arenite from Barknåre, about 9.5 km east-northeast of Skärplinge (6710300/660166). Photo: Benno Kathol.

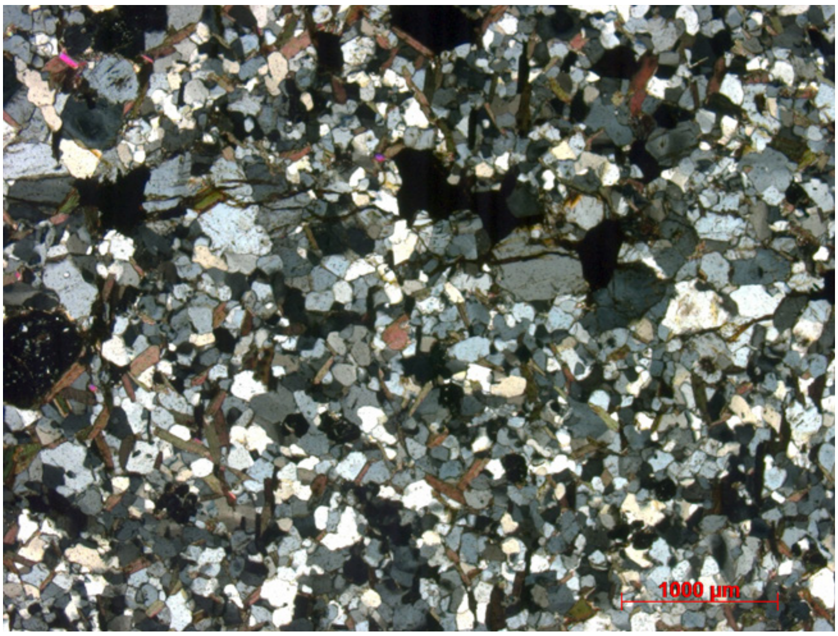


Figure 15b. Layered arenite from Barknåre, about 9.5 km east-northeast of Skärplinge (6710300/660166). Crossed nicols. Microphotograph: Benno Kathol.

Grangärde–Ludvika

At Grangärdes Hästberg and north of Norhyttan, there are two minor intercalations of sedimentary rocks in a sequence of felsic volcanic rocks extending from Skattlösberget in the southwest to Tuna-Hästberg in the northeast.

In the northern part of the intercalation at Grangärdes Hästberg, a massive, recrystallised, grey quartz arenite with a grain size of medium to coarse sand occurs. Despite recrystallisation, primary structures are preserved. The rock is poorly sorted with rounded to angular quartz grains. This rock was sampled at Lindbastmora north of Grangärdes Hästberg. According to Ripa & Kübler (2005b), there are fragments of volcanic rocks in the quartz arenite which implies that it is overlying at least some parts of the volcanic sequence. This probably also means that this quartz arenite cannot be correlated with quartz arenite to quartzite in the Larsbo series (Hjelmqvist 1938) from Solfallet at Norberg (see section *Norberg–Fagersta*).

At Lindbastmora, 117 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, none required correction for common lead. The U/Th ratios vary between 1.4 and 21.6, and 68% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 59% of the analysed zircons show dates that fall in the age interval 1,850–1,899 Ma with a dominating maximum probability peak at 1,873 Ma. About 10 and 8.5% of the zircons have dates in the intervals 1,800–1,849 and 1,900–1,949 Ma, respectively, with a peak at 1,945 Ma in the latter interval. The youngest zircon was dated to 1,695 Ma and the oldest to 3,037 Ma. Only four zircons (3.4%) are of Archaean age (Fig. 20).

The intercalation north of Norhyttan consists of layered and foliated, dark grey, recrystallised greywacke with biotite in the groundmass and sericite on the foliation surfaces. Andalusite porphyroblasts are common in the greywackes of the Norhyttan intercalation (Ripa & Kübler 2005a). According to the authors, the field relationship between the greywacke and the volcanic rocks is unclear. The grain size at the sampling point north of Södra Gåstjärnen is fine to medium sand and there is an alternate bedding in 2–5 cm scale between "finer" sand and "coarser" sand (Fig. 16). No zircon grains were found in the sample from Södra Gåstjärnen.

At the Håksberg mine north of Ludvika, a highly deformed, recrystallised, foliated and layered, dark grey to black rock occurs (Fig. 17a). At a first glance on a fresh surface it looks

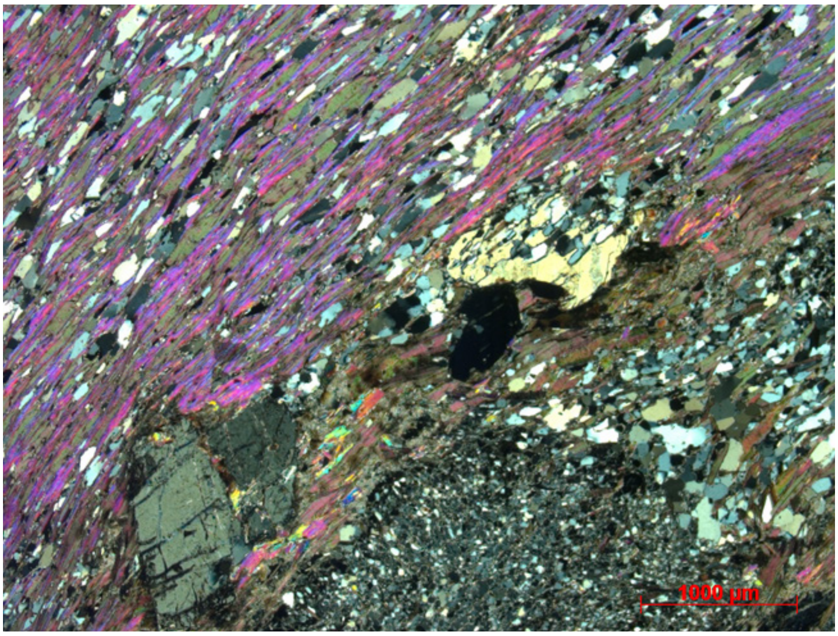


Figure 16. Greywacke with andalusite porphyroblast from Södra Gåstjärnen, about 5.5 km southwest of Grangärde (6678152/ 493850). Crossed nicols. Photomicrograph: Benno Kathol.

like a greywacke and was therefore sampled in the scope of this project. The rock consists of biotite and hornblende, quartz is completely absent or occurs only subordinately; on weathered surfaces, feldspar phenocrysts can be recognised. This mineral composition probably eliminates greywacke or sandstone as protolith. A potassium content of about 3% indicates an intermediate composition of the rock. In summary, the rock is interpreted as a volcaniclastic, intermediate volcanic rock. In the TAS-diagram of Le Bas et al. (1986), the rock plot in the field of phonotephrite. The tectonic discrimination diagrams of Pearce & Cann (1973) indicate a Mid-Ocean-Ridge magma type. The diagrams are not shown in this report.

It seems that this strongly foliated, dark grey rock is confined to a local shear zone. The rock in this zone exhibit high magnetic susceptibility values. Approximately 100 m southwest of the site with the strongly foliated rock, i.e. outside the shear zone, the rock is almost undeformed and shows bedding and 1 to 10 cm thick, bedding-parallel quartz-feldspar veins and quartz-feldspar

Figure 17a. Strongly foliated volcaniclastic rocks from Håksberg, about 5 km north of Ludvika (6673448/511177). Photo: Benno Kathol.

Figure 17b. Layered volcaniclastic rock with feldspar phenocrysts. Photo taken towards northwest. Håksberg, about 5 km north of Ludvika (6673448/511177). Photo: Benno Kathol.

pods, also 1–10 cm in size. Feldspar phenocrysts in the layered rocks suggest the volcanic character of the entire rock sequence (Fig. 17b). The sample was collected in the strongly foliated, dark grey rocks; due to the basic composition, no zircon grains were found in the sample.

Norberg–Fagersta

Geijer (1936, 1967) described two occurrences of quartzite in the area northwest of Norberg. He interpreted the quartzites as basal layers in the Larsbo series (Hjelmqvist 1938), which, according to him, overlies the volcanic sequence in the area. This age relationship was then revised by Ambros (1986, 1988) who considered the Larsbo series to be older than the volcanic sequence. This stratigraphic relationship has later been taken over and proved elsewhere by Persson (1997) and Stephens et al. (2009).

The southern quartzite occurrence is exposed in the road cut at Solfallet from which Geijer (1967) described an "iron-sand bed" containing plenty of magnetite and zircon. The exposed rocks in the road cut are foliated, weakly deformed, recrystallised, dark grey quartz arenites to quartzites with intercalations of mafic volcanic rocks with a similar appearance. The magnetic susceptibility varies strongly perpendicular to the foliation which is interpreted to be oriented more or less parallel to the bedding in the sedimentary rocks. The sample was taken from a high-magnetic part whose high susceptibility was considered likely to be caused by magnetite in dissemination and which was interpreted to be the iron-sand bed of Geijer (1967). Later, it turned out by lithogeochemical and thin section analyses that the sample stems from a high-magnetic intercalated mafic volcanic rock, rich in magnetite but barren in zircon (Fig. 18). In the TAS-diagram of Le Bas et al. (1986), the sampled rock from Solfallet rock plot in the andesite field. The tectonic discrimination diagrams of Pearce & Cann (1973) indicate a calc-alkaline magma type. The diagrams are not shown in this report.

However, detrital zircons from a quartzite, probably stemming from the same road cut have been analysed by Claesson et al. (1993), and their sample contained ten Palaeoproterozoic zircons in the age range 1.90–2.04 Ga and four Archaean zircons in the age range 2.60–2.97 Ga.

Figure 18. Andesite from the road cut at Solfallet, about 4 km northwest of Norberg (6661770/548370). Crossed nicols. Microphotograph: Benno Kathol.

Sala–Tillberga

At Nötbo east of Broddbo, a sample was collected from a layered and foliated, recrystallised, grey quartz arenite. The rock shows cross-bedding, it is moderately sorted, the grain size is fine to coarse sand, and the clasts are subrounded (Fig. 19a, b). Several way-up determinations using cross bedding, made in the area (Persson 1997, own observations) show that the sedimentary sequence underlies the volcanic sequence in this area. The sample was taken quite close to the top of the sedimentary sequence, close to the contact to the volcanic sequence.

A rhyolite of the basal part of the overlying volcanic sequence was dated approximately 70 m southeast of our sampling site to 1 906 ± 3 Ma (Stephens et al. 2009), providing a minimum age for the quartz arenite at Nötbo-Broddbo.

Figure 19a. Cross bedding with erosional surface in quartz arenite. Photo taken towards the southeast. Nötbo east of Broddbo, about 9 km north-north-west of Sala (6652242/587058). Photo: Benno Kathol.

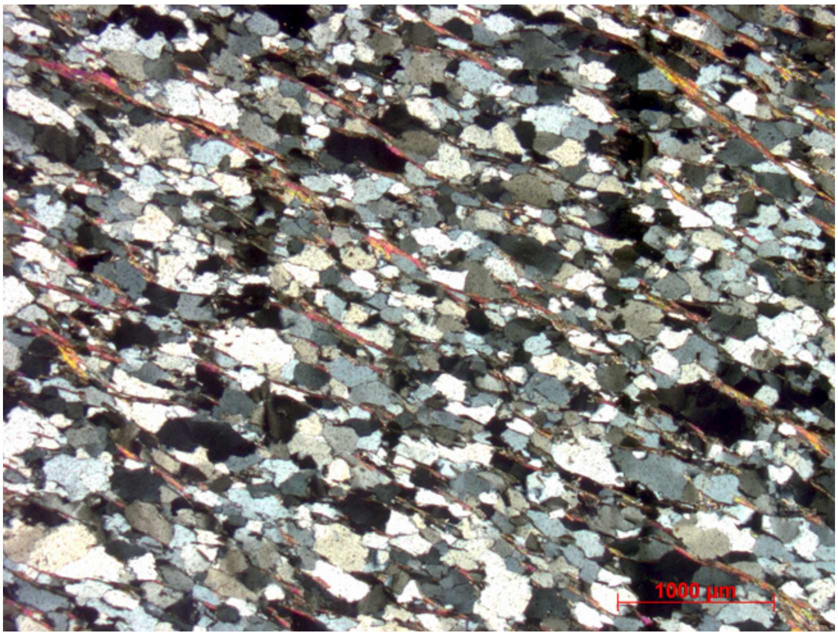


Figure 19b. Quartz arenite from Nötbo east of Broddbo, about 9 km north-northwest of Sala (6652242/587058). Crossed nicols. Photomicrograph: Benno Kathol.

The quartz arenite at Nötbo-Broddbo belongs to a sequence marked as greywacke, which is found in minor occurrences between Ludvika and Sala and was traditionally referred to as the Larsbo series (Hjelmqvist 1938) or Larsbo formationen (Strömberg & Nisca 1983).

At Nötbo-Broddbo, 122 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, 12 analyses required correction for common lead. The U/Th ratios vary between 1.5 and 17.9, and 34% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 34% of the analysed zircons show dates that fall in the age interval 1,850–1,899 Ma and about 42% in the interval 1,900–1,949 Ma. A significant maximum probability peak occurs at 1,907 Ma. Age intervals with 8 to 17.99% of the analysed zircons have not been determined in this sample. The youngest zircon was dated to 1,859 Ma and the oldest to 2,823 Ma. Only three zircons (2.9%) are of Archaean age (Fig. 20).

At Nötbo-Broddbo, 80 analyses show U/Th ratios >= 5.0, and these dates show a mean value of 1,922 Ma. The other 42 obtained dates with U/Th ratios < 5.0 show a mean value of 2,028 Ma. Though the age of 1,906 ± 3 Ma (Stephens et al. 2009), obtained in the overlying volcanic sequence can be considered as a minimum age for the quartz arenite at Nötbo-Broddbo, there is no significant difference in the U/Th ratio for analyses with dates below 1,906 Ma (U/Th mean value 6.2, n=53) and above 1,906 Ma (U/Th mean value 5.5, n=69). Thus, the

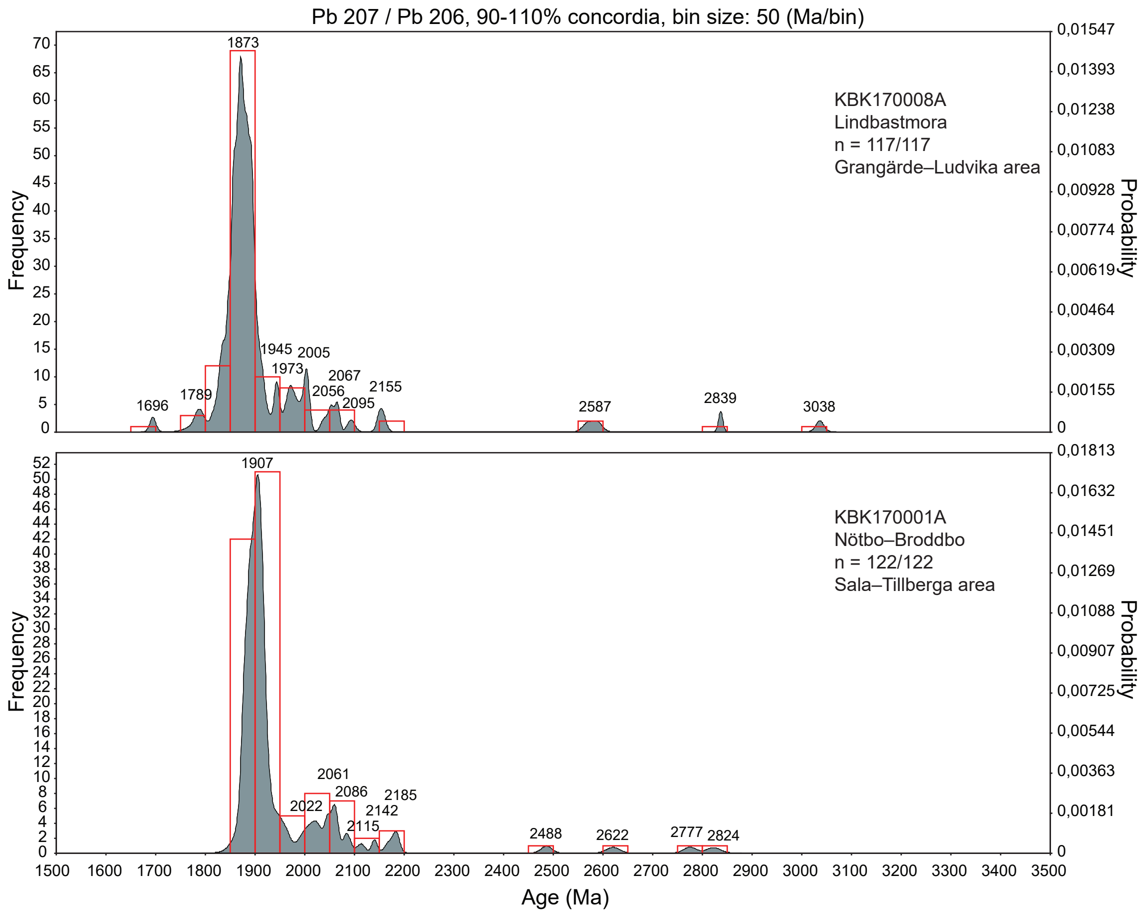


Figure 20. Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Grangärde–Ludvika and Sala–Tillberga areas with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.

general signature that higher U/Th ratios are concentrated in the lower age intervals (see Fig. 33 in section *U/Th ratios and youngest zircon*) cannot be confirmed in the sample and there seems to be no correlation between age and U/Th ratio.

Grythyttan

The supracrustal rocks of the Grythyttan area are divided by Lundström (1995) into Sången, Älgen and Torrvarpen formations, respectively. The Torrvarpen formation with the Hälgsnäs member as the basal unit overlies the siltstone-dominated Älgen formation, which in turn overlies the Sången formation, the latter mostly consisting of felsic volcanic rocks. The contacts between the Sången, Älgen and Torrvarpen formations have been described by Lundström (1995) as concordant but structurally disturbed in many places. An age determination of a rhyolite in the Älgen formation gave an age of 1.897 ± 6 Ma (Stephens et al. 2009) which has been interpreted by the authors to represent the final and waning phase of the volcanic development. Although the contact between the Älgen and the Torrvarpen formations near the dating site is a deformation zone, the age of the dated rhyolite is considered to provide a maximum age for the sedimentary rocks in the Torrvarpen formation.

All three samples from the Grythyttan area originate from the Torrvarpen formation, which represents the uppermost formation in greenschist facies according to Lundström (1995). It is divided into the Hälgsnäs member, consisting of slate, greywacke and conglomerate, and the Grythyttan and Hällefors members, the former consisting of graphite-bearing slate and the latter of graphite-free slate. The samples were collected in that unit which Lundström (1995) referred to as the Hälgsnäs member on his map. However, the sample from the road cut at Torrvarpsund has in this project been considered as a slate belonging to the Hällefors or Grythyttan member (see below).

The northernmost sample in the Grythyttan area, taken in the Hälgsnäs member at Lill-Sången north of Hällefors, is a foliated, recrystallised, grey arenite with a grain size of silt to fine sand.

In a road cut on the eastern side of road 205 at Torrvarpsund, south of Grythyttan, a strongly deformed rock with slaty cleavage and lineation was sampled (Fig. 21a, b). The pronounced cleavage is in 1–10 mm scale, and a grain size of clay to silt. There are also 1–5 cm long, elongated carbonate lenses parallel with the cleavage and 1–2 cm thick carbonate veins that cut the cleavage. On the bedrock map (Lundström 1991), the area around the sample site is marked as conglomerate of the Hälgsnäs member. Since no conglomerate clasts, not even strongly deformed ones have been observed, it is unclear if the sample site is located in the Hälgsnäs member, or in the Grythyttan or Hällefors member.

The southernmost sample, collected in the Grythyttan area is a foliated, recrystallised, dense, dark grey quartzite with a grain size of clay to silt (Fig. 22). The sampled, very fine-grained quartzite actually is the matrix in a matrix-supported conglomerate with strongly elongated clasts. The sample site is located at Yxhammarshöjden, north of Loka, and the rock is assigned to the Hälgsnäs member in the Torrvarpen formation.

At Lill-Sången, 106 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, 11 analyses required correction for common lead. The U/Th ratios vary between 1.8 and 17.2, and 51% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). Almost 22% of the analysed zircons show dates that fall in the age interval 1,850–1,899 Ma with a maximum probability peak at 1,896 Ma. About 18, 14 and 13% of the zircons have dates in the intervals 1,900–1,949, 1,950–1,999 and 2,000–2,049 Ma, respectively, with peaks at 1,906, 1,995 and 2,035 Ma, respectively. The youngest zircon was dated to 1,832 Ma and the oldest to 3,022 Ma. About 17.0% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,744 Ma (Fig. 23).

Figure 21a. Slate of the Grythyttan or Hällefors member or strongly deformed conglomerate of the Hälgsnäs member? Photo taken towards the south-southeast. Road cut (road 205) east of Lake Torrvarpen, about 2 km south of Grythyttan (6616730/473282). Photo: Benno Kathol.

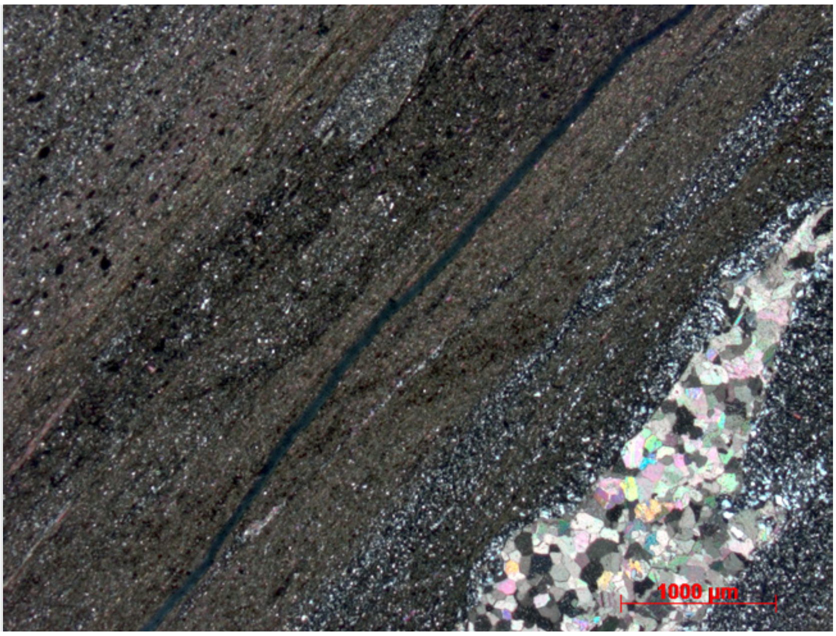


Figure 21b. Slate with carbonate vein. Road cut (road 205) east of Torrvarpen, about 2 km south of Grythyttan (6616730/473282). Microphotograph: Benno Kathol.

At Torrvarpsund, 116 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, 46 analyses required correction for common lead. The U/Th ratios vary between 1.0 and 14.8 with two outliers at 104.1 and 115.0, and 72% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 31% of the analysed zircons show dates that fall in the age interval 1,850–1,899 Ma with a maximum probability peak at 1,888 Ma. About 13 and 12%, respectively of the zircons have dates in the intervals 1,900–1,949 and 1,950–1,999 Ma with a peak at 1,971 Ma. The youngest zircon was dated to 1,752 Ma and the oldest to 3,459 Ma, which is the second oldest zircon grain observed in this project. About 17.2% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,693 Ma (Fig. 23).

The sample from Torrvarpsund (KBK170004A no. 168) contains the oldest Archaean and second oldest zircon of this study. It has an age of 3,459 ± 25 Ma and a size of 53 × 36 µm

Figure 22. Clay to silt sized groundmass in a conglomerate of the Hälgsnäs member at Yxhammarshöjden, about 3.3 km northeast of Loka (6609763/473155). Crossed nicols. Microphotograph: Benno Kathol.

which is around half the size of the Hadean zircon from Närkesberg (KBK170023B no. 216; Kathol et al. in prep.).

At Yxhammarshöjden, 106 zircon U–Pb dates were obtained, and 105 are within the 90–110% concordia interval, 54 analyses required correction for common lead. The U/Th ratios vary between 0.6 and 27.2 with a single outlier at 109.2, and 63% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 29.5% of the analysed zircons show deates that fall in the age interval 1,850–1,899 Ma with a maximum probablility peak at 1,894 Ma. About 12.4, 9.5, 13.3 and 8.6% of the zircons have ages in the intervals 1,800–1,850, 1,900–1,949, 1,950–1,999 and 2,000–2,049 Ma, respectively. The highest peaks in these intervals occur at 1,974 and 2,001 Ma. The youngest zircon was dated to 1,801 Ma and the oldest to 2,852 Ma. About 18.1% of the zircons are of Archaean age, and the Archaean zircons show a maximum at 2,708 Ma (Fig. 23).

The above-mentioned age of 1,897 ± 6 Ma (Stephens et al. 2009) of a rhyolite in the Älgen formation, represents a maximum age for the lowermost part of the overlying sedimentary sequence of the Torrvarpen formation. However, there are a lot of zircon analyses that yielded younger dates compared to the rhyolite age. This could on one hand imply that the three sampled horizons lie in younger parts of the Torrvarpen formation. On the other hand, there is a possibility of metamorphic influence on parts of the zircon populations in every sample. The samples from Lill-Sången and Torrvarpsund show slightly higher mean U/Th ratios for the zircon populations younger than the rhyolite compared with the older ones, 6.3 (n=29) to 5.4 (n=77) at Lill-Sången and 6.8 (n=47) to 5.4 (n=69) at Torrvarpsund. At Yxhammarshöjden the relationship between the younger and the older zircon populations is the other way around with a mean U/Th ratio of 5.5 (n=39) for the younger and 6.1 (n=66) for the older population, respectively. These figures do not give an explicit indication for the influence of younger metamorphic phases. On the other hand, the figures could indicate either that the samples stem from stratigraphically higher, i.e. younger horizons of the Torrvarpen formation and sedimentation lasted over a longer time, or that there is a hiatus between the deposition of the volcanic rocks and the onset of the Torrvarpen sedimentation.

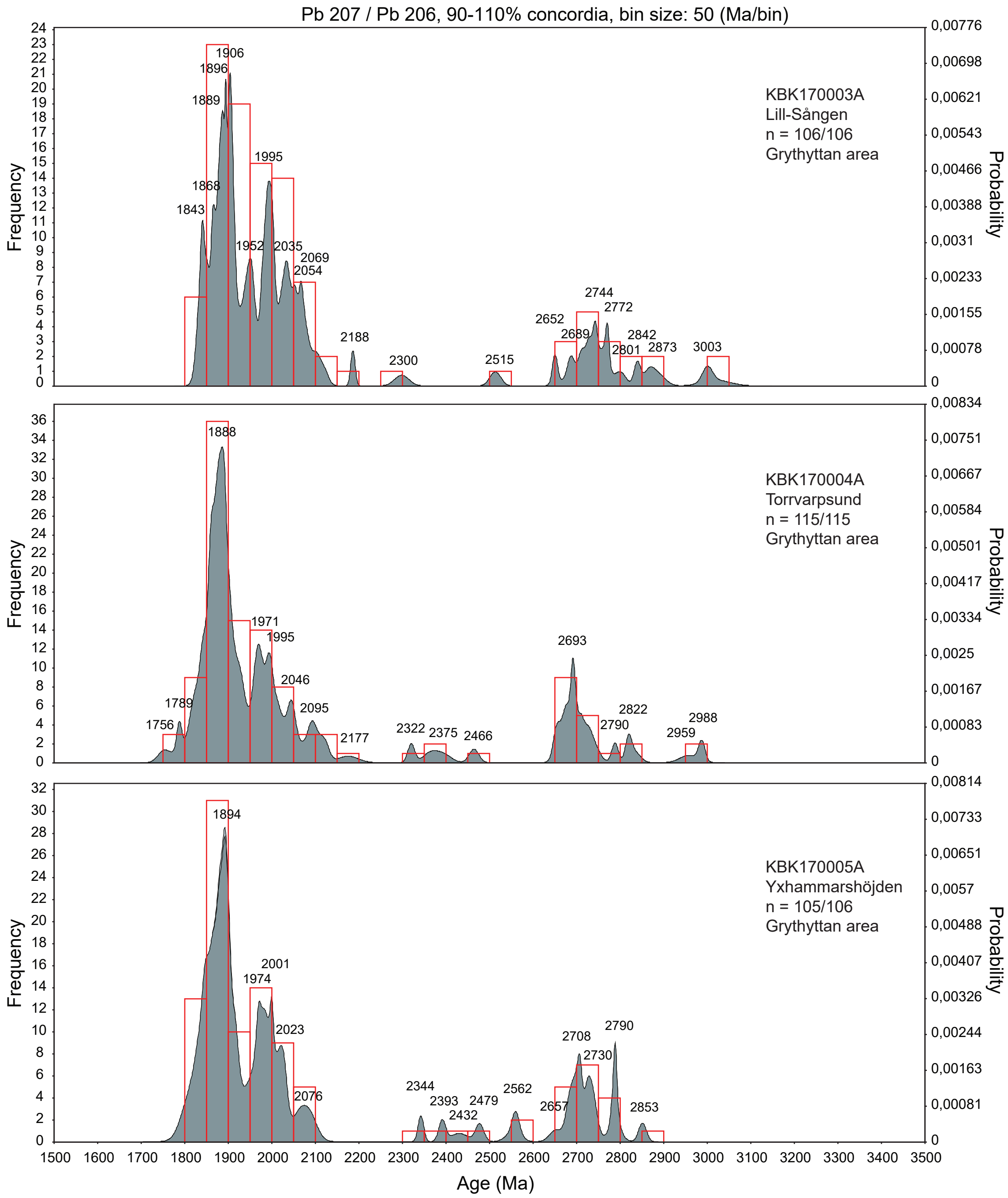


Figure 23. Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Grythyttan area with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.

Närkesberg–Hjortkvarn

The Palaeoproterozoic Svecofennian supracrustal rocks in the Närkesberg–Hjortkvarn area in southwestern Bergslagen were described in detail by Wikström & Karis (1991), who distinguished a Hjortkvarn group consisting of the volcanic Igelfors formation and the sedimentary Gryt formation which was deposited in a fluviatile environment. The authors considered the internal, stratigraphical relationships to, and between other occurrences of supracrustal rocks in the Närkesberg–Hjortkvarn area and its surroundings as to be uncertain, and thus described them without a mutual stratigraphy by areas as Billsbro, Boo, Ljusfallshammar, Dovern and Bredsjön.

Kumpulainen et al. (1996) summarized the supracrustal rocks in the area under the name Emme group, a group consisting of large volumes of felsic volcanic rocks as well as arkoses and greywackes of continental origin. According to the authors, the supracrustal rocks were deposited along an active continental margin. The Emme group is divided into, from stratigraphically below and upwards, the volcanic Igelfors formation, the sedimentary Närkesberg formation, corresponding to the Gryt formationen of Wikström & Karis (1991), the volcanic Mariedamm and Godegård units and, at the top, the turbiditic Vintergölen formation in the Bredsjö sedimentary area of Wikström & Karis (1991).

The Igelfors formation was deposited on land, which is indicated by the volcaniclastic nature of the rocks and the occurrence of subaerial ignimbrites (Wikström & Karis 1991). The depositional environment for the overlying Närkesberg formation was fluviatile to shallow marine within a wave-dominated (above wave base) tidal area. This is indicated by the occurrences of basic lavas which are showing hyaloclastic structures in their lower parts, indicating formation under water, and porous textures at the top, indicating subaerial conditions (Kumpulainen, pers. comm. 2020).

According to Kumpulainen et al. (1996), the Närkesberg formation is about 5 km thick and consists predominantly of arenites and arkoses of continental origin, deposited in a fluviatile to shallow marine environment. The deposition of the c. 5 km thick sedimentary succession with arenitic to arkosic composition, requires access to a nearby continental source (Kumpulainen, pers. comm. 2020).

The homogenous character throughout the entire Närkesberg succession also requires a regular subsidence of the sedimentary basin, which must be in balance with sediment supply from the source. This process most likely indicates the occurrence of an interim sediment deposit postdating weathering of the continental crust and predating the final emplacement in the subsiding basin. A scenario without an interim deposit would require a strongly weathered continental crust as source (Kumpulainen, pers. comm. 2020).

The Vintergölen formation, on the other hand, was considered by Kumpulainen et al. (1996) to have a different character compared to the other sedimentary rocks in the Emme group and was interpreted as the result of turbiditic deposits that represent a rapid subsidence of the depositional basin.

An age determination of a porphyritic rhyolite, collected in a roadside outcrop, about 1.5 km northeast of Gryts bruk gave a crystallization age of 1,901 ± 18 Ma. This rhyolite was interpreted as a part of a rhyolitic subvolcanic intrusion, best exposed south of Gryts bruk (Kumpulainen et al. 1996 and R. Allen, writ. comm. therein), which intruded into the rhyolites of the Igelfors formation and can hence be considered as a minimum age for the formation.

As the deposition of the Igelfors formation and the intrusion of the subvolcanic rhyolite are close in time (Allen et al. 1996a), this possibly also provides a maximum age constraint for the Närkesberg formation. However, it is unclear whether similar rhyolitic intrusions are limited to the Igelfors formation or if they also occur in the overlying Närkesberg formation, which would result in a lower maximum age for the Närkesberg formation. Three scenarios can be distinguished:

- **Scenario A:** If the dated subvolcanic intrusion is confined to the volcaniclastic rocks of the Igelfors formation, the entire overlying Närkesberg formation must be younger than 1,901 Ma.
- **Scenario B:** There are thin granite dykes in the lower part of the sedimentary sequence of the Närkesberg formation (Kumpulainen, pers. comm. 2020). It is crucial if these dykes can be related to the dated subvolcanic intrusion, which has been dated to 1,901 ± 18 Ma (Kumpulainen et al. 1996). If this is the case, these dykes will give a minimum age of 1,901 Ma for the lower parts of the Närkesberg formation.
- **Scenario C:** In that case that the dated subvolcanic intrusion is also intrusive into the lower part of the Närkesberg formation, these parts must be older than 1,901 Ma (minimum age of 1,901 Ma). This scenario can only be proven by more field work which is not in the scope of this project.

With the above-mentioned scenario A, which is the most likely, the onset of the sedimentation of the Närkesberg formation took place shortly after the minimum age of 1,901 ± 18 Ma of the Igelfors formation. This is indicated by the zircon age record of the samples from the Närkesberg formation (see Fig. 31a in section *Summary and interpretation of all analysed samples*), which is fairly complete from that age to the zircon date maximum probability peaks at c. 2.0 Ga.

The turbiditic Vintergölen formation is underlain by the Godegård volcanic unit (Kumpulainen et al. 1996). A feldspar-porphyritic rhyolite from the lower part of that unit was dated to 1,889 +35/-24 Ma, which can be considered as a rough maximum age for the lower parts of the Vintergölen formation.

A sample from the Vintergölen formation was collected at Grissjötorp northwest of Godegård in a layered and foliated, recrystallised, grey greywacke with a grain size of very fine to coarse sand. At the sampling point there is an alternate bedding of muddy-silty and sandy layers on decimetre scale. The sample was taken in a sandy layer, approximately 15 cm thick (Fig. 24a, b). The sample site is located in the low-metamorphic part of the Bredsjö sedimentary area (Bredsjö basin), east of the Höka deformation zone (Wikström & Karis 1991). The site lies about five kilometres northeast of the dating locality for the rhyolite from the Godegård volcanic unit.

In the Närkesberg formation, five samples were collected at four different localities. Between Siggetorp and Laggarfall northeast of Närkesberg, a layered, recrystallised, grey arkosic arenite exhibits cross-bedding, convolute bedding, load casts and graded bedding (Fig. 25a). The grain size is very fine to medium sand, the particles are angular to subangular and the rock is moderately sorted (Fig. 25b). Way up determinations in the sedimentary sequence indicate younging towards the southwest. At this locality, two samples were taken, one (KBK170023A) from a layered part and the other (KBK170023B) from a somewhat coarser grained, more massive layer.

The sampling site for the third sample lies between Linnerud and Stensätter east of Närkesberg. The rock there is a layered, recrystallised, grey arenite with a grain size of silt to fine sand. Load casts and graded bedding indicate that the sequence is getting younger to the southwest (Fig. 26a, b). The sampling sites at Siggetorp–Laggarfall and Linnerud–Stensätter are located in the lower part of the Närkesberg formation.

Two further samples were collected, one at Ångsågen west of Haddebo between Rön-

Figure 24a. Greywacke with alternate bedding of muddy-silty and sandy layers. The sample was taken in the sandy layer to the left of and parallel to the hammer. The photo was taken towards the north-east. Road cut southwest of Grissjötorp, about 6 km south-southeast of Zinkgruvan (6513731/ 507471). Photo: Benno Kathol.

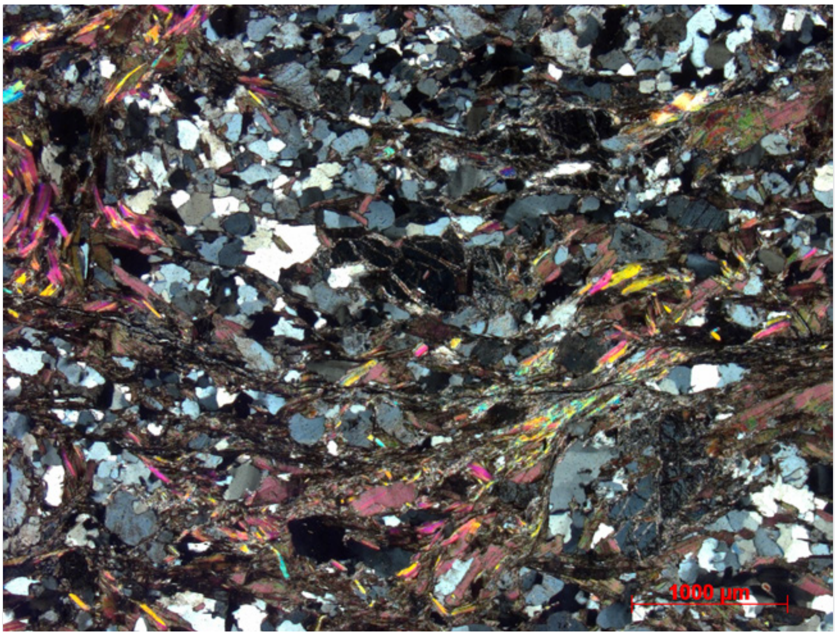


Figure 24b. Recrystallised greywacke, consisting of quartz (and feldspar) grains and mica flakes. Road cut southwest of Grissjötorp, about 6 km south-southeast of Zinkgruvan (6513731/ 507471). Crossed nicols. Microphotograph: Benno Kathol.

neshytta and Hjortkvarn and another at Lilla Fågelhult between Hjortkvarn and Grytstorp. The Ångsågen sample consists of a layered and foliated, recrystallised, dark grey arenite with a grain size of fine sand and the Lilla Fågelhult sample of a foliated and recrystallised, grey arenite with grainsize of silt to fine sand.

At Grissjötorp, 29 zircon U–Pb dates were obtained which is a low number for a reliable statistical approach. From these dates, 28 are within the 90–110% concordia interval, and 12 required correction for common lead. The U/Th ratios vary between 2.3 and 18.8 with two outliers at 49.0 and 73.0, and 41% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 21.4% of the analysed zircons show dates that fall in the age intervals 1,850–1,899 and 2,000–2,049 Ma each. Associated maxi-

Figure 25a. Graded bedding in the arenite of the Närkesbergs formation. The photo shows two sandy bases, of which the upper one lies about 2 cm above the pen. Approximately 7 cm above the lower sandy base, there is a layer with load casts. The photo is taken to the southwest. Outcrops south of the road between Siggetorp and Laggarfall, about 1.7 km northeast of Närkesberg (6530485/515673). Photo: Benno Kathol.

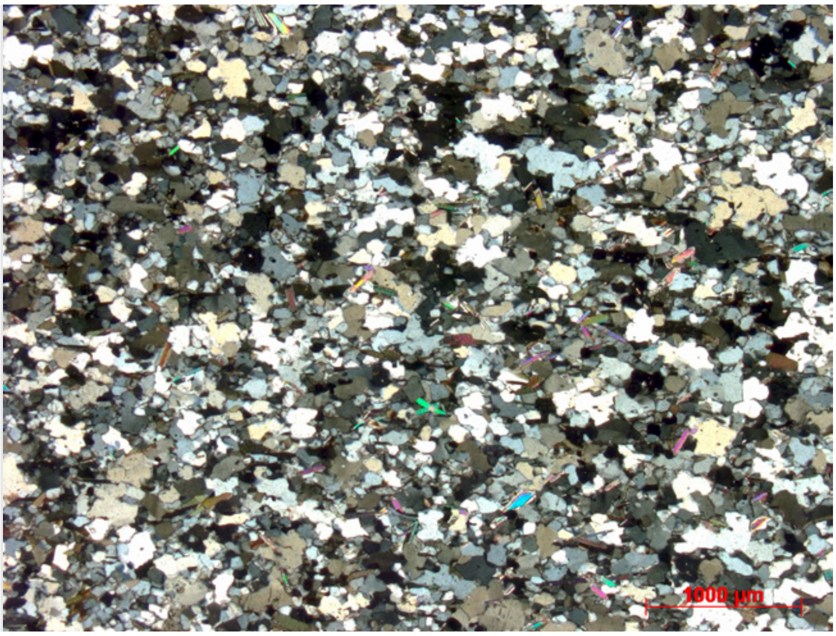


Figure 25b. Arenite from a massive layer (sample KBK170023B). Outcrops south of the road between Siggetorp and Laggarfall, about 1.7 km northeast of Närkesberg (6530485/515673). Crossed nicols. Microphotograph: Benno Kathol.

mum probability peaks occur at 1,880 and 2,037 Ma, respectively. About 14.3 and 10.7% of the zircons have dates in the intervals 1,900–1,949 and 1,950–1,999 Ma each. The youngest zircon was dated to 1,721 Ma and the oldest to 2,762 Ma. Two zircons are of Archaean age (7.1%), dated to 2,611 and 2,762 Ma (Fig. 27).

In the Vintergölen formation, ten zircons show younger dates than the maximum age of 1,889 Ma, provided by the dating of the rhyolite in the Godegård volcanic unit at 1,889 +35/-24 Ma (Kumpulainen et al. 1996). Here, it must be considered, that the dated rhyolite is in the lower part of the Godegård volcanic unit, which implies an even lower maximum age for the Vintergölen formation. The ten zircons with younger dates than 1,889 Ma have a mean U/Th ratio of 7.9 (n=19) which has to be compared with a mean U/Th ration of 12.2 (n=18) for the

Figure 26a. Bedding and load casts in arenite in the lower part of the Närkesberg formation. Way-up in the stratigraphic sequence, indicated by a yellow arrow, is towards the southwest. Between Linnerud and Stensätter, about 2.7 km east of Närkesberg. (6529500/516869). Photo: Benno Kathol.

Figure 26b. Arenite of silt to fine sand size from the lower part of the Närkesberg formation. Between Linnerud and Stensätter, about 2.7 km east of Närkesberg. (6529500/516869). Crossed nicols. Microphotograph: Benno Kathol.

older zircons. Thus, there is no indication for the influence of a younger metamorphic event on the younger zircons; which is also corroborated by the field conditions at Grissjötorp.

In the first sample from Siggetorp–Laggarfall (KBK170023A), 58 zircon U–Pb dates were obtained, and all are within the 90–110% concordia interval, 12 analyses required correction for common lead. The U/Th ratios vary between 1.3 and 37.0, and 66% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 20.7% of the analysed zircons have dates that fall in the age interval 1,950–1,999 Ma and about 29.3% in the interval 2,000–2,049 Ma with a dominating maximum probability peak at 2,007 Ma. About 12.1% of the zircons have dates in the interval 2,050–2,099 Ma. The youngest zircon was dated to 1,892 Ma and the oldest to 3,265 Ma. About 22.4% of the

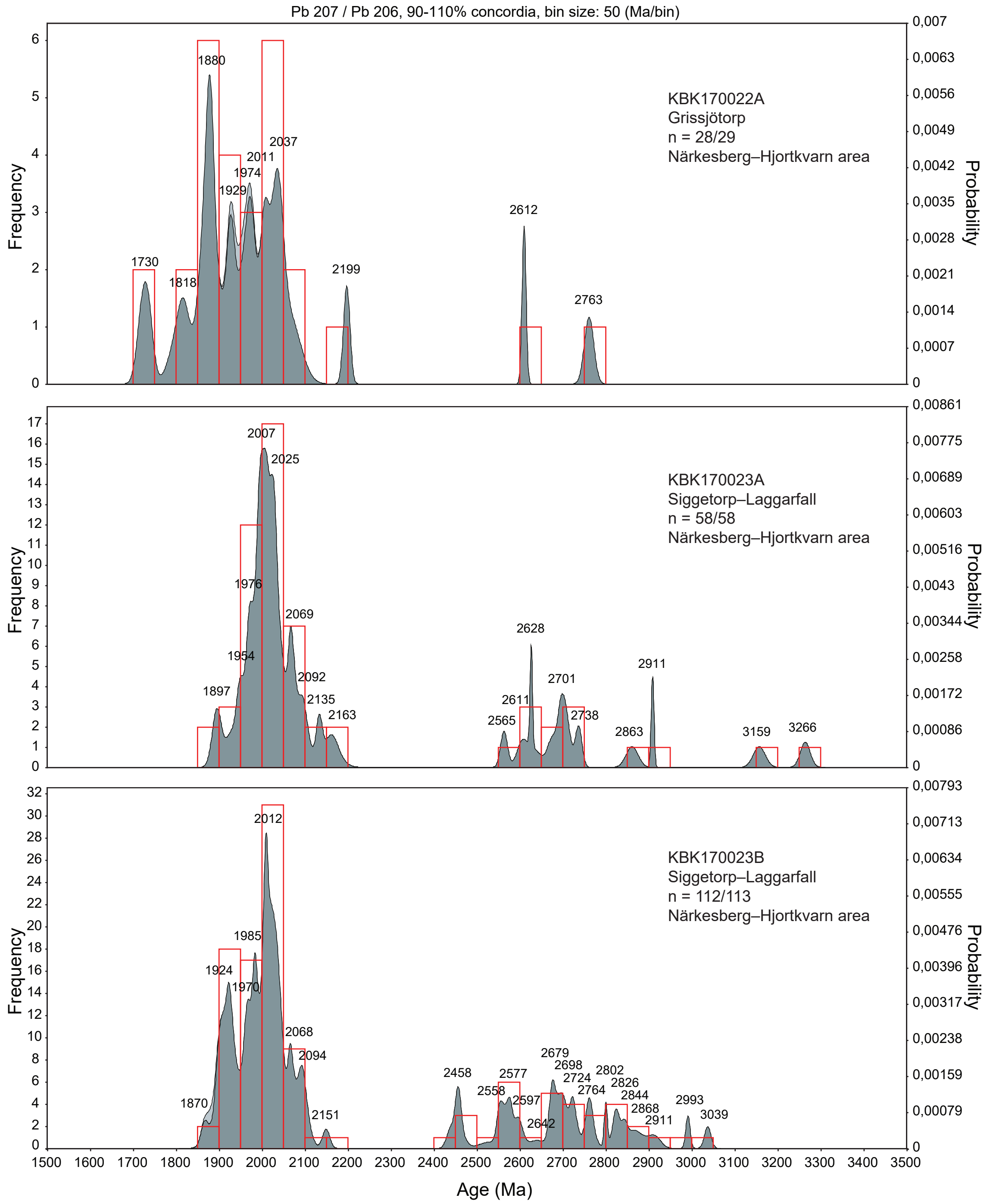


Figure 27. Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Närkesberg–Hjortkvarn area with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.

zircons are of Archaean age which is the second highest rate of all analysed samples, and the Archaean zircons show a maximum at 2,701 Ma (Fig. 27).

In the second sample from Siggetorp–Laggarfall (KBK170023B), 114 zircon U–Pb dates were obtained, and 113 dates are within the 90–110% concordia interval, 32 analyses required

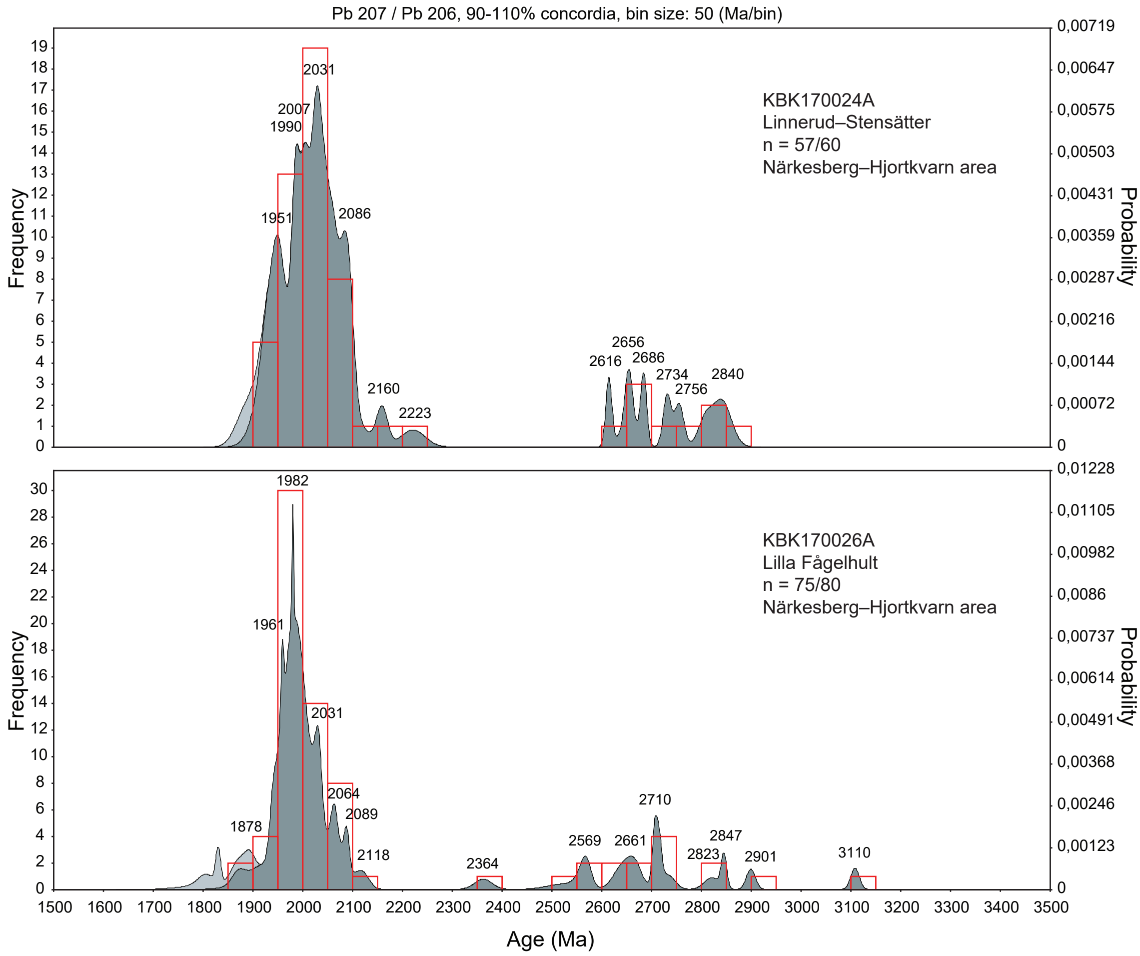


Figure 27. (continued) Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Närkesberg–Hjortkvarn area with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.

correction for common lead. The U/Th ratios vary between 1.0 and 27.2, and 68% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 27.4% of the analysed zircons show dates that fall in the age interval 2,000–2,049 Ma with a maximum probability peak at 2,012 Ma. About 15.9 and 15.0% of the zircons have dates in the intervals 1,900–1,949 and 1,950–1,999 Ma each. Maximum peaks lie at 1,924 and 1,985 Ma. The youngest zircon was dated to 1,867 Ma and the oldest to 4,008 Ma. About 25.7% of the zircons are of Archaean age which is the highest rate of all analysed samples and the Archaean zircons show several probability maxima, equally distributed between 2,558 and 3,039 Ma (Fig. 27).

At Linnerud–Stensätter, 60 zircon U–Pb dates were obtained on 105 zircon grains, and 57 of them are within the 90–110% concordia interval, 25 analyses required correction for common lead. The U/Th ratios vary between 1.7 and 25.7, and 62% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 22.8% of the analysed zircons show dates that fall in the age interval 1,950–1,999 Ma and about 33.3% in the interval 2,000–2,049 Ma with maximum probability peaks at 1,951 and

2,031 Ma, respectively. About 14.0% of the zircons have dates in the interval 2,050–2,099 Ma with a peak at 2,086. The youngest concordant zircon was dated to 1,913 Ma and the oldest to 2850 Ma. About 15.8% of the zircons are of Archaean age, and the Archaean zircons show several probability maxima, equally distributed between 2,616 and 2,840 Ma (Fig. 27).

In the sample from Ångsågen west of Haddebo, only 20 zircon grains have been found and 10 zircon U–Pb dates were obtained. The youngest zircon has an age of 1,730 Ma and the oldest of 2,607 Ma. Due to the low number of analyses, no combined frequency histogram and probability density distribution plot (PDP) was made.

At Lilla Fågelhult, 80 zircon U–Pb dates were obtained, and 75 of them are within the 90–110% concordia interval, 13 analyses required correction for common lead. The U/Th ratios vary between 1.4 and 40.0 with a single outlier at 136.0, and 64% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 40.0% of the analysed zircons show dates that fall in the age interval 1,950–1,999 Ma and about 18.7% in the interval 2,000–2,049 Ma with maximum probability peaks at 1,982 and 2,031 Ma, respectively. About 10.7% of the zircons have dates in the interval 2,050–2,099 Ma with a peak at 2,064. The youngest concordant zircon was dated to 1,872 Ma and the oldest to 3,109 Ma. About 20.0% of the zircons are of Archaean age with a maximum peak at 2,710 Ma (Fig. 27).

There is a discrepancy between the rocks of the Närkesberg formation in the Närkesberg–Hjortkvarn area and the other sampling areas in Bergslagen and surroundings. In the Närkesberg formation, the majority of the detrital zircons stem from rocks with an age range of 1,950 to 2,049 Ma, which means that 'normal' Svecokarelian intrusive and Svecofennian supracrustal rocks have not been the supplier for the rocks of the Närkesberg formation. In all other areas, most of the zircon dates are within the intervals 1,850–1,899 Ma or, in some cases 1,900–1,949 Ma (see Fig. 31a, b in section *Summary and interpretation of all analysed samples*).

If the underlying Igelfors formation represents a maximum age for the Närkesberg formation, there could be younger zircons in the latter formation. However, this is not the case which probably implies that there have not been any delivery areas with younger bedrock, which is due to that the samples were collected in the lower parts of the Närkesberg formation.

The exact fit of the lowest zircon dates to the age of the underlying Igelfors rocks implies that the onset of the sedimentation of the Närkesberg formation is close in time to the dated volcanic rock, and that there is no remarkable hiatus between the Igelfors and Närkesberg formations.

In the Närkesberg formation, significant zircon populations with more than 8% of the analysed zircons have dates in the 1,900–1,949 Ma interval or older (see Figs. 31a, b; 34 in section *Summary and interpretation of all analysed samples*). It thus seems unlikely that any of these zircons represent a Svecokarelian metamorphic event. This is also supported by the overall character of the well-preserved arenites from the Närkesberg formation.

In summary, it can be concluded that the rocks of the Närkesberg formation, except the sample from Lilla Fågelhult, probably originate from a delivery area with a felsic igneous signature (see Fig. 38 in section *Lithogeochemical analyses*) not affected by any Svecokarelian metamorphism.

Utö

The island of Utö is situated in the eastern part of the larger area of sedimentary rocks of southeastern Bergslagen (Fig. 1a), but the rocks are considerably better preserved than for example those at Udden in the western part of the larger area. According to Stålhös (1982), the best-preserved sedimentary sequence on the island of Utö occurs on northeastern Utö.

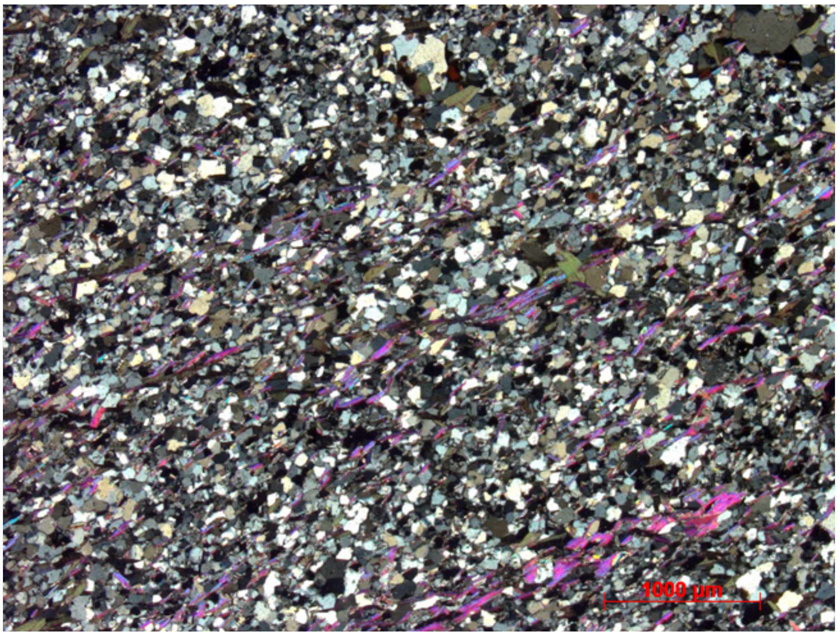


Figure 28. Greywacke of silt to very fine sand grain size with parallel-oriented mica flakes. Sample KBK170028A from Rävstavik västra (6540491/691909). Crossed nicols. Microphotograph: Benno Kathol.

Gavelin et al. (1976) divided this sequence into a unit with greywackes that exhibit decimetre scale alternate bedding of light, sandy layers and dark, more silty-muddy layers containing abundant andalusite and cordierite porphyroblasts. The greywackes contain several metres thick layers of massive arenite and pass to the northwest into a unit of arenite (Gavelin et al. 1976). Graded bedding in the greywackes and cross-bedding in the overlying arenite indicate that the sedimentary sequence is younging to the northwest and that it is stratigraphically overlain by a sequence of felsic volcanic rocks and limestones (Gavelin et al. 1976, Stålhös 1982).

An ignimbritic rhyolite of the overlying volcanic sequence from Nasknäsudd, about 1.8 km northeast of the sampling sites, gave a crystallisation age of 1,904 ± 4 Ma (Lundström et al. 1998), which represents a minimum age for the deposition of the greywacke sequence. The development from greywacke sedimentation over the deposition of thicker arenitic layers to the formation of ignimbritic volcanic rocks has been interpreted by Gavelin et al. (1976) and Lundström et al. (1998) as a transition in the depositional environment from deep to shallow water.

In the Utö area, one sample (Rävstavik västra) was collected from a layered and foliated, recrystallised, grey greywacke with a grain size of silt to very fine sand (Fig. 28). The sampling site below the resting place at the end of the path from Gruvbyn is close to the contact with the overlying felsic volcanic rocks.

Another sample (Rävstavik östra) was collected from a several metres thick sandy layer in the greywacke sequence (Fig. 29) at an old demolished bunker on the headland north of Rävstavik. This sample is of a layered and foliated, recrystallised, grey arenite.

At Rävstavik västra, 140 grains have been prepared, 35 zircon U–Pb dates were obtained, and all of them are within the 90–110% concordia interval, none of the analyses required correction for common lead. The U/Th ratios vary between 2.7 and 10.3, and 69% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 22.9% of the analysed zircons show dates that fall in the age interval 1,850–1,899 Ma and about 62.9% in the interval 1,900–1,949 Ma with a dominating maximum probability peak at 1,914 Ma. About 8.6% of the zircons have dates in the 1,950–1,999 Ma interval without any distinct maximum but belonging to the dominating peak at 1,914 Ma. The youngest zircon was dated to 1,876 Ma and the oldest to 2,075 Ma. Zircons of Archaean age are not recorded (Fig. 30).

Figure 29. Part of a several metres thick succession of sandstone beds in the greywacke sequence close to the site for sample Rävstavik östra (KBK170027A) at an old demolished bunker on the headland north of Rävstavik (6540387/692066). The photo is taken towards the northwest. Width of the photo is about two metres. Photo: Benno Kathol.

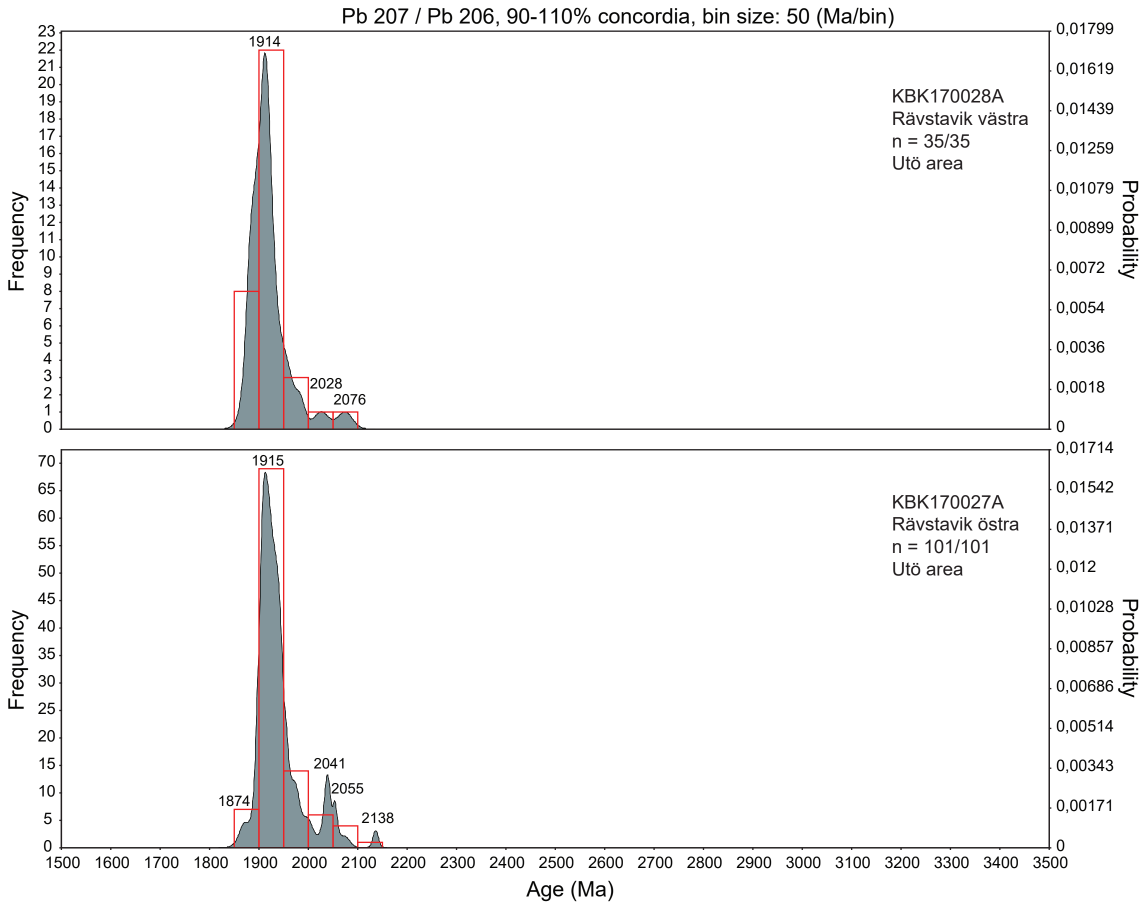


Figure 30. Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from the Utö area with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. Note different vertical scales, corresponding to the number of included analyses.

At Rävstavik östra, 101 zircon U–Pb dates were obtained, and all of them are within the 90–110% concordia interval, 9 analyses required correction for common lead. The U/Th ratios vary between 1.3 and 11.0, and 31% of the analysed zircons have U/Th ratios below 5.0 (see Fig. 32a, b in section *U/Th ratios and youngest zircon*). About 68.3% of the analysed zircons show dates that fall in the age interval 1,900–1,949 Ma with a dominating maximum probability peak at 1,915 Ma. About 13.9% have dates in the interval 1,950–1,999 Ma without any distinct maximum but belonging to the dominating peak at 1,915 Ma. The youngest zircon was dated to 1,865 Ma and the oldest to 2,137 Ma. Zircons of Archaean age are not recorded (Fig. 30).

The minimum age for the greywacke sequence on northeastern Utö of 1,904 Ma is provided by the dating of the rhyolite from Nasknäsudd at the northeasternmost part of Utö (Lundström et al. 1998). In the sample from Rävstavik västra, about 25% of the zircons show dates below the minimum age of 1,904 Ma. At Rävstavik östra this figure is about 8% of the analysed zircons. In both cases, the lowest obtained date is 1,865 Ma. Thus, there are no extremely low dates as for example in the Eskörönningen and Persbacka samples in the Gävle area (Fig. 31a, b). The zircon populations younger than the minimum age show in both samples slightly higher mean U/Th ratios than the populations above the minimum age, 5.5 (n=9) compared with 4.6 (n=26) for the Rävstavik västra and 6.7 (n=8) and 6.1 n=93) for the Rävstavik östra sample. This may indicate influence of a metamorphic event in the time interval 1,850–1,899 Ma.

SUMMARY AND INTERPRETATION OF ALL ANALYSED SAMPLES

A summarising diagram of all obtained ^{207}Pb / ^{206}Pb ages, falling in the 90–110% interval of the Wetherill Concordia is given in figure 31a. The samples are grouped according to sample areas and listed in a roughly north–south geographical order. An exception from this is made for the Udden sample, which has been combined with the samples from the Gävle area, due to the higher metamorphic grade of these rocks. Additionally, the samples from Lindbastmora and Nötbo-Broddbo are shown together.

The lowermost line in figure 31a shows the results from an additional sampling at Siggetorp–Laggarfall in the Närkesberg–Hjortkvarn area. However, this sampling was performed for another purpose (see section *Additional sampling at Siggetorp–Laggarfall 2018*), and for this reason, this sample is not included in the present study.

The samples of this study show Palaeoproterozoic zircon populations in the age interval c. 2.2–1.7 Ga. With the exception for the samples from Eskörönningen, Udden and Utö västra and östra, all samples contain Archaean zircons in different amounts and age intervals.

The analysed samples from Bergslagen and surrounding areas (this study) include only a few or no zircon dates in the age range 2.5–2.2 Ga. This compares well to results of previous studies in Sweden and Finland. Bergman et al. (2008) showed a gap between 2.5 and 2.2 Ga in the zircon material from quartzites and quartz mica schists from the Hamrånge area in the east-central part of the present study area. Sultan et al. (2005) did not report any zircon dates from the age interval 2.68–2.13 Ga in the Västervik quartzites. Williams et al. (2009) have very few zircons in the age range 2.6–2.1 Ga in their samples from Poland, and Claesson et al. (1993) suggested that there is no evidence of 2.6–2.1 Ga protoliths for the Svecofennian sedimentary rocks in central Sweden and southern Finland.

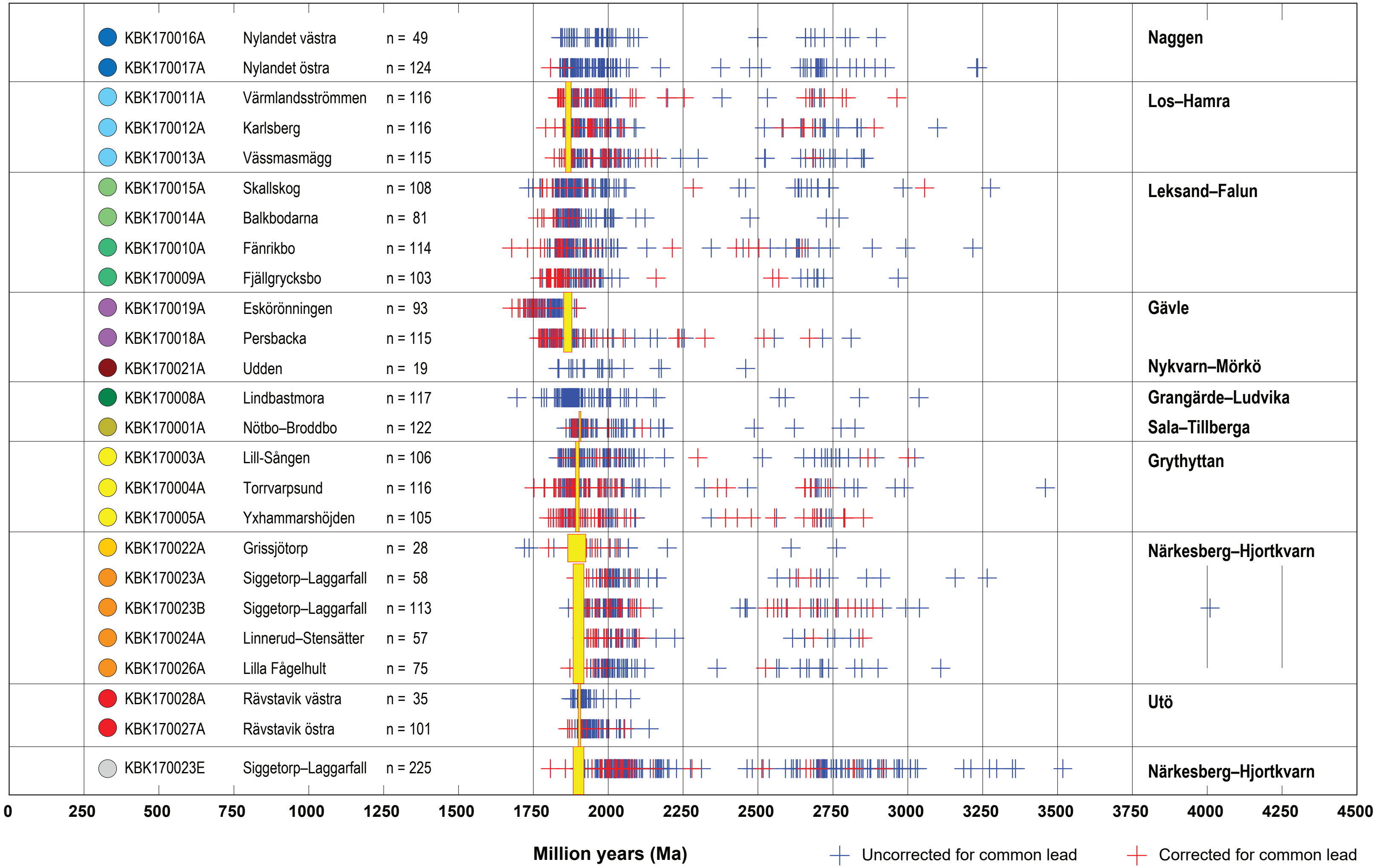


Figure 31a. Diagram summarising the obtained ^{207}Pb / ^{206}Pb ages of all analyses lying in the 90–110% Concordia interval according to Wetherill (1956). The samples are grouped according to sample areas and listed in a roughly north–south geographical order. Dated igneous rocks, constraining the sedimentary sequences, are marked by yellow bars. The coloured dots refer to grouping of the samples, used in the geochemical diagrams (see section *Lithogeochemical analyses*).

Palaeoproterozoic zircons

Figure 31b shows a comparable approach to illustrate the zircon ages in the Palaeoproterozoic age range. In this diagram, the zircon ages are divided into the 50 m.y. intervals similar to the combined frequency histograms and probability density distribution plots (PDP) (e.g. Fig. 3). The frequencies are expressed as percentages of the entire number of analysed zircons per sample, divided into four groups using a fracture method (singularity analysis method; frequency anomalies) as described by Zhu & Cheng (2019). In addition, the 1st, the 2nd and 3rd order probability peaks, if present, are shown within the maximum 50 m.y. intervals for each sample.

Most of the samples from the Bergslagen area show maximum zircon populations in the 50 m.y. intervals 1,850–1,899 and 1,900–1,949 Ma (Fig.31b, c). Exceptions are the two samples from the Naggen area and the Udden sample which also show large zircon populations in the 1,950–1,999 Ma interval. The occurrence of younger maximum zircon populations at Eskörönningen and Persbacka and Fänrikbo and Fjällgrycksbo is probably due to overprint by younger metamorphic events. The oldest maximum zircon populations are found in the 2,000–2,050 Ma interval and occur in the Närkesberg–Hjortkvarn area (Fig. 31b).

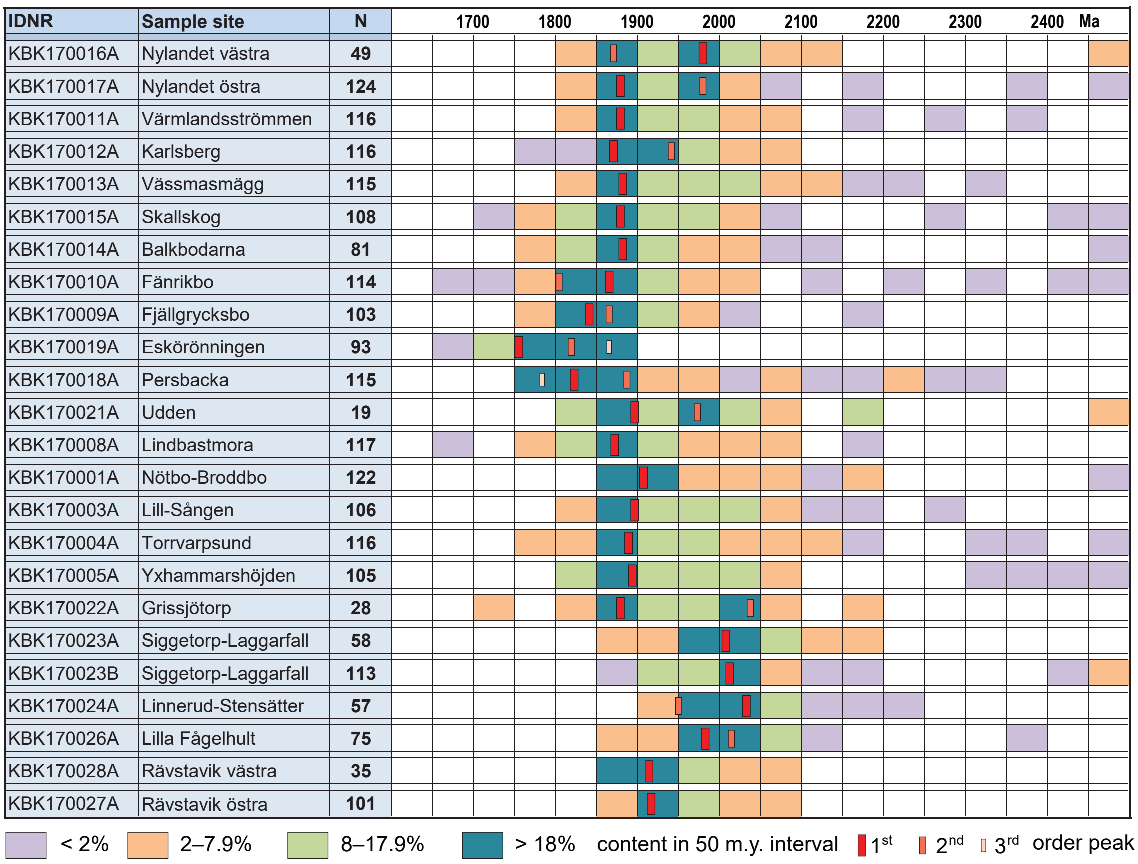


Figure 31b. Diagram summarising the acquired concordant (Wetherill 1956) Palaeoproterozoic ^{207}Pb / ^{206}Pb dates in percentage proportion, divided in intervals of 50 m.y. The samples are listed in the same, roughly north–south geographical order as used in figure 31a. The percentages are defined using a fracture method (singularity analysis method; frequency anomalies) as described in Zhu & Cheng (2019). The 1st, 2nd and 3rd order probability peaks are taken from the combined frequency histograms and probability density distribution plots (PDP) for the 1,500–3,500 Ma age interval (e.g. Fig. 3).

Considering the 50 m.y. age intervals that contain the 1st order peak or maximum probability peak (Fig. 31b, c) on the combined histogram and PDP charts, the general picture is repeated but is more complex. Even in this case, most of the 1st order peak ages occur in the 1,850–1,899 Ma interval or in the 1,900–1,949 Ma interval. The latter is the case for the sample from Nötbo-Broddbo and the samples from Utö. This implies that most of the detrital zircons in these areas include dates that are close to or lie within the time span for the deposition of the sedimentary sequences in these areas. This, in turn, indicates that the sedimentary material has been derived from relatively proximal Svecokarelian intrusive and Svecofennian volcanic rocks, situated in the Fennoscandian Shield. Köykkä et al. (2019) linked Palaeoproterozoic detrital zircon age populations from northern Fennoscandia to the surrounding granitoids in northern Finland and Sweden.

The sedimentary rocks in the Närkesberg–Hjortkvarn area are, or at least belong to, the best-preserved rocks in the studied subareas. In the arenites and arkoses of the Närkesberg formation in the Närkesberg–Hjortkvarn area, the 1st order peaks occur in the 2,000–2,049 Ma interval (Siggetorp–Laggarfall and Linnerud–Stensätter) or in the upper part of the 1,950–1,999 Ma interval. This indicates sediment supply from a >= 2.0 Ga continent, which has not been affected by Svecokarelian metamorphism at the time of erosion and probably also the time of sediment transport. The latter circumstance is indicated by the absence of zircons overprinted by younger metamorphic events in the Närkesberg formation (Fig. 31a).

Continental crust, formed in the interval 2.05–1.95 Ga, with major felsic igneous belts is not exposed in the Fennoscandian Shield. However, Andersson et al. (2011) analysed Hf isotopes in zircon from Svecofennian (Svecokarelian) magmatic rocks and rapakivi granites in Sweden and postulated that their data confirm the existence of juvenile, what they call proto-Svecofennian crust, <2.2–1.9 Ga in age, southwest of the Archaean nucleus in the northern part of the Fennoscandian Shield.

Detrital zircons of up to 2.12 Ga in age were reported by Claesson et al (1993) from central and southern Finland and from Norberg in Bergslagen, by Bergman et al. (2008) from Hamrånge to the north of Bergslagen and surrounding areas, by Sultan et al. (2005) from the Västervik area southeast of the study area and by Lahtinen et al. (2002) from southern Finland. Lahtinnen et al. (2002) tentatively suggested a Sarmatian segment as a possible provenance area for the 2.1–1.95 Ga clastic zircon population in the southern Svecofennian (southern Svecokarelian) orogen.

Bogdanova et al. (2006) described a 2.20–2.10 orogenic and a 2.00–1.95 Ga igneous belt (Osnitsk-Mikashevichi Igneous Belt) from areas southeast of the Fennoscandia–Sarmatia suture. Continental crust of that age was mentioned by Shumlyanskyy et al. (2012). These authors described a 2.10–2.05 Ga amphibolite facies belt with numerous granitic intrusions and a 2.00–1.95 Ga igneous belt in the northwestern part of Sarmatia in the northwestern region of the Ukrainian Shield.

Williams et al. (2009) analysed detrital zircons from two drill cores in northeastern Poland. They found dominant zircon populations at 2.10–1.90 Ga, subordinate late Archaean populations at 2.9–2.7 Ga and a few Archaean grains up to 3.4 Ga. The authors noticed that the dates of their detrital zircons did not match any known igneous rocks currently exposed in the Fennoscandian Shield. Thus, they suggested that the ages match with the 2.00–1.95 Osnitsk-Mikashevichi Igneous Belt on the western margin of Sarmatia. Krzeminska et al. (2013) postulated that the youngest crust in domains close to the margin of Sarmatia include rocks with ages of c. 2.20–2.10 Ga and 2.00–1.95 Ga, respectively.

Thus, it seems likely that the sedimentary rocks of the Närkesberg formation have been derived from the area at the border of the Fennoscandian and Ukrainian Shields, rather than from areas to the north or the northeast. It is possible that detritus from these areas has been

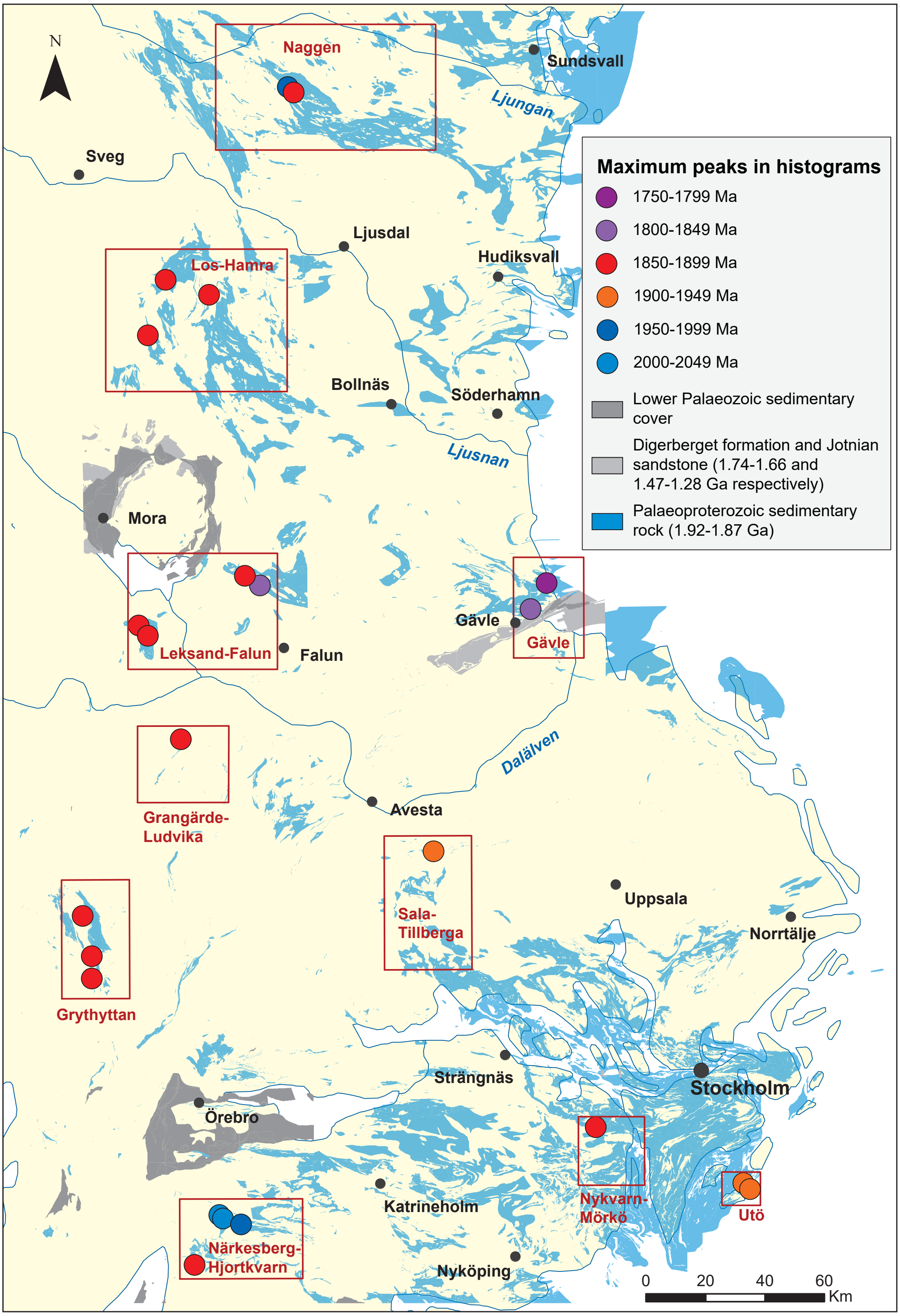


Figure 31c. Map showing the spatial distribution of age intervals with the 1st order peaks, as extracted from the combined histogram and PDP charts (e.g. Fig. 3).

deposited in a marginal basin system adjacent to the Archaean craton, ranging from the present day southern Bergslagen (Närkesberg) to northeastern Poland, and possibly as an interim deposit predating the final emplacement. This is corroborated by Sultan et al. (2005), who ascertained that the age groups documented in the Västervik Basin are poorly represented in the presently exposed crust in the Baltic (Fennoscandian) Shield but on the other hand do occur in Sarmatia.

U/Th ratios and youngest zircon

The Th–U composition of zircon has become an easy-to-acquire and widely used criteria for zircon classification (Rubatto 2017). According to the author, the Th/U ratios of metamorphic zircons are generally lower than 0.1, which corresponds to U/Th higher than 10. Most magmatic zircons have Th/U ratios above 0.1 (e.g. Belousova et al. 2002, Grimes et al. 2015), corresponding to U/Th lower than 10. However, there are exceptions as metamorphic zircons from high and ultra high temperature (> 900°C) rocks can have Th/U > 0.1. In this study, we use the U/Th ratio and set a limit for U/Th ratios at 5, with ratios above that figure indicating metamorphic zircons.

The U/Th ratios of all analysed zircons, which are lying inside the 90–110% Concordia interval, are shown in in figure 32a. Figure 32b shows the number of analysed zircons with U/Th ratios below 5.0, given as percentage of the total amount of analyses per sample.

High U/Th ratios and a low number of zircons having U/Th ratios below 5.0, have, as expected, been found in the higher metamorphic grade rocks in the Gävle area (Figs. 32a, b). High U/Th ratios in zircons occur also in the Leksand–Falun area; especially the sample from Fjällgrycksbo has a low percentage of grains with U/Th ratios below 5.0. Less than 40% of zircons with U/Th ratios below 5.0 are also found in the samples from Nötbo-Broddbo and Rävstavik östra. Elsewhere, the number of zircons with U/Th ratios below 5.0 lies in the interval 40–70% (Fig. 32b).

As expected, the influence of metamorphic events, as most probably shown by high U/Th ratios (above 20) in zircons, is more common in the grains also showing exceptionally low ages (between c. 1,750 and 1,850 Ma). This is valid for analyses, both uncorrected and corrected for common lead (Fig. 33). The feature is most apparent in the samples from the Gävle area (Fig 32a, b).

In figure 34, the spatial distribution of zircon ages in the youngest 50 m.y. interval, which contains at least two percent of the analyses, is shown for each sample. Except for the sample at Grissjötorp in the Närkesberg–Hjortkvarn area, they occur in the central part of Bergslagen and surrounding areas (Grythyttan, Leksand–Falun and Gävle areas and the Lindbastmora sample). Samples with higher ages for the intervals with the youngest zircons occur in the samples from Nötbo-Broddbo and the Utö area, and especially in the samples from the Närkesberg formation in the Närkesberg–Hjortkvarn area which in the latter case is entirely due to the absence of Svecokarelian metamorphic overprint.

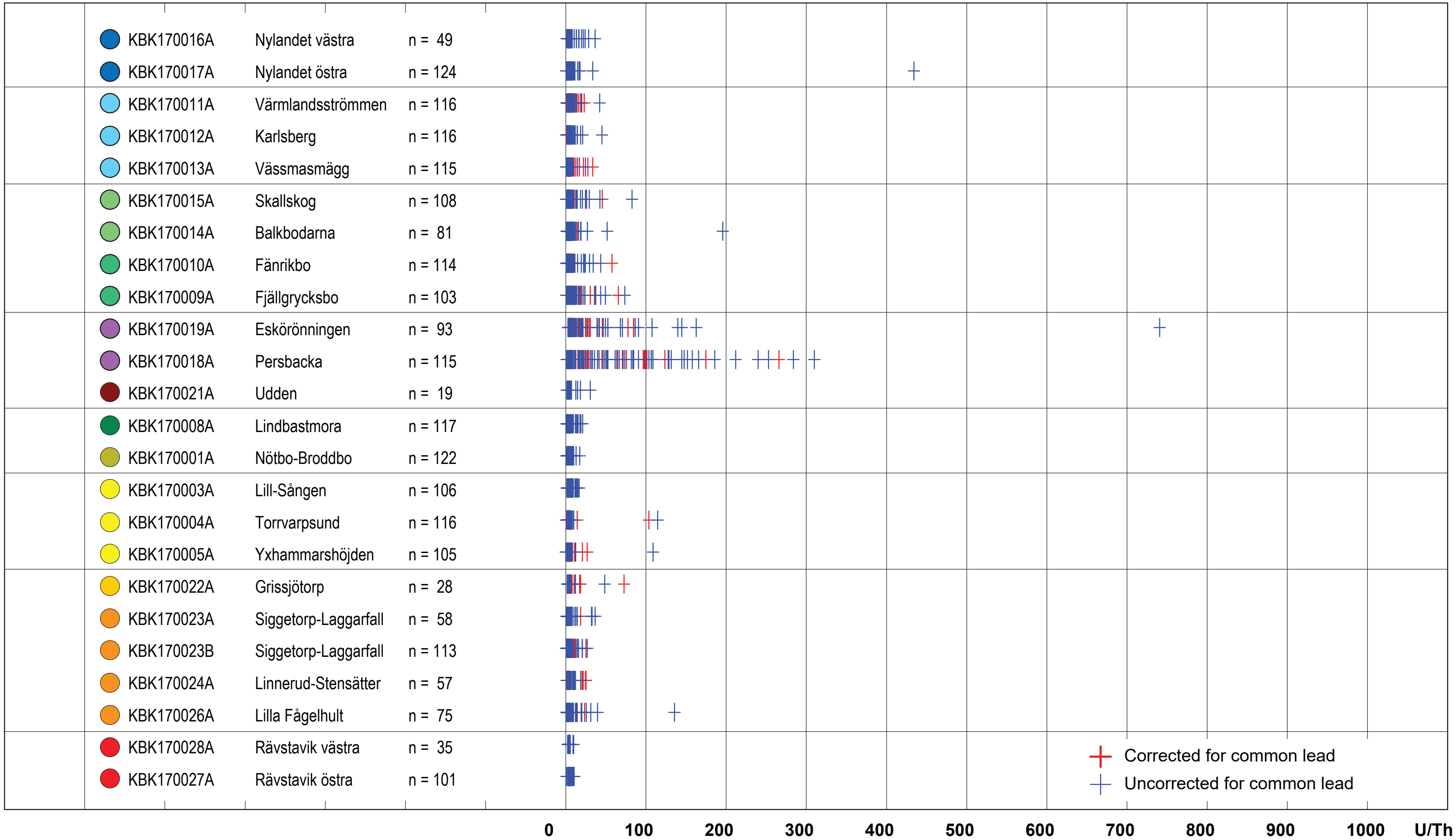


Figure 32a. U/Th ratios of the analysed samples with all analyses within 10% Concordia. The coloured dots refer to grouping of the samples, used in the geochemical diagrams (see section *Lithogeochemical analyses*).

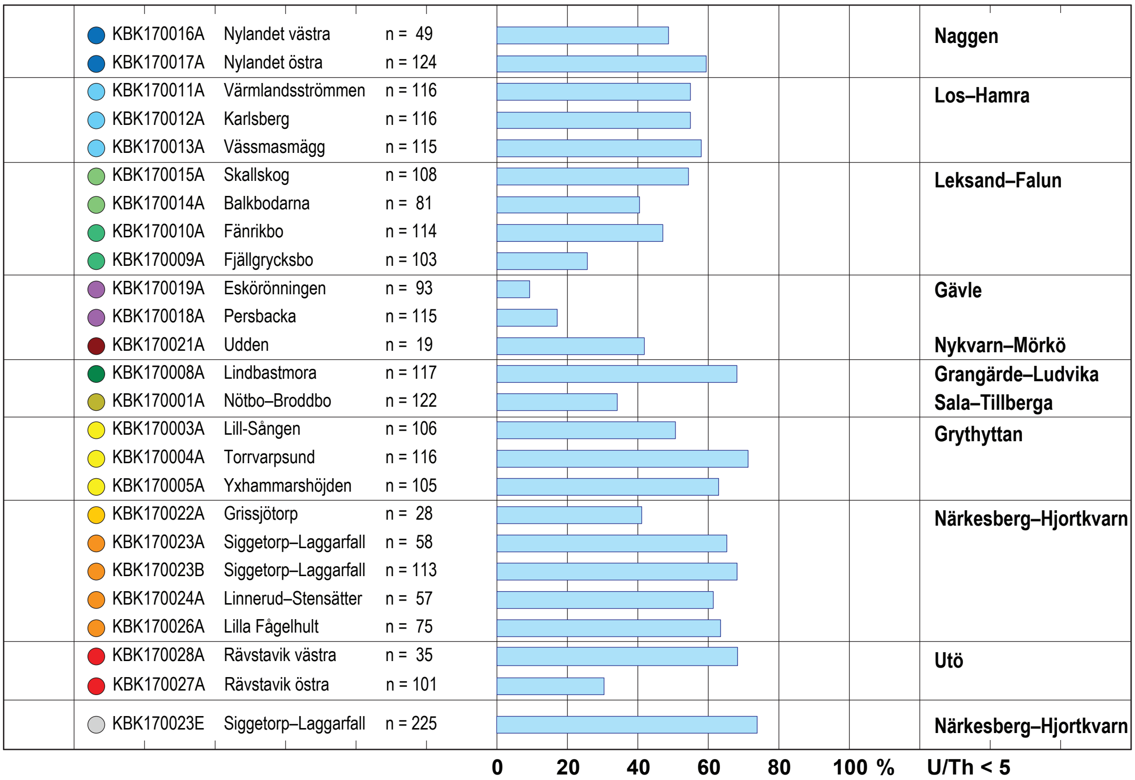


Figure 32b. U/Th ratios below 5.0 of the analysed samples with all analyses within 10% Concordia. The bars show the proportion of U/Th ratios < 5.0 as percentage of the total amount of analyses per sample. The coloured dots refer to grouping of the samples, used in the geochemical diagrams.

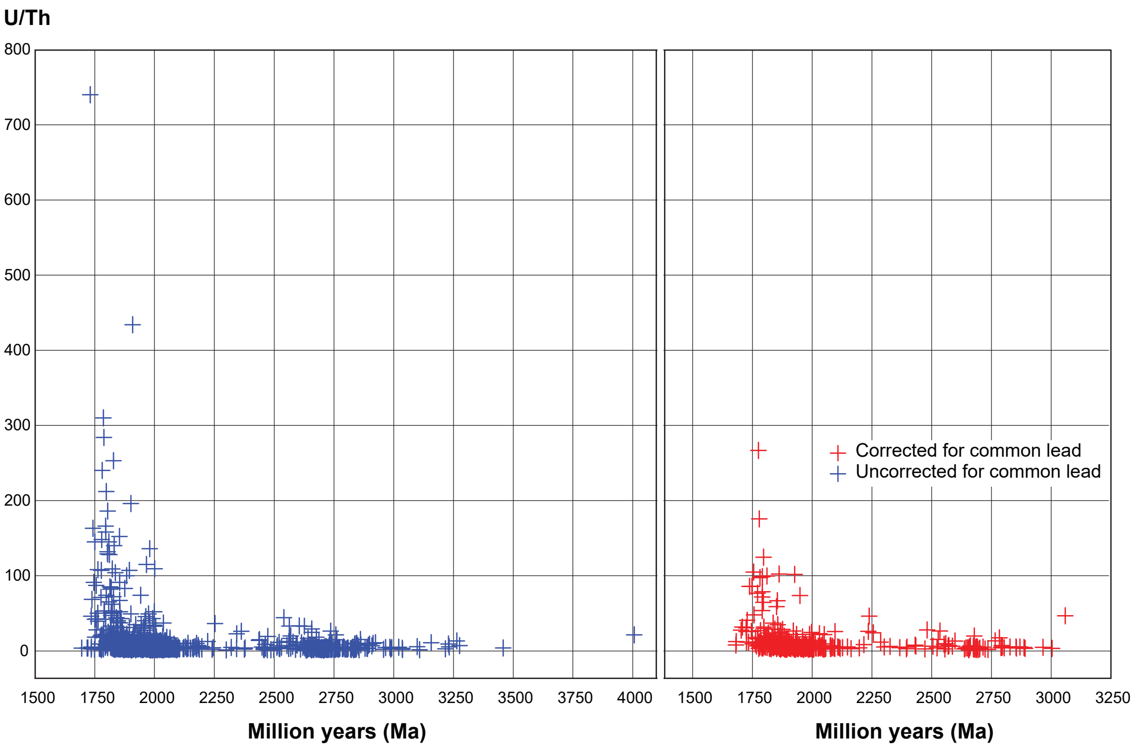


Figure 33. U/Th ratios in zircons of the analysed samples with all analyses within 10% Concordia versus zircon ages.

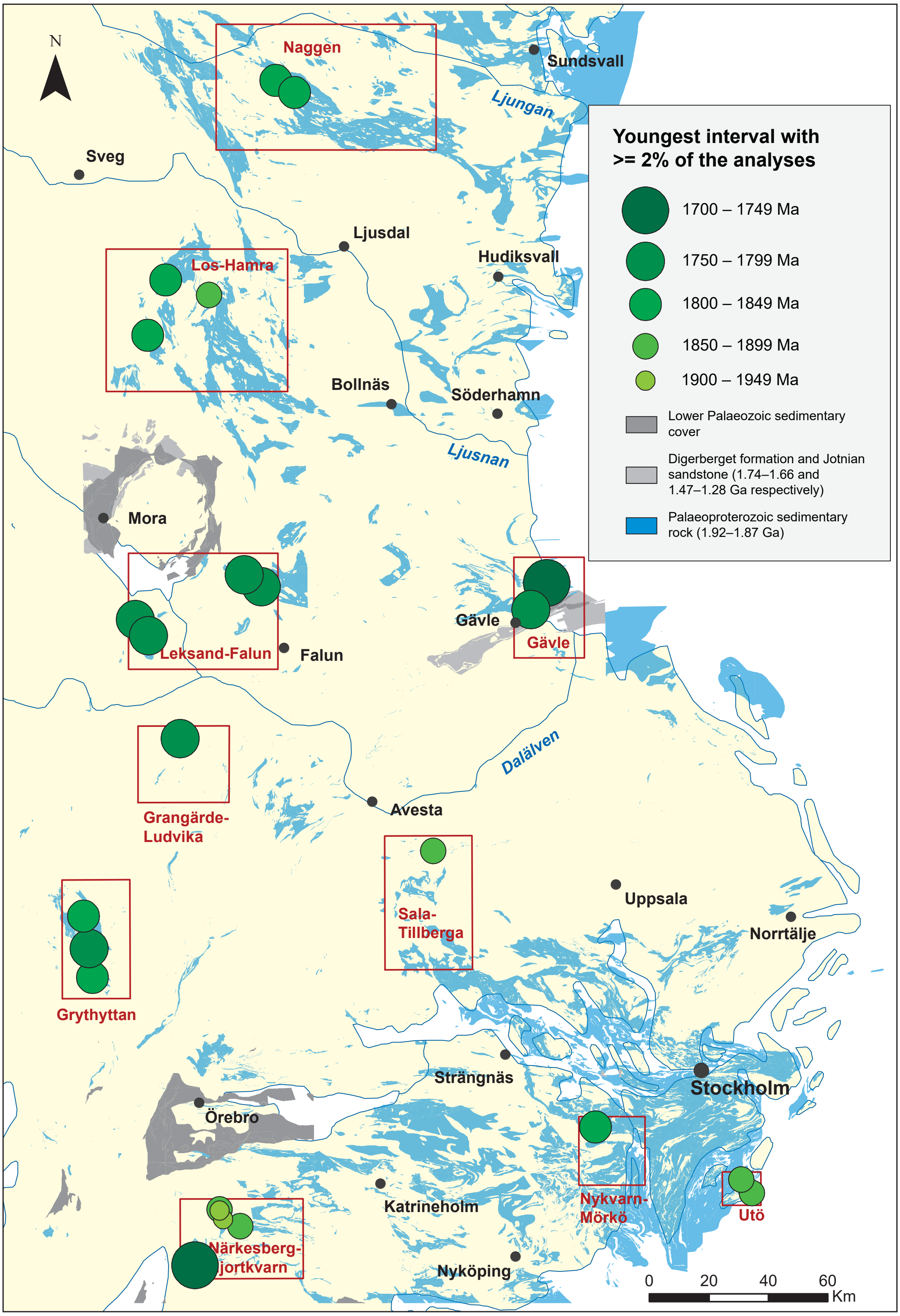


Figure 34. Map showing the distribution of the youngest zircon populations in Bergslagen and surrounding areas. Only intervals (bin size 50 m.y.) with more than two percent of the analysed zircons have been considered (cf. Fig. 31b).

Archaean zircons

Most of the obtained Archaean zircon ages lie in the age interval 2,500–2,949 Ma which is in the Neoarchaean and the late Mesoarchaean (Fig. 35a). Six zircons of Palaeoarchaean age are found, and the oldest zircon is even older.

In northern Fennoscandia, an Archaean continental nucleus comprise 2.80–2.50 Ga old orthogneisses and migmatised gneisses of tonalite–trondhjemite–granodiorite composition and 3.20–2.75 Ga and possibly older supracrustal rocks (Gaál & Gorbetschev 1987, Lindström et al. 2000). It seems likely, that most of the Archaean zircons in Bergslagen and surrounding areas have been derived from here. According to Köykkä et al. (2019), Archaean age populations from northern Fennoscandia have provenances from the surrounding basement complexes of granitoids and tonalite-trondhjemite-granodiorite (TTG) gneisses.

As described above, it is likely that the Palaeoproterozoic zircons in the Närkesberg formation in the Närkesberg–Hjortkvarn area originate from border areas between the Fennoscandian and the Ukrainian Shields in the present southeast of the study area. This suggests that the Archaean zircon populations in the samples from the Närkesberg formation more likely originate from Sarmatia in the southeast, rather than from the Archaean nucleus in the north.

Shchipansky et al. (1996) described three coherent crustal units belonging to the Ukrainian Shield and the Voronezh Massif (Volgo–Uralia). These are the Oskol–Azov, Sumy–Dniepr and Sevsk–Ivulets crustal domains together forming Sarmatia which is the southernmost crustal segment of the East European Precambrian Craton. According to Shchipansky et al. (1996), these three domains have Archaean crustal ages of 3.65–3.0, 3.2–3.1 and 3.1–2.8 Ga, respectively. Thus, these ages indicate that at least the older Archaean zircon populations in the Närkesberg–Hjortkvarn area, and possibly also from other subareas, which show zircons older than 3.2 Ga (cf. Figs. 31a, 35a) have been derived from Sarmatia. Sultan et al. (2005) report Archaean zircon ages of ~3.64 Ga, 3.03–2.95 Ga and 2.72–2.69 Ga from quartzites in the Västervik basin, that are poorly represented in the outcropping crust of the Baltic (Fennoscandian) Shield, however, they are represented in Sarmatia.

Figure 35b shows the spatial distribution of Archaean zircons in Bergslagen and surrounding areas. Most of the Archaean zircons occur in the samples from the southwestern, central western and northwestern parts of the study area, whereas only few or no Archaean zircons were found in the samples from the central and southeastern parts of Bergslagen.

Samples totally lacking Archean zircons are those from Eskörönningen, Udden and Rävstavik västra and östra. The highest amount of Archean zircons occurs in the sample KBK170023B from the massive arenite layer at Siggetorp–Laggerfall. In this sample, the oldest zircon in the study area was also recorded (Kathol et al in prep.).

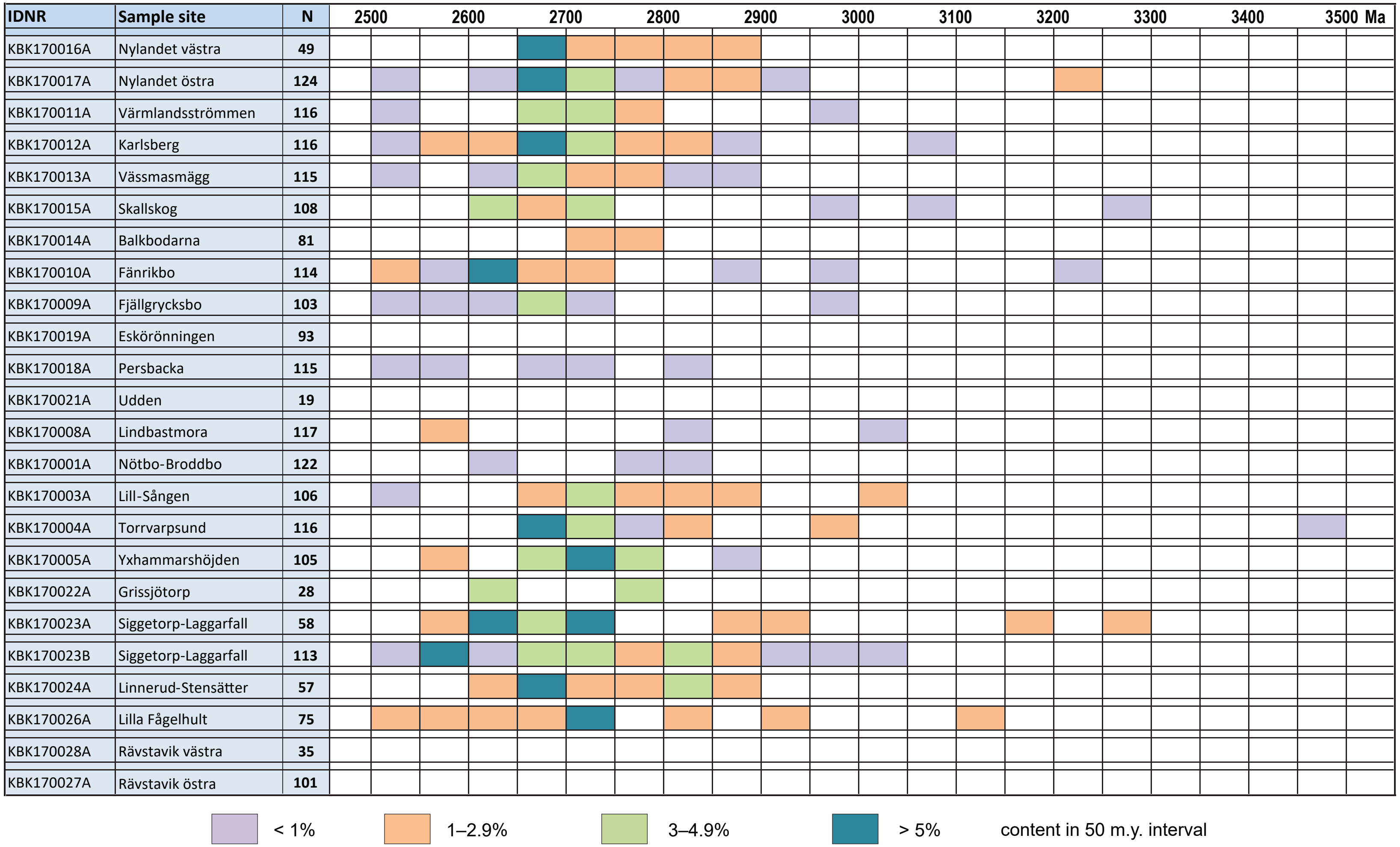


Figure 35a. Diagram summarising the obtained Archaean ^{207}Pb / ^{206}Pb ages, classified after percentage in intervals of 50 m.y., from all analyses, which are lying in the 90–110% Concordia interval according to Wetherill (1956). The samples are listed in the same, roughly north–south geographical order as used in figure 31a.

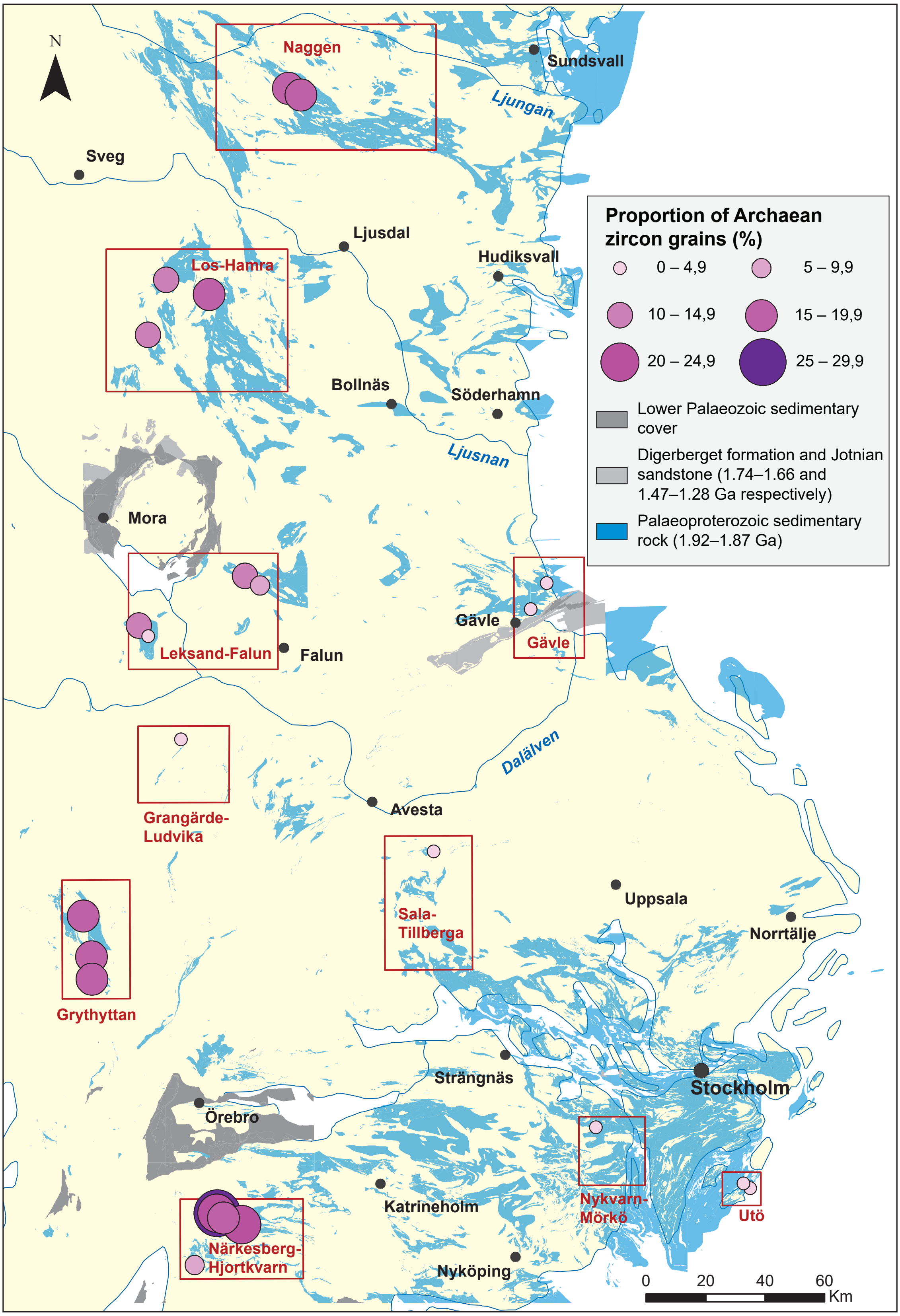


Figure 35b. Map showing the distribution of the proportion of Archaean zircons in each analysed sample in Bergslagen and surrounding areas.

LITHOGEOCHEMICAL ANALYSES

Lithogeoeochemical analyses were performed on all samples by ALS Scandinavia AB using dissolved bulk rock material and the analytical techniques ICP-AES and ICP-MS. However, the two samples that originate from basic volcanic rocks at Norberg-Solfallet and the Håksberg mine in the Grangärde–Ludvika area are excluded from the diagrams.

The results of the lithogeochemical analyses are listed in Appendix 2. They can also be accessed through the map viewer Bergartskemi (in Swedish) at www.sgu.se.

The following diagrams for tectonic setting, provenance and mineral composition must be considered as a complementary, fairly uncertain attempt to describe and classify the sedimentary rocks of this project. They might be quite useful to demonstrate the uncertainty in the interpretation of lithogeochemical analyses done on metamorphic Palaeoproterozoic sedimentary rocks. Nevertheless, they show some consistent results that locally are consistent with the general concept that the bedrock in the entire Bergslagen region was formed at a convergent, active continental plate margin (Stephens et al. 2009, Stephens & Jansson 2020). With that in mind some geochemical diagrams are shown here.

The K_2O/Na_2O versus SiO_2 discrimination diagram for tectonic settings of sandstones and mudstones according to Roser & Korsch (1986) shows an almost explicit spatial distribution of the analysed samples (Fig. 36a, b). Those from the northern, western and central parts of the area plot in a passive margin tectonic setting, whereas those from the eastern and southern parts plot in an active continental margin setting. The diagram thus does not support the above-named general concept of a convergent, active continental plate margin.

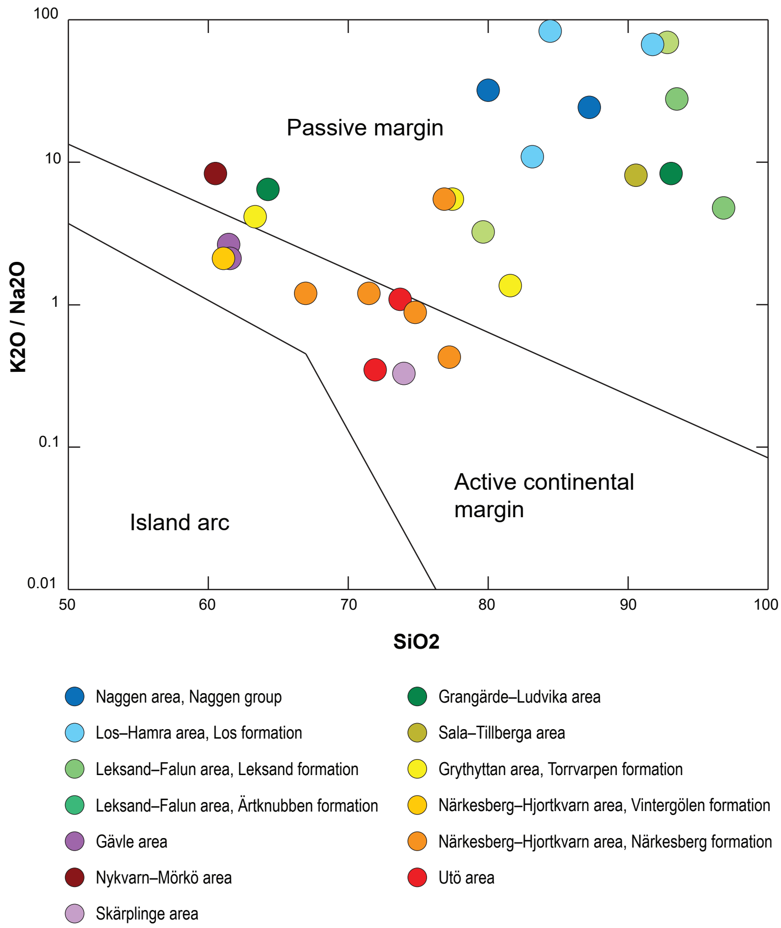


Figure 36a. Discrimination diagram for sandstones and mudstones, using K_2O/Na_2O versus SiO_2, obtained after volatile-free adjustment of the ten major elements to 100 wt.%. (Roser & Korsch 1986).

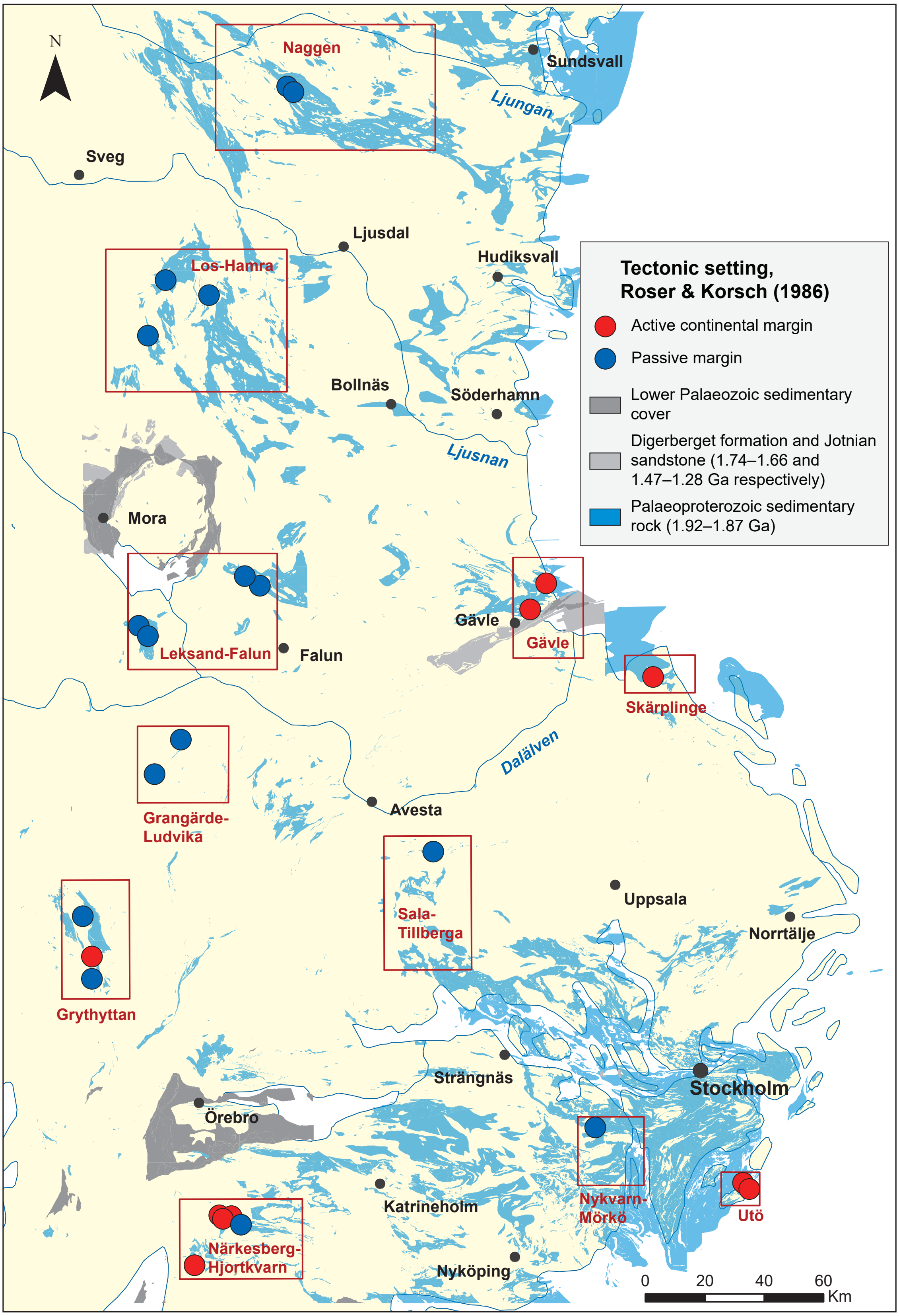


Figure 36b. Spatial distribution of different tectonic settings, according to Roser & Korsch (1986) in Bergslagen and surrounding areas.

The sample from Lilla Fågelhult in the eastern part of the Närkesberg formation plots in the field of passive margin which contrasts to the other samples from the Närkesberg–Hjortkvarn area, which all settle in the active margin field. This configuration of the samples from the Närkesberg–Hjortkvarn area is repeated in the discrimination diagram of Bathia (1983) which is shown in figure 37a.

The results from the diagram of Roser & Korsch (1986; figure 36a, b) are in contrast to the corresponding discrimination diagram for sandstones, using discriminant functions for major elements according to Bhatia (1983; figure 37a, b). Here, the picture is more complicated, in that way, that the samples from several areas (Los–Hamra, Leksand–Falun, Grangärde–Ludvika and Närkesberg–Hjortkvarn) plot in both active continental margin and passive margin settings. However, according to the diagram, an active continental margin setting is dominating in the southwestern, southeastern, eastern and northern parts of the area. In the northwestern part, indications for both active continental and passive margin settings occur.

The discriminant diagram of Roser & Korsch (1988; Fig. 38a) is used to evaluate the overall petrological character of the source areas of sandstones and mudstones. The method is suggested by the authors to be a viable technique for provenance determination which is largely independent of grain-size effects.

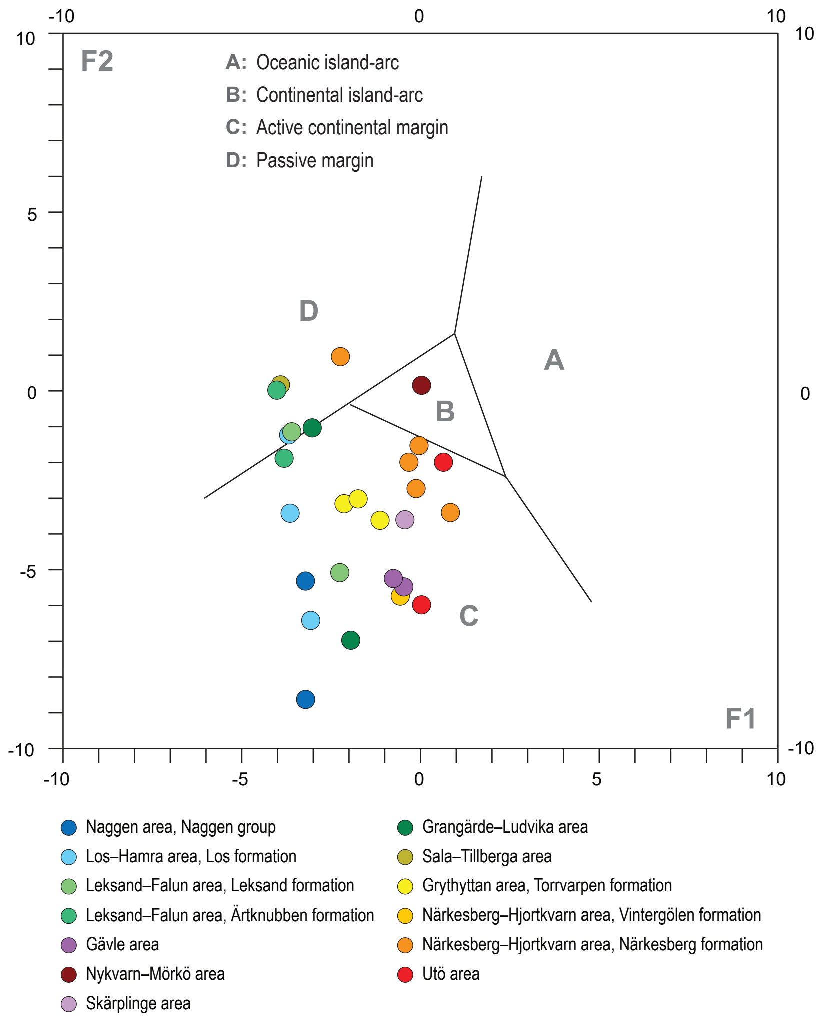


Figure 37a. Discrimination diagram for sandstones, using discriminant functions for major elements. After Bhatia (1983).

Discriminant function F1 = $- 0.0447\ SiO_2 - 0.972\ TiO_2 + 0.008\ Al_2O_3 - 0.267\ Fe_2O_3 + 0.208\ FeO - 3.082\ MnO + 0.140\ MgO + 0.195\ CaO + 0.719\ Na_2O - 0.032\ K_2O + 7.510\ P_2O_5 + 0.303$

Discriminant function F2 = $- 0.421\ SiO_2 + 1.988\ TiO_2 - 0.526\ Al_2O_3 - 0.551\ Fe_2O_3 - 1.610\ FeO + 2.720\ MnO + 0.881\ MgO - 0.907\ CaO - 0.177\ Na_2O - 1.840\ K_2O + 7.244\ P_2O_5 + 43.57$

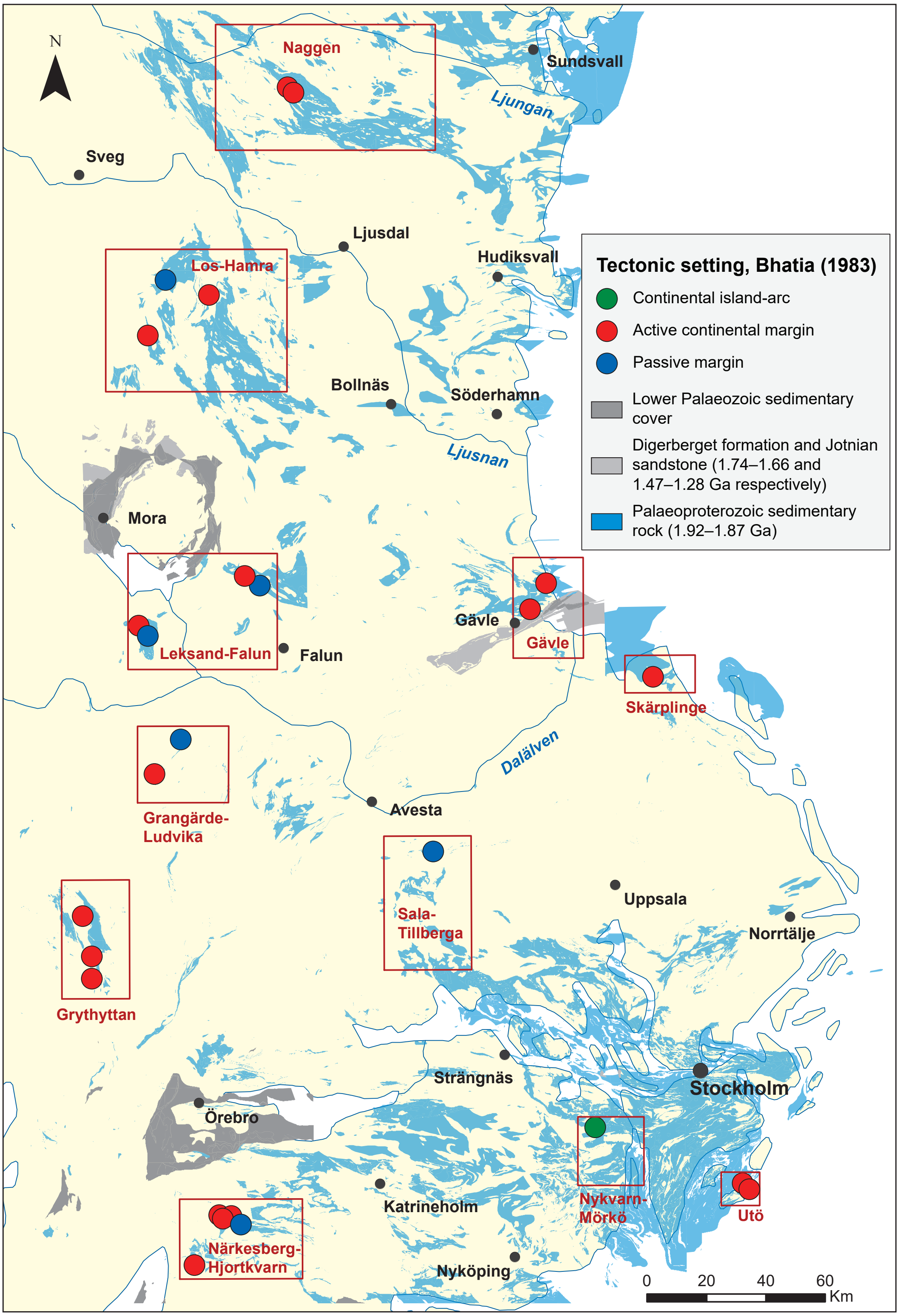


Figure 37b. Spatial distribution of different tectonic settings, according to Bhatia (1983) in Bergslagen and surrounding areas.

Most of the samples plot in the field for a quartzose sedimentary provenance, which indicates mature polycyclic quartzose detritus as source material. A felsic igneous provenance is indicated for the samples from Siggetorp–Laggarfall and Linnerud–Stensätter in the Närkesberg formation, and for the sample from Rävstavik östra at the island of Utö, an intermediate igneous provenance is suggested for the samples from Grissjötorp in the Vintergölen formation, Barknåre in the Skärplinge area and Rävstavik västra on the island of Utö.

A map over the spatial distribution of the inferred provenances (Fig. 38b) shows that the sedimentary rocks in the northern, northwestern and central parts of the Bergslagen area consistently have a quartzose sedimentary provenance. In the eastern part of the area, intermediate to felsic igneous provenances prevail, with the exception for the paragneiss at Udden in the Nykvarn–Mörkö area.

In the Närkesberg–Hjortkvarn area, three provenance groups have contributed. The turbiditic greywackes of the Vintergölen formation show an intermediate igneous provenance, and the arenites in the western part of the Närkesberg formation a felsic igneous provenance. In this diagram too, samples from the eastern part of the Närkesberg formation plot differently from those of the western part, showing quartzose sedimentary provenance at Haddebo and Lilla Fågelhult (cf. Figs 36, 37).

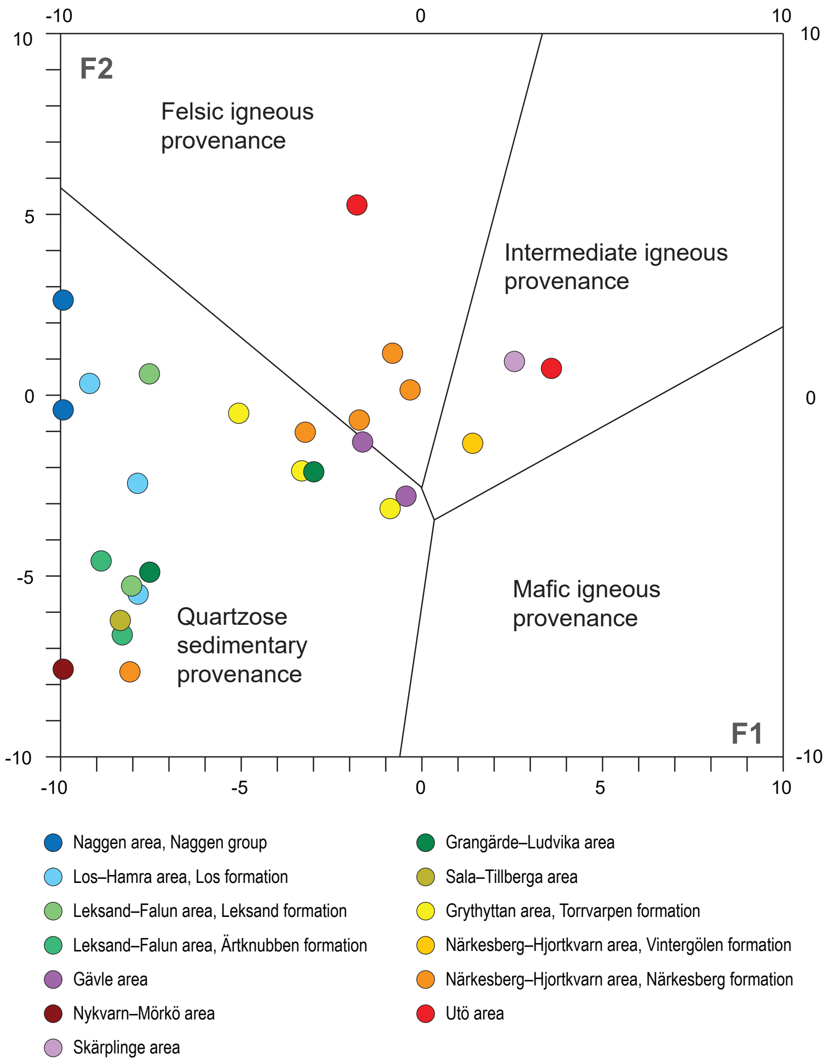


Figure 38a. Discrimination diagram for the provenance signature of sandstones and mudstones, using discriminant functions for major elements. After Roser & Korsch (1988).

Discriminant function F1 = $-1.773\ TiO_2 + 0.607\ Al_2O_3 + 0.760\ Fe_2O_{3(total)} - 1.500\ MgO + 0.616\ CaO + 0.509\ Na_2O - 1.224\ K_2O - 9.09$

Discriminant function F2 = $0.445\ TiO_2 + 0.070\ Al_2O_3 - 0.250\ Fe_2O_{3(total)} - 1.142\ MgO + 0.438\ CaO + 1.475\ Na_2O + 1.426\ K_2O - 6.861$

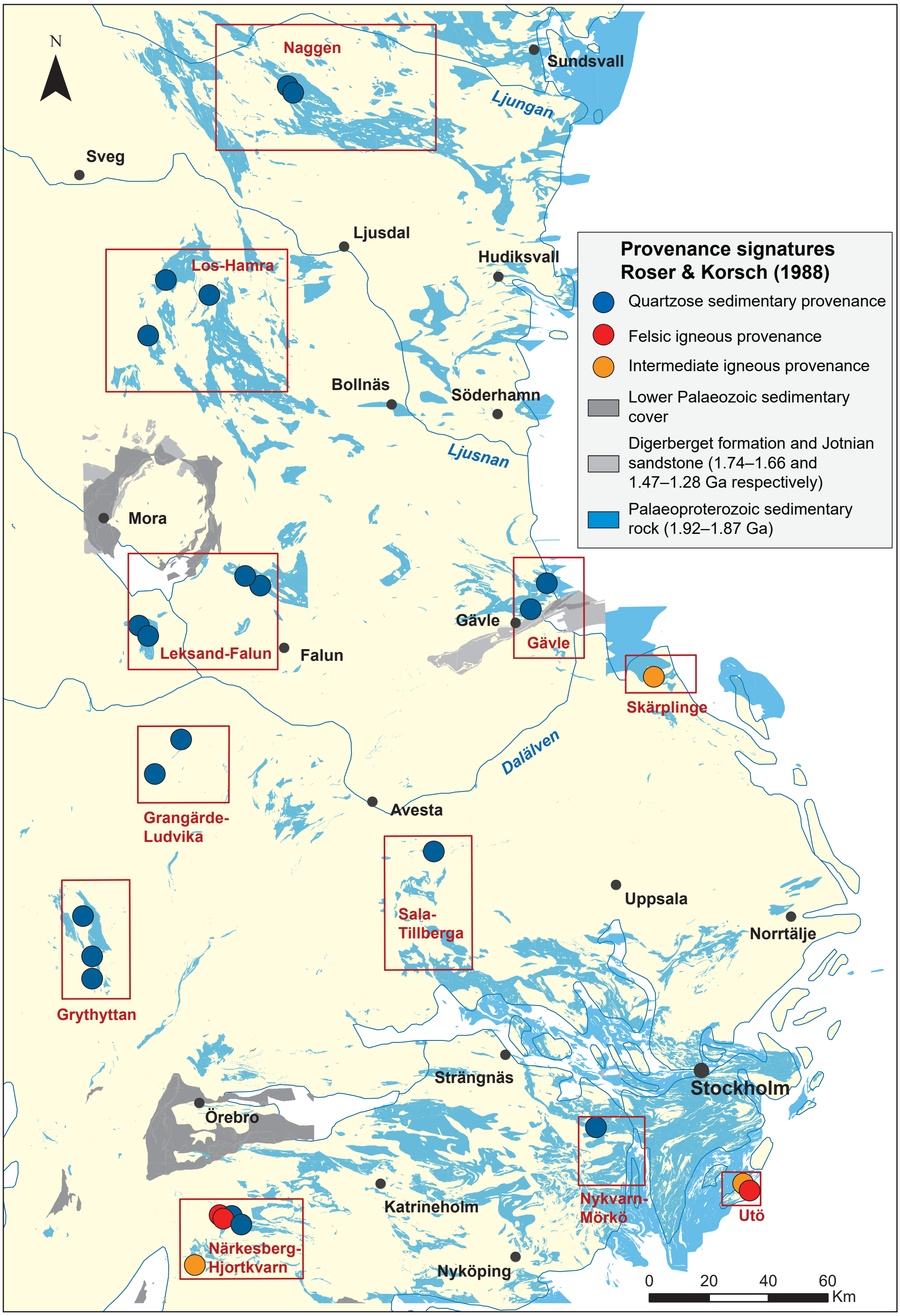


Figure 38b. Spatial distribution of different provenance signatures, according to Roser & Korsch (1988) in Bergslagen and surrounding areas.

None of the samples plot in the field of a mafic igneous provenance, probably according to the scope of this project. A mafic igneous provenance implies first-cycle basaltic and lesser andesitic detritus, which probably is not preserved in rocks which were sampled with the main scope of zircon analyses.

Two more recent multi-dimensional diagrams for tectonic discrimination of siliciclastic sediments (owing their origin mainly to land sources) with application to Precambrian basins has been proposed by Verma & Armstrong-Altrin (2013). The discriminant functions are based on major elements (oxides) and plots for high silica (SiO_{2adj} = 63–95%) and low silica rocks (SiO_{2adj} = 35–63%), respectively, have been constructed. SiO_{2adj} refers to the SiO_2 value obtained after volatile-free adjustment of the ten major-elements to 100 wt.%.

Most of the samples from Bergslagen and surrounding areas have an SiO_{2adj} value above 63% and the diagram for these high silica rocks is shown in figure 39a. Figure 39b shows the diagram for the remaining, low silica rocks, which in this case are the highly metamorphic rocks of the Gävle and the Nykvarn–Mörkö areas and the turbiditic greywacke from Grissjötorp in the Närkesberg–Hjortkvarn area.

The analysed samples from the northern, western and central parts of the study area form a cluster in the field for rocks with collision tectonic provenances (Fig. 39a). Most variable tectonic provenances were recorded for the samples of the Närkesberg–Hjortkvarn area. The samples of the Närkesberg formation from Siggetorp–Laggarfall and Linnerud–Stensätter suggest an island or continental arc origin, whereas the sample from the Vintergölen formation from Grissjötorp has a continental rift signature (Fig. 39a, b, c). As in most other diagrams (Figs. 36a, b; 37a, b; 38a, b), the sample from Lilla Fågelhult in the eastern part of the Närkesberg formation shows a different signature than the other samples from that area (Fig 39a, c). Contradictory signatures were also recorded in the Gävle, Skärplinge and Utö areas in the eastern part of the study area with continental rift and island or continental arc provenances, respectively.

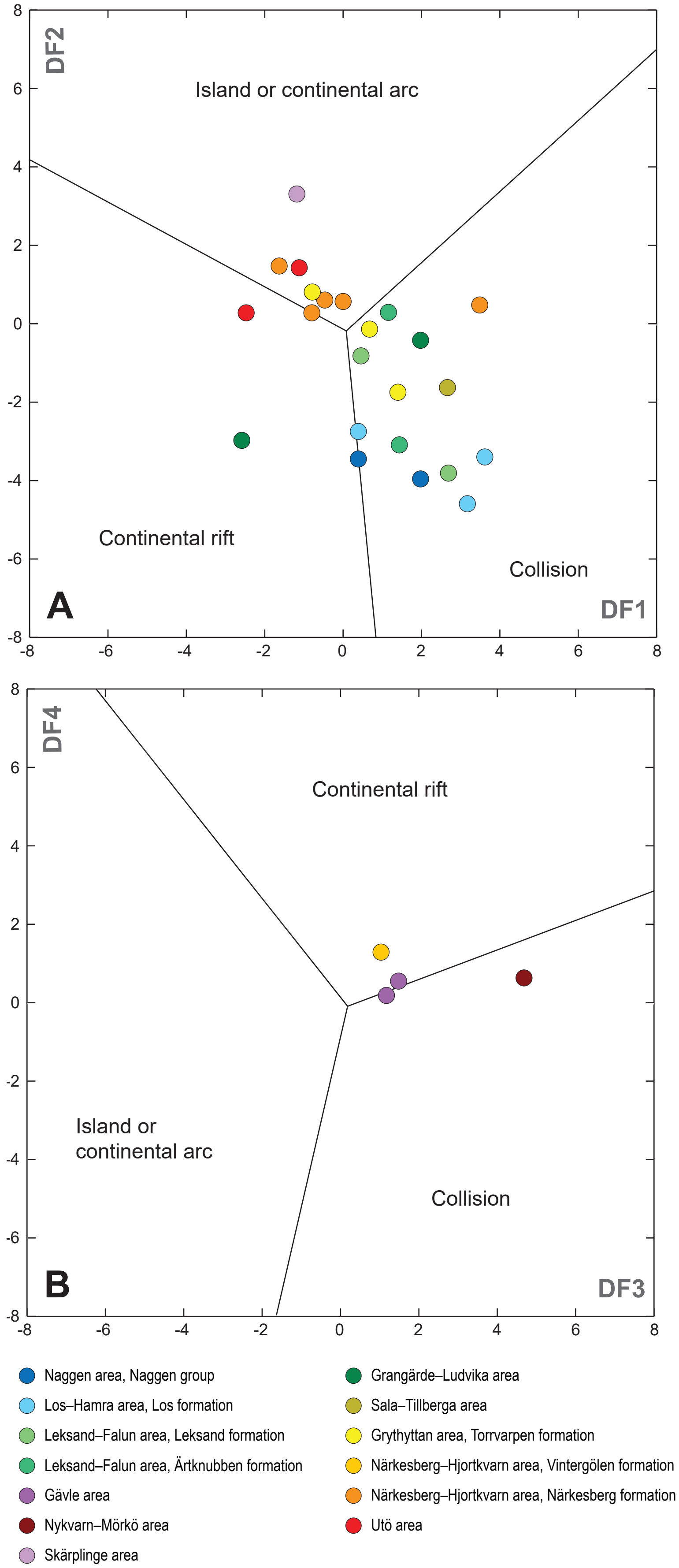
▶ **Figure 39ab.** Discriminant-function multi-dimensional diagrams, using major elements for three tectonic provenance settings after Verma & Armstrong-Altrin (2013). **A**. Diagram for high silica rocks with $SiO_{2(adj)}$ = 63–95%. **B**. Diagram for low silica rocks with $SiO_{2(adj)}$ = 35–63%.

$DF1 = (-0.263 \times \ln(TiO_2/SiO_2)_{adj}) + (0.604 \times \ln(Al_2O_3/SiO_2)_{adj}) + (-1.725 \times \ln(Fe_2O_3/SiO_2)_{adj}) + (0.660 \times \ln(MnO/SiO_2)_{adj}) + (2.191 \times \ln(MgO/SiO_2)_{adj}) + (0.144 \times \ln(CaO/SiO_2)_{adj}) + (-1.304 \times \ln(Na_2O/SiO_2)_{adj}) + (0.054 \times \ln(K_2O/SiO_2)_{adj}) + (-0.330 \times \ln(P_2O_5/SiO_2)_{adj}) + 1.588$

$DF2 = (-1.196 \times \ln(TiO_2/SiO_2)_{adj}) + (1.064 \times \ln(Al_2O_3/SiO_2)_{adj}) + (0.303 \times \ln(Fe_2O_3/SiO_2)_{adj}) + (0.436 \times \ln(MnO/SiO_2)_{adj}) + (0.838 \times \ln(MgO/SiO_2)_{adj}) + (-0.407 \times \ln(CaO/SiO_2)_{adj}) + (1.021 \times \ln(Na_2O/SiO_2)_{adj}) + (-1.706 \times \ln(K_2O/SiO_2)_{adj}) + (-0.126 \times \ln(P_2O_5/SiO_2)_{adj}) - 1.068$

$DF3 = (0.608 \times \ln(TiO_2/SiO_2)_{adj}) + (-1.854 \times \ln(Al_2O_3/SiO_2)_{adj}) + (0.299 \times \ln(Fe_2O_3/SiO_2)_{adj}) + (-0.550 \times \ln(MnO/SiO_2)_{adj}) + (0.120 \times \ln(MgO/SiO_2)_{adj}) + (0.194 \times \ln(CaO/SiO_2)_{adj}) + (-1.510 \times \ln(Na_2O/SiO_2)_{adj}) + (1.941 \times \ln(K_2O/SiO_2)_{adj}) + (0.003 \times \ln(P_2O_5/SiO_2)_{adj}) - 0.294$

$DF4 = (-0.554 \times \ln(TiO_2/SiO_2)_{adj}) + (-0.995 \times \ln(Al_2O_3/SiO_2)_{adj}) + (1.765 \times \ln(Fe_2O_3/SiO_2)_{adj}) + (-1.391 \times \ln(MnO/SiO_2)_{adj}) + (-1.034 \times \ln(MgO/SiO_2)_{adj}) + (0.225 \times \ln(CaO/SiO_2)_{adj}) + (0.713 \times \ln(Na_2O/SiO_2)_{adj}) + (0.330 \times \ln(K_2O/SiO_2)_{adj}) + (0.637 \times \ln(P_2O_5/SiO_2)_{adj}) - 3.631$


DF2
Island or continental arc
Continental rift
Collision
A
DF1
DF4
Continental rift
Island or continental arc
Collision
B
DF3
Naggen area, Naggen group
Los–Hamra area, Los formation
Leksand–Falun area, Leksand formation
Leksand–Falun area, Ärtknubben formation
Gävle area
Nykvarn–Mörkö area
Skärplinge area
Grangärde–Ludvika area
Sala–Tillberga area
Grythyttan area, Torrvarpen formation
Närkesberg–Hjortkvarn area, Vintergölen formation
Närkesberg–Hjortkvarn area, Närkesberg formation
Utö area

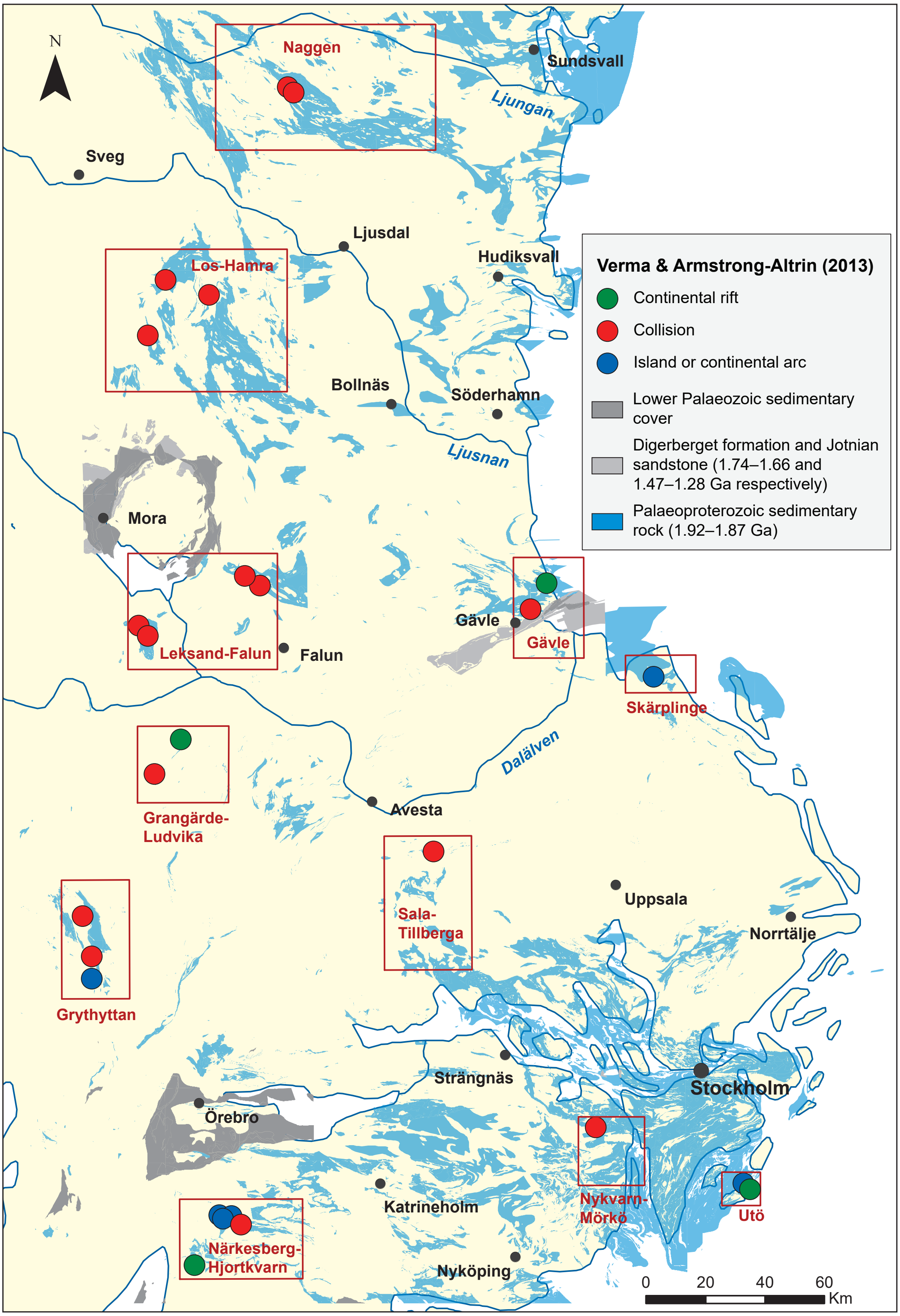


Figure 39c. Spatial distribution of different tectonic provenance settings, according to Verma & Armstrong-Altrin (2013) in Bergslagen and surrounding areas.

The diagrams for tectonic setting and provenance (Figs. 36–39) are based on major elements. Trace elements are used in sedimentary geochemistry only in a minor extent. Bhatia & Crook (1986) studied Palaeozoic turbidite sequences and identified immobile trace elements such as La, Ce, Nd, Th, Zr, Nb, Y, Sc and Co being very useful in discrimination of tectonic settings. They constructed distinctive fields for oceanic island-arc, continental island-arc, active continental margin and passive margin. In figure 40 a,b, the trivariate diagrams La–Th–Sc and Th–Sc–Zr/10 are shown. In the first diagram (Fig. 40a), the fields for active continental margin and passive margin are overlapping.

Figure 40c, d show the spatial distribution of the obtained tectonic settings. The results from both diagrams are not consistent, neither to each other nor to the results of the diagram of Bhatia (1983; Figs. 37a, b). Furthermore, they do not support the above-named general concept that the bedrock in the entire Bergslagen region was formed at a convergent, active continental plate margin (Stephens et al. 2009, Stephens & Jansson 2020). Thus, diagrams, based on immobile trace elements might also be quite useful to demonstrate the uncertainty in the interpretation of lithogeochemical analyses done on metamorphic Palaeoproterozoic sedimentary rocks.

The diagrams by Pettijohn et al. (1972; Fig. 41a) and Herron (1988; Fig. 41b) are attempts to mineralogical classifications of sedimentary rocks by lithogeochemical analyses. It is not used for rock classification in this study, but it is interesting that these diagrams show a grouping of samples from the southern part of the area (reddish–orange–yellow symbols) and from the northern part (bluish and greenish symbols). This was also observed in other geochemical diagrams (Figs. 36a, 37a, 38a and 39a). Values in the diagram of Pettijohn et al. (1972; Fig. 41a) for log (Na_2O/K_2O) below -1 depend on unusually low values for Na_2O.

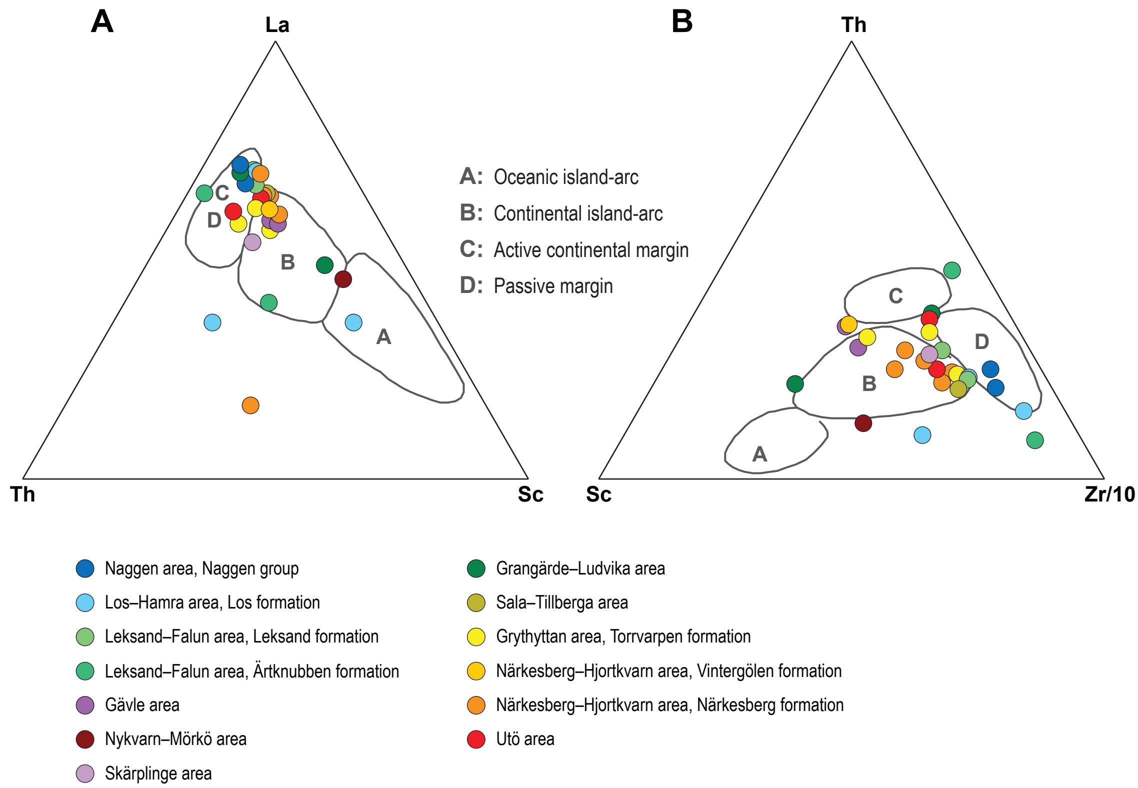


Figure 40ab. Discrimination diagrams based on immobile trace elements and designed for greywackes in Palaeozoic turbidite sequences after Bhatia & Crook (1986). **A.** La-Th-Sc diagram. **B.** Th-Sc-Zr/10 diagram.

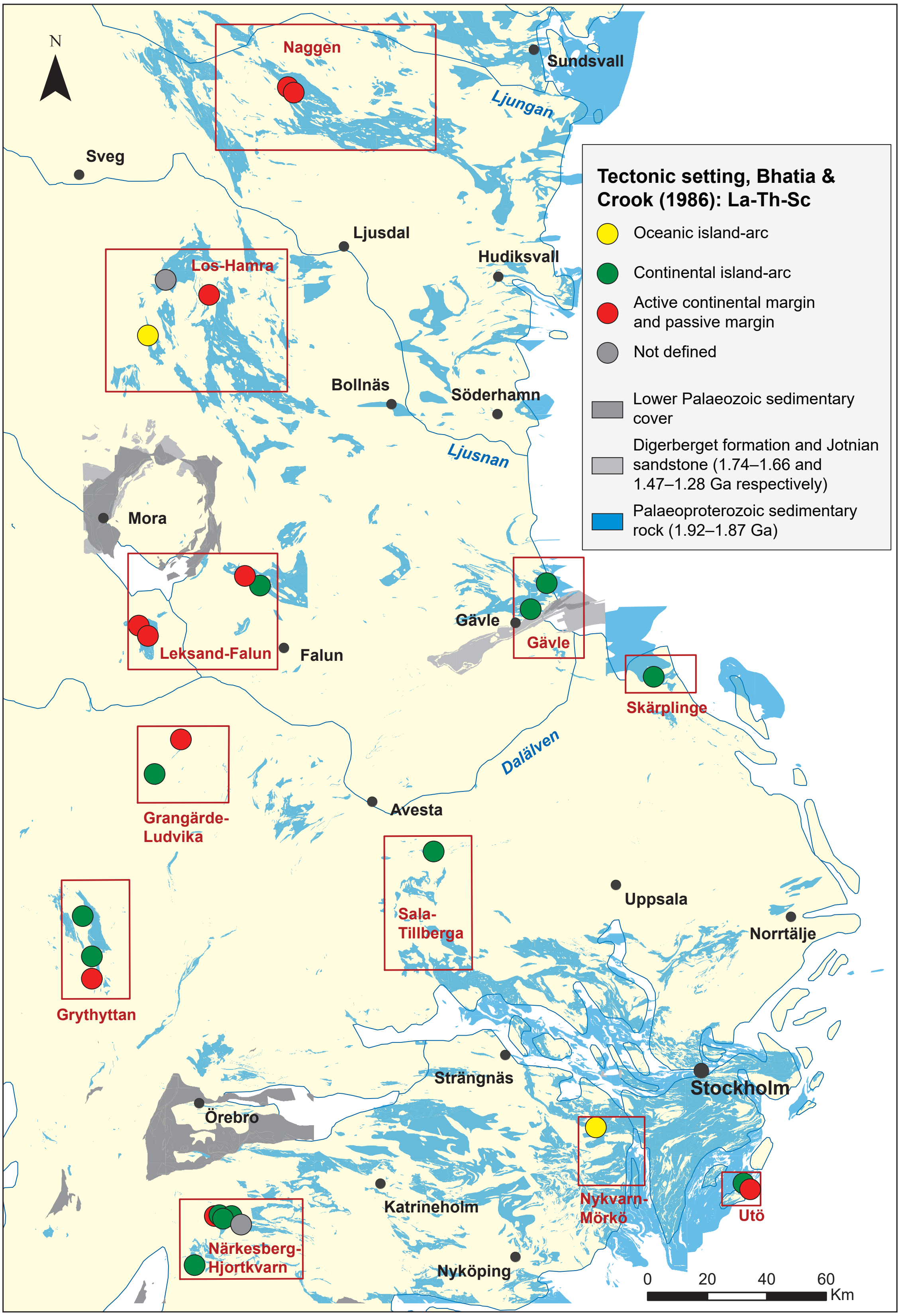


Figure 40c. Spatial distribution of different tectonic settings, according to Bhatia & Crook (1986) in Bergslagen and surrounding areas. According to the La-Th-Sc diagram.

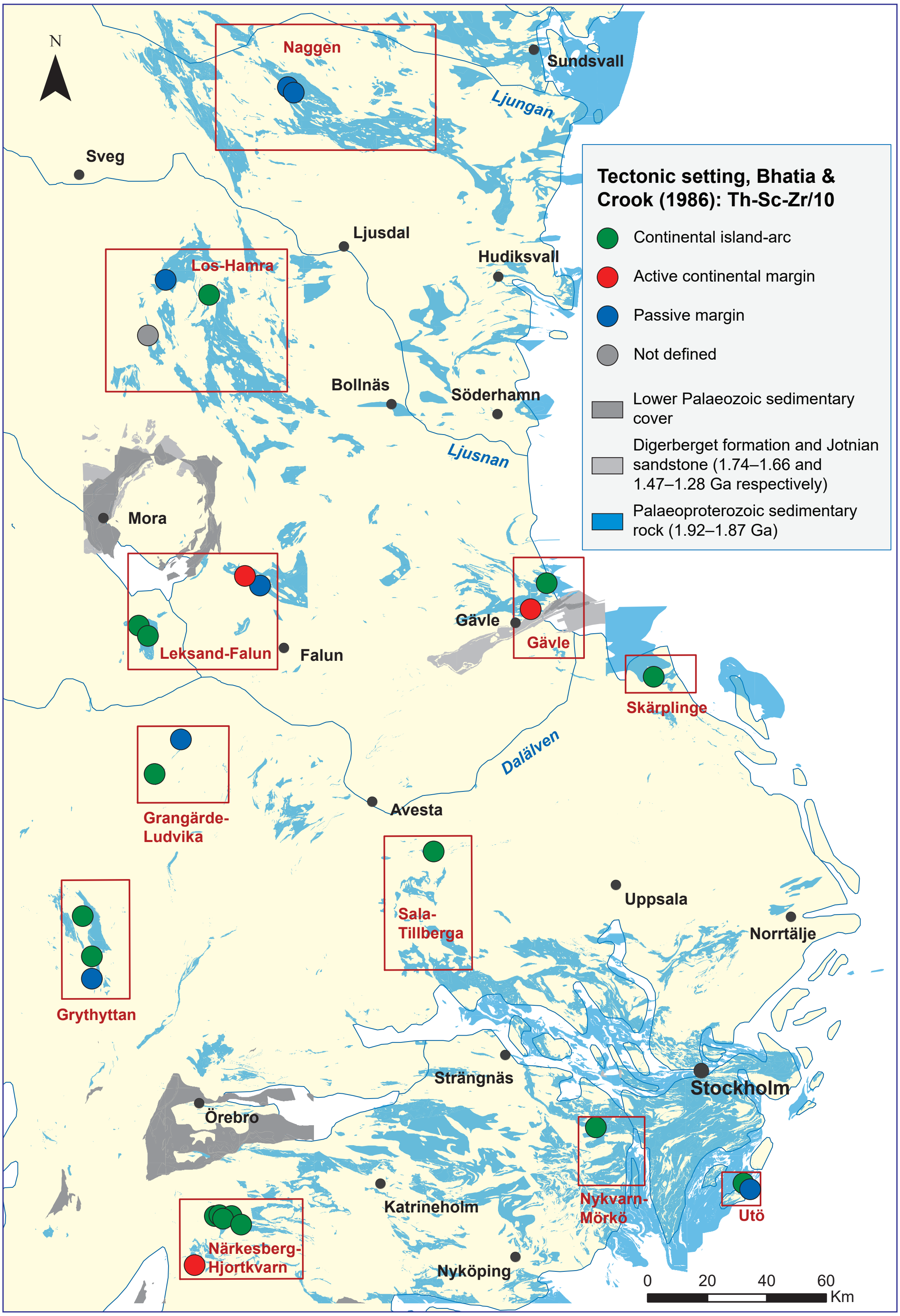


Figure 40d. Spatial distribution of different tectonic settings, according to Bhatia & Crook (1986) in Bergslagen and surrounding areas. According to the Th-Sc-Zr/10 diagram.

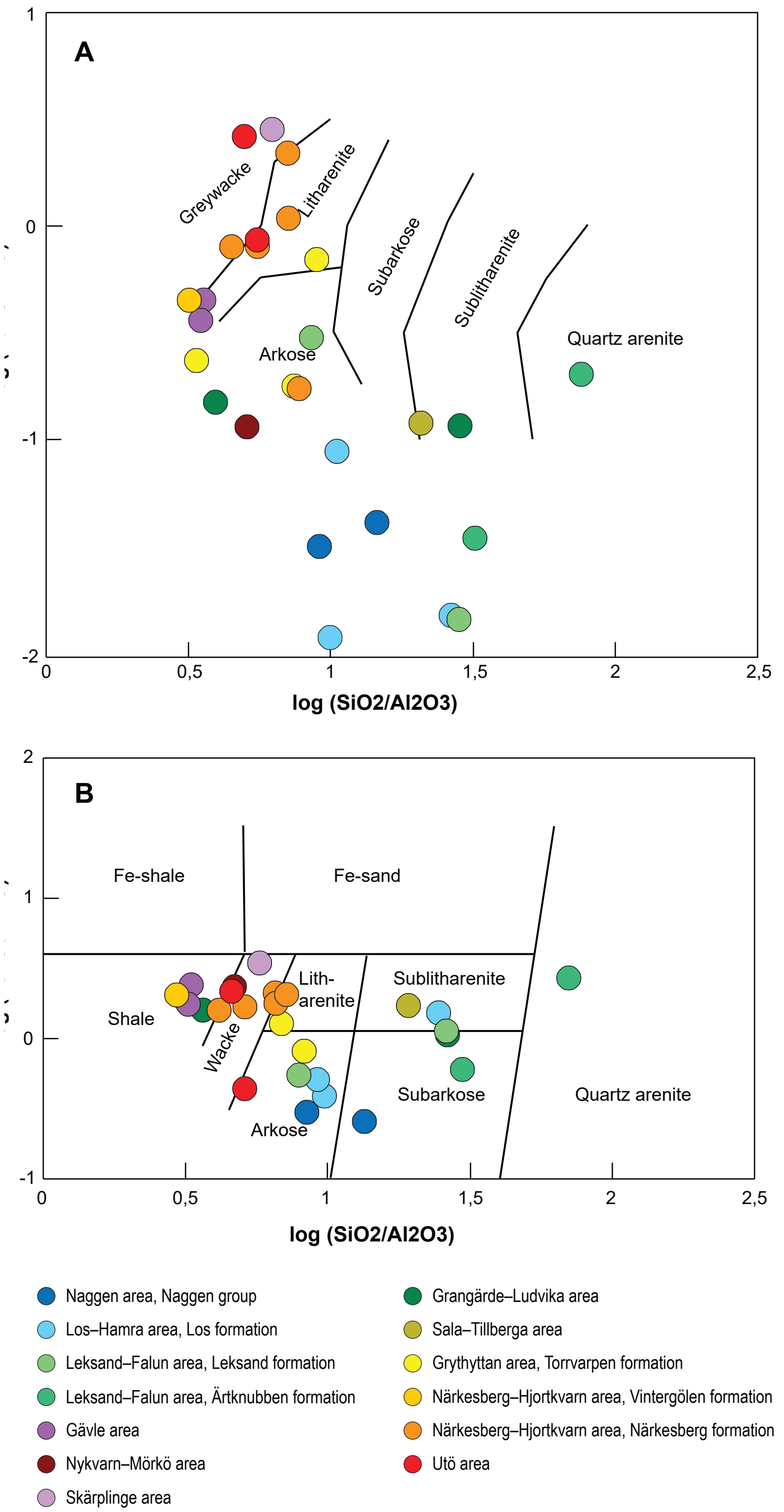


Figure 41. Diagrams showing an attempt of mineralogical classification by lithogeochemical analyses from the Bergslagen provenance project. **A**. Classification diagram for sedimentary rocks according to Pettijohn et al. (1972). **B**. Classification diagram for sedimentary rocks according to Herron (1988).

ADDITIONAL SAMPLING AT SIGGETORP–LAGGARFALL 2018

Sample KBK170023B from Siggetorp–Laggarfall in the Närkesberg–Hjortkvarn area turned out to contain a zircon with a Hadean age of 4,008 ± 16 Ma, obtained by Laser ablation ICP-MS analysis at GEUS. The Hadean age of this zircon was afterwards confirmed at the NORDSIM ion microprobe laboratory in Stockholm (c.f. Kathol et al. in prep.).

In order to find further Hadean or Eoarchaean zircons, four complementary samples were collected at the locality Siggetorp–Laggarfall from three adjacent arenite beds of the Närkesberg formation, including the bed where sample KBK170023B was collected from. These samples were put together to one, KBK170023E. In this, 230 zircon zircon U–Pb dates were obtained, of which 225 are within the 90–110% concordia interval, 34 analyses required correction for common lead. The U/Th ratios vary between 1.0 and 78.3, and 74% of the analysed zircons have U/Th ratios below 5.0 (Fig. 32b). About 24.0% of the analysed zircons have dates that fall in the age interval 2,000–2,049 Ma with a maximum probability peak at 2,028 Ma. About 10.2 and 15.1% of the zircons have dates in the intervals 1,950–1,999 and 2,050–2,099 Ma, respectively, both belonging to the dominant peak at 2,028 Ma. The youngest concordant zircon is dated to 1,808 Ma and the oldest to 3,519 Ma. The latter is not shown in figure 42. About 33.8% of the zircons are of Archaean age with 8.9% of the analysed zircons in the interval 2,700–2,750 Ma and with a maximum at 2,719 Ma (Fig. 42).

However, due to the purpose of this sub-study, spot analyses locations were selected specifically for core analyses in the search for the oldest zircon, which to some extent (apparently ~8%) biased the age density towards a larger proportion of older zircons. For this reason, this sample has not been included into the above described provenance study.

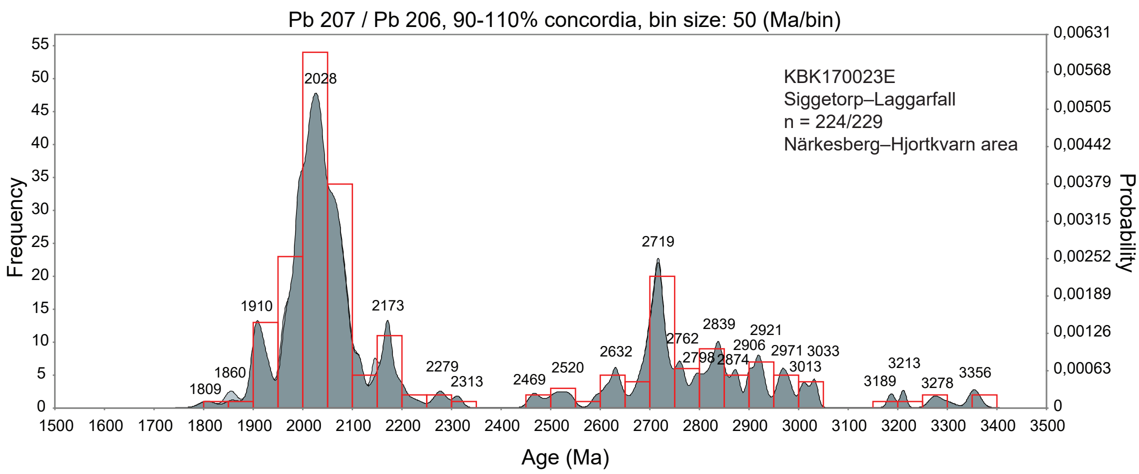


Figure 42. Combined binned frequency histograms and probability density distribution plots (PDP) in the 1,500–3,500 Ma interval from sample KBK170023E in the Närkesberg–Hjortkvarn area with calculated maximum probability ages for distinct distribution peaks of zircon populations from a single sample, using $^{207}Pb/^{206}Pb$ single zircon mineral dates. A Fixed bin size of 50 m.y./bin and a Concordia Filter of ± 10% are used. The oldest obtained age of 3,519 ± 12 Ma is, due to the age range of the diagram, not shown here.

FUTURE WORK

The following list gives a compilation of issues for future work which turned up during the making of this report. Future work could be carried out by the SGU or other academic institutions.

- Extended sampling and analyses as proposed in Kathol (2018; Fig. 43) and renewed sampling at Solfallet in the Norberg–Fagersta area.
- More detailed work on the zircon material, especially on zircon morphology.
- Additional analyses of other minerals: Titanite, rutile and phosphates like apatite and monazite all have lower, and different, closure temperatures than zircon. Thus, these minerals might offer additional information e.g. about metamorphic overprint stages in some rocks which most probably is not recorded in the zircons.
- Analyses of these minerals thus have the potential to contribute with further information to unravel the more complete metamorphic history of the rocks in the area, than just what zircons can provide, and in turn of the entire Bergslagen region. For example, the occurrence of younger maximum zircon populations at Eskörönningen and Persbacka and Fänrikbo and Fjällgrycksbo, which was interpreted as a result of an overprint by younger metamorphic events, could most probably be confirmed by analyses of titanite, rutile or apatite if present.
- Mapping analysis and synthesis of sediment transport directions, especially in the well-preserved rocks of the Närkesberg–Hjortkvarn area, to get more information about the position and the spatial distribution of sediment delivery areas.
- Relationships between a subvolcanic rhyolite, the Igelfors and Närkesberg formations should be worked out in order to get a better age constrain for the rocks of the Närkesberg formation.

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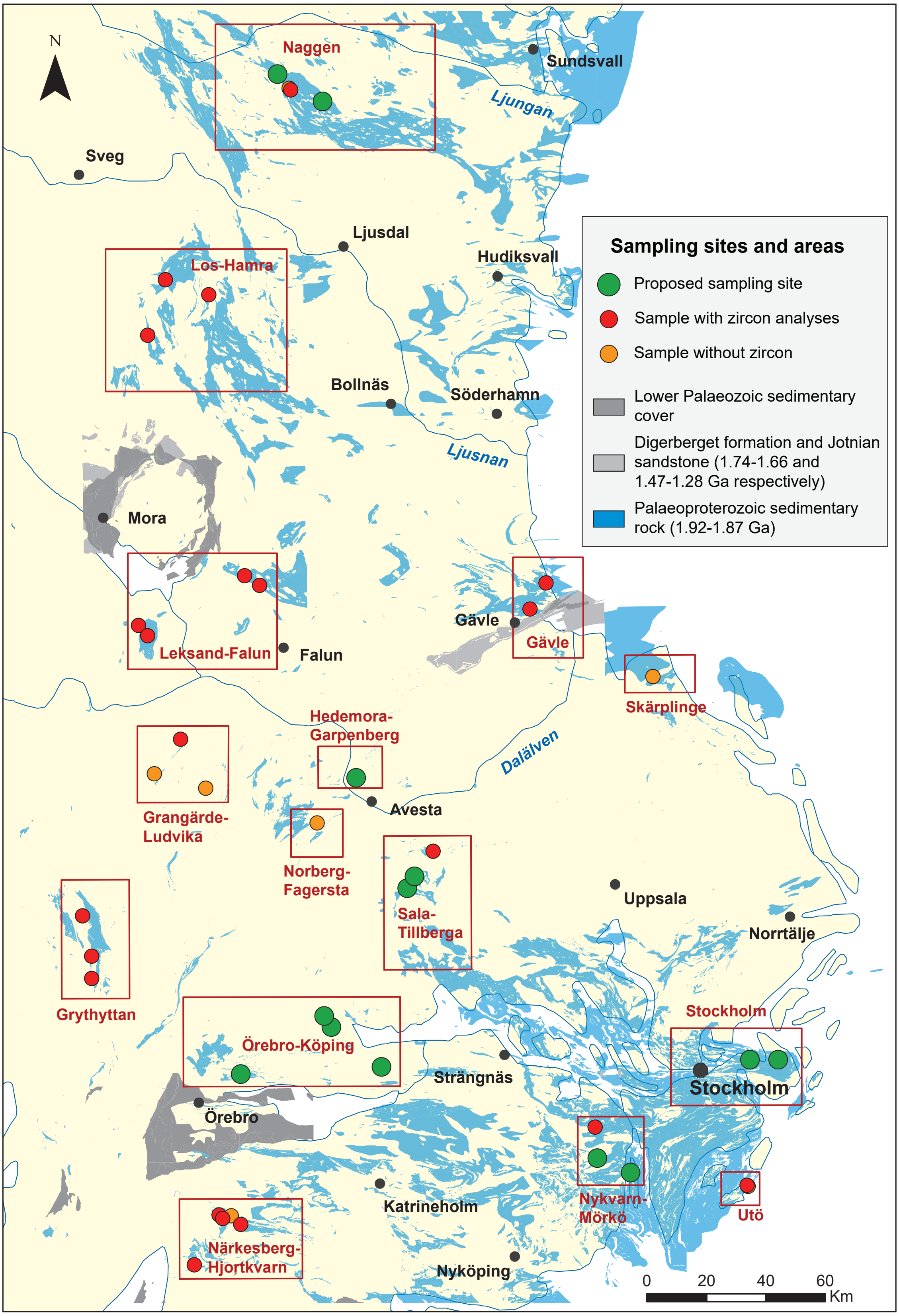

Figure 43. Proposed new sampling sites and areas in Bergslagen and surrounding areas.

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APPENDIX 1. SUMMARY OF THE ZIRCON U–PB ANALYSES

Appendix 1. Summary of the zircon U–Pb analyses. Information about coordinates, rock type, sampling area and stratigraphic unit of the samples is given in Table 2

No	Sample	Sample name	Zircon	Number of analyses	Analyses within 10 % Concordia	Corrected for common lead	U/Th minimum	U/Th maximum	U/Th < 5 number	U/Th < 5 percent	Number Archaean zircons	Percent Archaean zircons	Youngest date	Oldest date	Range	Other minerals
1	KBK170016A	Nylandet västra	OK	49	49	0	1,6	37,0	24	49	8	16,3	1841	2895	1054	None
2	KBK170017A	Nylandet östra	OK	124	124	2	1,2	434,0	74	60	24	19,4	1808	3233	1425	None
3	KBK170011A	Värmlandsströmmen	OK	116	116	51	1,5	42,8	64	55	13	11,2	1831	2963	1132	None
4	KBK170012A	Karlsberg	OK	116	116	34	1,0	45,5	64	55	22	19,0	1793	3099	1306	None
5	KBK170013A	Vässmasmägg	OK	115	115	33	1,2	34,1	67	58	16	13,9	1820	2854	1034	None
6	KBK170015A	Skallskog	OK	108	108	11	0,8	83,0	59	55	14	13,0	1735	3277	1542	None
7	KBK170014A	Balkbodarna	OK	81	81	10	1,5	196,0	33	41	2	2,5	1764	2771	1007	None
8	KBK170010A	Fänrikbo	OK	114	114	21	1,1	58,1	54	47	16	14,0	1698	3217	1519	None
9	KBK170009A	Fjällgrycksbo	OK	108	103	46	1,2	74,0	28	26	9	8,7	1722	2967	1245	None
10	KBK170019A	Eskörönningen	OK	94	93	24	3,2	740,0	9	10	0	0,0	1679	1895	216	Few apatites
11	KBK170018A	Persbacka	OK	115	115	35	1,7	310,0	20	17	5	4,3	1769	2810	1041	None
12	KBK170021A	Udden	OK	19	19	0	1,8	31,1	8	42	0	0,0	1832	2458	626	Apatite
13	KBK170020A	Barknåre	10 grains*	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	None
14	KBK170008A	Lindbastmora	OK	117	117	0	1,4	21,6	80	68	4	3,4	1695	3037	1342	None
15	KBK170006A	Södra Gåstjärnen	None	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	Apatite
16	KBK170007A	Håksberg mine	None	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	None
17	KBK170002A	Solfallet	None	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	×××	None
18	KBK170001A	Nötbo-Broddbo	OK	122	122	12	1,5	17,9	42	34	3	2,9	1859	2823	964	None
19	KBK170003A	Lill-Sången	OK	106	106	11	1,8	17,2	54	51	18	17,0	1832	3022	1190	None
20	KBK170004A	Torrvarpsund	OK	116	116	46	1,0	115,0	83	72	20	17,2	1752	3459	1707	None
21	KBK170005A	Yxhammarshöjden	OK	106	105	54	0,6	109,2	67	63	19	18,1	1801	2852	1051	None
22	KBK170022A	Grissjötorp	OK	29	28	12	2,3	73,0	12	41	2	7,1	1721	2762	1041	None
23	KBK170023A	Siggetorp-Laggarfall	OK	58	58	12	1,3	37,0	38	66	13	22,4	1892	3265	1373	Apatite
24	KBK170023B	Siggetorp-Laggarfall	OK	114	113	32	1,0	27,2	78	68	29	25,7	1867	4008	2141	None
25	KBK170024A	Linnerud-Stensätter	105 grains	60	57	25	1,7	25,7	37	62	9	15,8	1913	2850	937	Apatite
26	KBK170025A	Ångsågen	20 grains**	10	10	7	3,9	20,7	3	30	1	10,0	1730	2607	877	None
27	KBK170026A	Lilla Fågelhult	OK	80	75	13	1,4	136,0	51	64	15	20,0	1872	3109	1237	None
28	KBK170028A	Rävstavik västra	140 grains	35	35	0	2,7	10,3	24	69	0	0,0	1876	2075	199	Apatite
29	KBK170027A	Rävstavik östra	OK	101	101	9	1,3	11,0	31	31	0	0,0	1895	2137	242	None

OK = c. 200 grains
* = not analysed
** = analysed but not used in this study

APPENDIX 2. LITHOGEOCHEMICAL ANALYSIS RESULTS

Methods

Lithogeochemical analyses were conducted at ALS Minerals in 2018 using analytical packages referred to as ME-ICP06, ME-MS81, ME-MS42, ME-4ACD81, CIR07, SIR08 and PGMICP23. ALS method code refers to analytical method used for each element and is described in ALS methodology factsheets at http://www.alsglobal.com.

Sample preparation was carried out by ALS Minerals in Piteå (Sweden) and subsequent analytical work performed at ALS Minerals lab in Ireland. Preparation involved crushing of the sample and pulverising it to a powder using low-chrome steel grinding mills.

Appendix 2. Lithogeochemical analysis results

Sample ID			KBK170001A	KBK170002A	KBK170003A	KBK170004A	KBK170005A	KBK170006A
N			6652242	6661770	6630602	6616730	6609763	6678152
E			587058	548370	470258	473282	473155	493850
Locality			Nötbo-Broddbo	Solfallet	Lill-Sången	Torrvarpsund	Yxhammarshöjden	Södra Gåstjärnen
Rock type			Quartz arenite	Mafic volcanic rock	Arenite	Slate	Quartzite	Greywacke
SiO2	ME-ICP06	%	91.6	58	76.3	61.3	81.8	63.5
Al2O3	ME-ICP06	%	4.77	15.75	11.1	19.65	9.91	17.45
Fe2O3	ME-ICP06	%	1.84	10.05	3.39	7.18	2.27	7.76
CaO	ME-ICP06	%	0.06	5.68	2.77	0.32	0.27	0.7
MgO	ME-ICP06	%	1.07	3.67	0.96	2.62	0.78	2.78
Na2O	ME-ICP06	%	0.13	3.32	0.48	0.89	1.98	0.74
K2O	ME-ICP06	%	1.07	1.68	2.65	3.73	2.79	4.86
Cr2O3	ME-ICP06	%	0.007	0.029	0.017	0.015	0.005	0.01
TiO2	ME-ICP06	%	0.45	0.97	0.48	0.76	0.2	0.64
MnO	ME-ICP06	%	0.01	0.12	0.11	0.04	0.04	0.1
P2O5	ME-ICP06	%	<0.01	0.1	0.09	0.12	0.04	0.04
SrO	ME-ICP06	%	<0.01	0.02	<0.01	<0.01	<0.01	<0.01
BaO	ME-ICP06	%	0.04	0.04	0.18	0.08	0.07	0.12
C	C-IR07	%	0.04	0.03	0.29	0.05	0.06	0.03
S	S-IR08	%	<0.01	<0.01	0.01	<0.01	0.01	0.01
LOI	OA-GRA05	%	0.94	0.82	2.66	3.89	1.29	1.93
Total	TOT-ICP06	%	101.99	100.25	101.19	100.6	101.45	100.63
Ba	ME-MS81	ppm	318	366	1500	703	598	990
Ce	ME-MS81	ppm	24.9	45.6	75.4	90.1	48.3	67.6
Cr	ME-MS81	ppm	60	200	120	130	40	90
Cs	ME-MS81	ppm	1.23	3.83	3.97	10.15	1.6	4.92
Dy	ME-MS81	ppm	1.94	3.78	5.27	4.55	4.85	4.33
Er	ME-MS81	ppm	1.22	2.19	3.29	2.56	3.28	2.37
Eu	ME-MS81	ppm	0.55	1.29	0.94	1.04	0.73	1.01
Ga	ME-MS81	ppm	8.7	22.4	16.8	28	14.5	23.2
Gd	ME-MS81	ppm	1.77	3.95	5.19	5.23	4.14	4.7
Hf	ME-MS81	ppm	2.6	3.6	8.5	5.3	4.7	4.1
Ho	ME-MS81	ppm	0.41	0.76	1.12	0.83	1.09	0.79
La	ME-MS81	ppm	12.3	21.6	35.5	43.5	24.8	35.7
Lu	ME-MS81	ppm	0.16	0.3	0.47	0.4	0.51	0.34
Nb	ME-MS81	ppm	5.3	9.1	11.6	17.6	10.8	10.6
Nd	ME-MS81	ppm	11.5	23.4	31.5	35.4	21.4	30.7
Pr	ME-MS81	ppm	3.12	5.98	8.48	10.15	5.91	7.97
Rb	ME-MS81	ppm	26.8	93.5	133	191	83.7	171
Sm	ME-MS81	ppm	1.86	4.56	5.82	6.39	4.11	5.57
Sn	ME-MS81	ppm	1	2	6	4	2	3
Sr	ME-MS81	ppm	10	289	68.9	149.5	37.8	19.1
Ta	ME-MS81	ppm	0.4	0.6	0.8	1.4	0.7	1
Tb	ME-MS81	ppm	0.32	0.65	0.85	0.76	0.76	0.77
Th	ME-MS81	ppm	3.53	6.22	13.05	17.15	11.85	11.35
Tm	ME-MS81	ppm	0.16	0.3	0.44	0.37	0.47	0.35
U	ME-MS81	ppm	0.96	1.71	3.13	3.4	4.05	2.89
V	ME-MS81	ppm	52	210	47	105	24	99
W	ME-MS81	ppm	6	4	2	3	<1	4
Y	ME-MS81	ppm	11.3	19	29.4	24.4	29.9	22.7
Yb	ME-MS81	ppm	1.08	2.12	3.29	2.19	3.4	2.36
Zr	ME-MS81	ppm	104	139	325	197	173	146
As	ME-MS42	ppm	0.1	0.4	3.3	0.5	1.9	0.3
Bi	ME-MS42	ppm	0.01	0.17	0.2	0.12	0.33	0.15
Hg	ME-MS42	ppm	0.006	0.005	0.007	<0.005	<0.005	<0.005
Sb	ME-MS42	ppm	0.19	0.39	2.09	0.49	1.33	0.14
Se	ME-MS42	ppm	<0.2	<0.2	0.2	<0.2	<0.2	0.3
Te	ME-MS42	ppm	<0.01	<0.01	0.01	0.01	0.02	<0.01
Ag	ME-4ACD81	ppm	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	ME-4ACD81	ppm	<0.5	0.6	<0.5	<0.5	0.5	0.5
Co	ME-4ACD81	ppm	3	26	5	16	3	12
Cu	ME-4ACD81	ppm	2	1	27	14	6	17
Mo	ME-4ACD81	ppm	1	1	3	<1	1	<1
Ni	ME-4ACD81	ppm	6	18	11	46	6	23
Pb	ME-4ACD81	ppm	<2	8	21	21	21	20
Sc	ME-4ACD81	ppm	3	25	9	16	6	26
Zn	ME-4ACD81	ppm	17	103	68	126	47	152
Li	ME-4ACD81	ppm	10	10	20	70	10	40
Tl	ME-MS42	ppm	0.02	0.46	0.07	0.04	0.11	0.61
Au	PGM-ICP23	ppm	0.001	<0.001	0.001	0.001	<0.001	0.001
Pt	PGM-ICP23	ppm	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Pd	PGM-ICP23	ppm	0.001	0.001	0.002	0.002	0.001	0.001

Appendix 2. Continuation.

Sample ID			KBK170007A	KBK170008A	KBK170009A	KBK170010A	KBK170011A	KBK170012A
N			6673448	6689220	6740962	6744231	6843218	6838321
E			511177	502933	529193	524435	497781	512142
Locality			Håksberg mine	Lindbastmora	Fjällgrycksbo	Fänrikbo	Värmlandsströmmen	Karlsberg
Rock type			Intermediate volcaniclastic rock	Quartz arenite	Dense quartzite	Dense quartzite	Quartz arenite	Quartz arenite
SiO2	ME-ICP06	%	49.7	94.3	98.4	94.8	92.9	84.2
Al2O3	ME-ICP06	%	18.15	3.58	1.4	3.19	3.79	8.65
Fe2O3	ME-ICP06	%	11.35	1.35	0.92	1.03	2	1.87
CaO	ME-ICP06	%	2.26	0.17	0.02	0.06	0.21	0.28
MgO	ME-ICP06	%	5.86	0.11	0.25	0.27	0.48	0.6
Na2O	ME-ICP06	%	4.1	0.15	0.07	0.06	0.02	0.43
K2O	ME-ICP06	%	4.64	1.27	0.34	1.71	1.31	4.8
Cr2O3	ME-ICP06	%	<0.002	0.004	0.008	0.006	0.007	0.008
TiO2	ME-ICP06	%	1.42	0.09	0.04	0.08	0.26	0.26
MnO	ME-ICP06	%	0.1	0.01	0.01	0.01	0.02	0.02
P2O5	ME-ICP06	%	0.85	0.11	<0.01	0.02	0.04	0.04
SrO	ME-ICP06	%	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
BaO	ME-ICP06	%	0.08	0.02	<0.01	0.03	0.01	0.09
C	C-IR07	%	0.03	0.04	0.03	0.05	0.07	0.05
S	S-IR08	%	0.01	<0.01	<0.01	<0.01	0.01	0.01
LOI	OA-GRA05	%	1.54	0.67	0.48	0.71	0.8	0.71
Total	TOT-ICP06	%	100.05	101.83	101.94	101.98	101.85	101.96
Ba	ME-MS81	ppm	618	163	21.7	314	47.3	819
Ce	ME-MS81	ppm	34.2	34.8	2.9	35.7	13	59.6
Cr	ME-MS81	ppm	30	50	60	40	40	60
Cs	ME-MS81	ppm	7.34	3.92	0.59	2.62	3.54	2.77
Dy	ME-MS81	ppm	5.01	2.62	0.61	2.76	1.55	3.39
Er	ME-MS81	ppm	3.01	1.65	0.73	1.56	1.16	2.03
Eu	ME-MS81	ppm	1.68	0.41	0.04	0.47	0.25	0.85
Ga	ME-MS81	ppm	26.9	6.6	4.9	3.9	5.1	9.9
Gd	ME-MS81	ppm	5.05	2.69	0.36	3.04	1.09	3.66
Hf	ME-MS81	ppm	1.9	1.8	2.9	2.4	8.5	5.4
Ho	ME-MS81	ppm	0.96	0.52	0.19	0.6	0.39	0.72
La	ME-MS81	ppm	16.2	17.2	1.4	18.2	5.4	30.3
Lu	ME-MS81	ppm	0.4	0.29	0.17	0.23	0.24	0.32
Nb	ME-MS81	ppm	8.4	3.6	2.1	2.2	6.2	4.5
Nd	ME-MS81	ppm	19.1	15.4	1.3	16.5	5.3	25.3
Pr	ME-MS81	ppm	4.82	4.22	0.34	3.99	1.33	6.48
Rb	ME-MS81	ppm	94.9	111.5	20.3	64.8	50.2	134
Sm	ME-MS81	ppm	4.58	3.12	0.31	3.41	1.13	4.66
Sn	ME-MS81	ppm	7	3	1	6	2	2
Sr	ME-MS81	ppm	60.3	5.8	3.2	9.8	6	61.9
Ta	ME-MS81	ppm	0.5	0.3	0.2	0.4	0.5	0.4
Tb	ME-MS81	ppm	0.72	0.42	0.09	0.47	0.21	0.57
Th	ME-MS81	ppm	2.39	5.36	1.07	8.71	6.66	7.97
Tm	ME-MS81	ppm	0.38	0.21	0.1	0.25	0.21	0.31
U	ME-MS81	ppm	2.53	1.88	1.09	2.5	2.25	2.03
V	ME-MS81	ppm	258	8	8	15	24	31
W	ME-MS81	ppm	3	4	<1	4	3	3
Y	ME-MS81	ppm	24.9	16.1	4.8	15.5	10.4	19.5
Yb	ME-MS81	ppm	2.61	1.75	1.04	1.62	1.41	1.98
Zr	ME-MS81	ppm	77	66	99	85	324	213
As	ME-MS42	ppm	0.3	1.3	0.3	0.4	1.4	0.9
Bi	ME-MS42	ppm	0.26	0.04	0.08	0.03	0.07	0.23
Hg	ME-MS42	ppm	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Sb	ME-MS42	ppm	0.12	0.12	0.11	0.12	0.31	0.38
Se	ME-MS42	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Te	ME-MS42	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ag	ME-4ACD81	ppm	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	ME-4ACD81	ppm	0.7	<0.5	<0.5	<0.5	<0.5	<0.5
Co	ME-4ACD81	ppm	19	1	<1	<1	2	<1
Cu	ME-4ACD81	ppm	1	5	5	2	3	1
Mo	ME-4ACD81	ppm	<1	<1	2	2	<1	2
Ni	ME-4ACD81	ppm	6	3	2	2	5	8
Pb	ME-4ACD81	ppm	9	7	2	<2	5	11
Sc	ME-4ACD81	ppm	33	2	1	1	3	5
Zn	ME-4ACD81	ppm	94	17	14	9	10	16
Li	ME-4ACD81	ppm	20	30	<10	<10	30	40
Tl	ME-MS42	ppm	0.26	0.2	0.02	0.03	0.16	0.2
Au	PGM-ICP23	ppm	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Pt	PGM-ICP23	ppm	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Pd	PGM-ICP23	ppm	0.002	0.001	0.001	0.001	0.001	0.001

Appendix 2. Continuation.

Sample ID			KBK170013A	KBK170014A	KBK170015A	KBK170016A	KBK170017A	KBK170018A
N			6824853	6724615	6727565	6907292	6906821	6733040
E			491770	491642	489181	538845	539532	618922
Locality			Vässmasmägg	Balkbodarna	Skallskog	Nylandet västra	Nylandet östra	Persbacka
Rock type			Quartzite	Arenite	Arenite	Arkosic arenite	Arkosic arenite	Gneissose quartzite–quartz arenite
SiO2	ME-ICP06	%	84	93.5	79.9	79.9	87.8	60.4
Al2O3	ME-ICP06	%	9.13	3.58	10.1	9.47	6.53	18.25
Fe2O3	ME-ICP06	%	1.7	1.55	2.39	1.95	1.11	9.05
CaO	ME-ICP06	%	0.01	0.06	0.56	0.58	0.14	1.16
MgO	ME-ICP06	%	0.68	0.33	1.07	0.62	0.26	3.26
Na2O	ME-ICP06	%	0.04	0.02	1.33	0.21	0.18	1.72
K2O	ME-ICP06	%	3.33	1.37	4.35	6.54	4.33	3.75
Cr2O3	ME-ICP06	%	0.009	0.006	0.01	0.008	0.007	0.023
TiO2	ME-ICP06	%	0.34	0.13	0.31	0.28	0.12	0.81
MnO	ME-ICP06	%	0.01	0.02	0.04	0.03	0.02	0.08
P2O5	ME-ICP06	%	<0.01	0.05	0.03	0.02	0.06	0.07
SrO	ME-ICP06	%	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
BaO	ME-ICP06	%	0.06	0.04	0.11	0.08	0.07	0.06
C	C-IR07	%	0.04	0.05	0.02	0.1	0.05	0.07
S	S-IR08	%	<0.01	<0.01	<0.01	0.01	<0.01	0.05
LOI	OA-GRA05	%	1.53	0.76	0.96	0.72	0.61	2.24
Total	TOT-ICP06	%	100.84	101.42	101.16	100.41	101.24	100.87
Ba	ME-MS81	ppm	560	395	1010	671	621	553
Ce	ME-MS81	ppm	18.3	48.4	69.4	54.7	46.9	120.5
Cr	ME-MS81	ppm	70	40	70	60	50	170
Cs	ME-MS81	ppm	6.71	3.03	3.5	11.95	4.93	4.64
Dy	ME-MS81	ppm	2.22	4.27	4.4	2.93	2.21	6.81
Er	ME-MS81	ppm	1.28	2.6	2.63	1.99	1.46	3.84
Eu	ME-MS81	ppm	0.31	0.78	0.95	0.7	0.57	1.22
Ga	ME-MS81	ppm	8.7	4.7	12.7	13	6.7	28.7
Gd	ME-MS81	ppm	1.79	3.99	4.61	2.89	2.39	7.64
Hf	ME-MS81	ppm	6.7	2.6	6.5	7.3	3.8	5.8
Ho	ME-MS81	ppm	0.46	0.92	0.92	0.65	0.49	1.47
La	ME-MS81	ppm	9.7	19.9	31.3	25.7	19	62.2
Lu	ME-MS81	ppm	0.19	0.39	0.37	0.34	0.24	0.6
Nb	ME-MS81	ppm	7.7	4.5	8.8	7.4	3.6	23.7
Nd	ME-MS81	ppm	7.5	19.7	26.5	20.6	16.9	52
Pr	ME-MS81	ppm	1.82	4.44	6.78	5.24	4.3	13.3
Rb	ME-MS81	ppm	114	53.7	122	205	145.5	204
Sm	ME-MS81	ppm	1.88	4.7	5.6	3.36	3.1	9.06
Sn	ME-MS81	ppm	4	1	2	2	1	1
Sr	ME-MS81	ppm	3.7	5.7	133.5	61	49.7	143.5
Ta	ME-MS81	ppm	0.7	0.3	0.7	0.7	0.3	1.2
Tb	ME-MS81	ppm	0.35	0.65	0.68	0.44	0.39	1.13
Th	ME-MS81	ppm	4.5	5.33	9.35	8.36	5.59	22.6
Tm	ME-MS81	ppm	0.2	0.38	0.38	0.3	0.22	0.6
U	ME-MS81	ppm	1.18	1.99	2.49	1.7	1.14	3.18
V	ME-MS81	ppm	69	20	40	32	19	139
W	ME-MS81	ppm	9	4	2	3	3	3
Y	ME-MS81	ppm	9.7	26	24.8	17.9	13.6	39.4
Yb	ME-MS81	ppm	1.48	2.69	2.44	2.33	1.51	4.07
Zr	ME-MS81	ppm	255	97	253	272	145	202
As	ME-MS42	ppm	0.7	5.6	2.4	0.9	0.7	0.3
Bi	ME-MS42	ppm	0.21	0.06	0.18	0.04	0.04	0.06
Hg	ME-MS42	ppm	<0.005	0.005	<0.005	<0.005	<0.005	<0.005
Sb	ME-MS42	ppm	0.12	0.36	0.88	0.32	0.16	0.07
Se	ME-MS42	ppm	<0.2	0.2	<0.2	<0.2	<0.2	0.2
Te	ME-MS42	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	0.02
Ag	ME-4ACD81	ppm	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	ME-4ACD81	ppm	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Co	ME-4ACD81	ppm	<1	1	7	4	2	18
Cu	ME-4ACD81	ppm	3	5	1	<1	<1	19
Mo	ME-4ACD81	ppm	<1	2	1	1	1	1
Ni	ME-4ACD81	ppm	1	4	12	8	5	56
Pb	ME-4ACD81	ppm	<2	<2	32	10	8	19
Sc	ME-4ACD81	ppm	13	3	6	4	2	21
Zn	ME-4ACD81	ppm	24	23	60	16	6	152
Li	ME-4ACD81	ppm	30	10	20	30	20	40
Tl	ME-MS42	ppm	0.05	0.17	0.2	0.39	0.17	0.72
Au	PGM-ICP23	ppm	<0.001	0.001	<0.001	<0.001	<0.001	0.002
Pt	PGM-ICP23	ppm	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Pd	PGM-ICP23	ppm	0.001	0.001	0.001	0.001	0.002	0.001

Appendix 2. Continuation.

Sample ID			KBK170019A	KBK170020A	KBK170021A	KBK170022A	KBK170023A	KBK170023B
N			6741910	6710300	6559820	6513731	6530485	6530485
E			624490	660166	640941	507471	515673	515673
Locality			Eskörönningen	Barknåre	Udden	Grissjötorp	Siggetorp-Laggarfall	Siggetorp-Laggarfall
Rock type			Gneissose quartzite–quartz arenite	Arenite to quartz arenite	Paragneiss	Greywacke	Layered arkosic arenite	Massive arkosic arenite
SiO2	ME-ICP06	%	60.6	74.6	58.9	60.3	66.6	77.8
Al2O3	ME-ICP06	%	18.75	12.95	12.55	20.5	16.05	11.9
Fe2O3	ME-ICP06	%	7.98	4.81	11.25	7.78	5.67	3.09
CaO	ME-ICP06	%	0.89	1.82	0.76	0.71	1.64	1.74
MgO	ME-ICP06	%	3.01	0.64	6.54	2.25	1.81	0.78
Na2O	ME-ICP06	%	1.67	4.02	0.56	1.74	2.9	3.27
K2O	ME-ICP06	%	4.54	1.39	4.8	3.8	3.56	1.46
Cr2O3	ME-ICP06	%	0.019	0.002	0.004	0.016	0.014	0.007
TiO2	ME-ICP06	%	0.76	0.21	1.45	0.66	0.68	0.34
MnO	ME-ICP06	%	0.07	0.24	0.05	0.04	0.09	0.06
P2O5	ME-ICP06	%	0.12	<0.01	0.3	0.09	0.22	0.06
SrO	ME-ICP06	%	<0.01	<0.01	<0.01	<0.01	0.01	0.02
BaO	ME-ICP06	%	0.06	0.02	0.01	0.08	0.1	0.03
C	C-IR07	%	0.07	0.12	0.11	0.09	0.16	0.11
S	S-IR08	%	0.09	0.1	<0.01	<0.01	<0.01	<0.01
LOI	OA-GRA05	%	3.15	0.66	1.7	2.49	1.93	0.73
Total	TOT-ICP06	%	101.62	101.36	98.87	100.46	101.27	101.29
Ba	ME-MS81	ppm	537	167.5	114	732	882	282
Ce	ME-MS81	ppm	100	53.6	72.3	108.5	95.1	67.8
Cr	ME-MS81	ppm	140	10	30	120	100	60
Cs	ME-MS81	ppm	9.49	3.08	9.01	5.25	2.79	2.05
Dy	ME-MS81	ppm	6.21	6.04	8.83	5.62	5.05	3.26
Er	ME-MS81	ppm	3.71	4.8	7.2	3.27	3.13	1.98
Eu	ME-MS81	ppm	1.27	0.79	0.63	1.47	1.45	1.07
Ga	ME-MS81	ppm	30.7	19.8	18.4	30.5	22.2	13.5
Gd	ME-MS81	ppm	6.42	4.98	7.16	6.33	5.8	3.77
Hf	ME-MS81	ppm	6.1	6.4	8.4	4.7	6.3	5.2
Ho	ME-MS81	ppm	1.38	1.49	2.31	1.12	1.06	0.69
La	ME-MS81	ppm	51.6	26.2	35.7	57.3	49.4	33.3
Lu	ME-MS81	ppm	0.62	0.79	1.11	0.47	0.46	0.28
Nb	ME-MS81	ppm	24.2	15.1	13.8	16.2	16	9.4
Nd	ME-MS81	ppm	45	26.2	34.1	44.9	40.3	26.9
Pr	ME-MS81	ppm	11.15	6.16	8.33	11.75	10.1	6.82
Rb	ME-MS81	ppm	269	130.5	341	151	128	61.4
Sm	ME-MS81	ppm	8.11	5.25	7.18	7.85	7.21	4.93
Sn	ME-MS81	ppm	2	5	1	5	3	1
Sr	ME-MS81	ppm	105.5	65.6	34.8	102	218	242
Ta	ME-MS81	ppm	3.3	1.4	1	1.2	1.3	0.7
Tb	ME-MS81	ppm	1.02	0.9	1.31	1	0.94	0.55
Th	ME-MS81	ppm	17.55	13.15	10.45	18.7	14.9	8.56
Tm	ME-MS81	ppm	0.6	0.7	1.09	0.49	0.48	0.27
U	ME-MS81	ppm	5.53	4.44	3.02	4.04	3.45	2.45
V	ME-MS81	ppm	123	6	64	117	93	50
W	ME-MS81	ppm	2	1	2	3	3	1
Y	ME-MS81	ppm	34.3	40.7	57.8	30.5	27.4	18.8
Yb	ME-MS81	ppm	4	5.23	7.28	3.09	3.09	1.87
Zr	ME-MS81	ppm	209	235	365	169	232	204
As	ME-MS42	ppm	0.4	0.3	0.8	0.2	0.3	0.2
Bi	ME-MS42	ppm	0.78	0.14	0.03	0.3	0.03	0.04
Hg	ME-MS42	ppm	0.005	0.005	<0.005	<0.005	0.005	<0.005
Sb	ME-MS42	ppm	0.05	0.06	0.05	0.06	0.11	0.11
Se	ME-MS42	ppm	0.4	0.2	<0.2	<0.2	<0.2	<0.2
Te	ME-MS42	ppm	0.03	0.04	<0.01	0.03	<0.01	<0.01
Ag	ME-4ACD81	ppm	<0.5	<0.5	0.5	<0.5	<0.5	<0.5
Cd	ME-4ACD81	ppm	0.5	<0.5	0.7	<0.5	0.5	<0.5
Co	ME-4ACD81	ppm	18	4	15	17	14	7
Cu	ME-4ACD81	ppm	56	16	1	23	2	2
Mo	ME-4ACD81	ppm	<1	3	<1	1	<1	<1
Ni	ME-4ACD81	ppm	46	1	48	40	34	13
Pb	ME-4ACD81	ppm	17	14	5	8	14	8
Sc	ME-4ACD81	ppm	19	9	32	17	12	6
Zn	ME-4ACD81	ppm	147	47	101	48	43	26
Li	ME-4ACD81	ppm	70	30	20	60	10	10
Tl	ME-MS42	ppm	1.01	0.89	1.93	0.48	0.24	0.22
Au	PGM-ICP23	ppm	0.001	0.001	<0.001	<0.001	<0.001	<0.001
Pt	PGM-ICP23	ppm	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Pd	PGM-ICP23	ppm	0.002	<0.001	<0.001	0.001	<0.001	<0.001

Appendix 2. Continuation.

Sample ID			KBK170024A	KBK170025A	KBK170026A	KBK170027A	KBK170028A
N			6529500	6530264	6527322	6540387	6540491
E			516869	519730	522829	692066	691909
Locality			Linnerud-Stensätter	Ångsågen	Lilla Fågelhult	Rävstavik östra	Rävstavik västra
Rock type			Arenite	Arenite	Arenite	Arenite	Greywacke
SiO2	ME-ICP06	%	71.3	74.9	75.2	73.5	71.4
Al2O3	ME-ICP06	%	13.95	11.4	10.5	14.4	15.55
Fe2O3	ME-ICP06	%	4.71	4.26	4.68	1.8	2.24
CaO	ME-ICP06	%	1.94	1.65	0.26	1.68	4.95
MgO	ME-ICP06	%	1.83	1.91	3.94	0.33	0.7
Na2O	ME-ICP06	%	2.29	2.65	0.4	3.6	2.76
K2O	ME-ICP06	%	2.8	2.39	2.27	4.1	1.03
Cr2O3	ME-ICP06	%	0.01	0.006	0.01	0.006	0.004
TiO2	ME-ICP06	%	0.51	0.51	0.37	0.11	0.34
MnO	ME-ICP06	%	0.09	0.05	0.04	0.03	0.05
P2O5	ME-ICP06	%	0.15	0.14	0.04	0.03	0.11
SrO	ME-ICP06	%	0.01	<0.01	<0.01	0.01	<0.01
BaO	ME-ICP06	%	0.06	0.03	0.07	0.04	0.04
C	C-IR07	%	0.14	0.06	0.08	0.05	0.06
S	S-IR08	%	0.01	0.01	<0.01	0.03	0.01
LOI	OA-GRA05	%	1.17	1.45	2.66	0.47	0.62
Total	TOT-ICP06	%	100.82	101.35	100.44	100.11	99.79
Ba	ME-MS81	ppm	615	278	669	342	355
Ce	ME-MS81	ppm	58	94.4	6.9	32.2	70.6
Cr	ME-MS81	ppm	80	40	80	50	30
Cs	ME-MS81	ppm	3.37	2.44	4.03	2.71	1.85
Dy	ME-MS81	ppm	3.52	8.57	1.23	1.06	4.52
Er	ME-MS81	ppm	2.06	5.29	1.06	0.49	2.69
Eu	ME-MS81	ppm	0.99	1.36	0.19	0.54	1.65
Ga	ME-MS81	ppm	19	15.6	19.1	23.8	20
Gd	ME-MS81	ppm	4.07	8.74	0.75	2.21	4.65
Hf	ME-MS81	ppm	4.2	9.5	4.4	3.3	6.2
Ho	ME-MS81	ppm	0.75	1.84	0.3	0.17	0.95
La	ME-MS81	ppm	29	49.8	3.2	16	36.6
Lu	ME-MS81	ppm	0.33	0.77	0.19	0.06	0.34
Nb	ME-MS81	ppm	13.6	16	11.2	10.9	13.7
Nd	ME-MS81	ppm	26	44.6	3	15.5	33.3
Pr	ME-MS81	ppm	6.13	10.95	0.74	3.75	7.99
Rb	ME-MS81	ppm	137	129.5	100.5	137	61.2
Sm	ME-MS81	ppm	4.79	9.08	0.77	3.66	6.22
Sn	ME-MS81	ppm	2	4	5	4	1
Sr	ME-MS81	ppm	220	99.5	13.9	208	124.5
Ta	ME-MS81	ppm	1	1.2	0.6	1.2	1
Tb	ME-MS81	ppm	0.61	1.38	0.15	0.25	0.75
Th	ME-MS81	ppm	8.97	14.3	8.81	7.22	11.55
Tm	ME-MS81	ppm	0.33	0.79	0.18	0.07	0.36
U	ME-MS81	ppm	3.11	4.42	1.43	4.55	4.58
V	ME-MS81	ppm	80	37	59	17	29
W	ME-MS81	ppm	2	3	6	2	<1
Y	ME-MS81	ppm	21	47	9.7	5.2	25.1
Yb	ME-MS81	ppm	1.99	4.9	1.24	0.41	2.63
Zr	ME-MS81	ppm	163	367	167	93	247
As	ME-MS42	ppm	0.2	0.2	0.2	0.7	0.7
Bi	ME-MS42	ppm	0.38	0.07	0.03	0.84	0.55
Hg	ME-MS42	ppm	0.006	0.005	0.005	<0.005	<0.005
Sb	ME-MS42	ppm	<0.05	<0.05	0.05	0.1	0.05
Se	ME-MS42	ppm	<0.2	0.2	<0.2	<0.2	<0.2
Te	ME-MS42	ppm	<0.01	0.01	<0.01	<0.01	0.03
Ag	ME-4ACD81	ppm	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	ME-4ACD81	ppm	<0.5	<0.5	<0.5	<0.5	<0.5
Co	ME-4ACD81	ppm	14	3	14	3	2
Cu	ME-4ACD81	ppm	21	97	<1	20	<1
Mo	ME-4ACD81	ppm	<1	<1	<1	1	<1
Ni	ME-4ACD81	ppm	31	9	30	2	2
Pb	ME-4ACD81	ppm	29	<2	2	5	7
Sc	ME-4ACD81	ppm	10	13	7	3	9
Zn	ME-4ACD81	ppm	97	43	35	24	25
Li	ME-4ACD81	ppm	10	10	10	10	10
Tl	ME-MS42	ppm	0.57	0.05	0.13	0.28	0.3
Au	PGM-ICP23	ppm	<0.001	0.001	<0.001	<0.001	0.002
Pt	PGM-ICP23	ppm	<0.005	<0.005	<0.005	<0.005	<0.005
Pd	PGM-ICP23	ppm	0.002	0.001	0.001	0.001	0.001