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PRECAMBRIAN GEOLOGY OF FINLAND

KEY TO THE EVOLUTION OF THE FENNOSCANDIAN SHIELD

EDITED BY
M. LEHTINEN, P.A. NURMI, O.T. RÄMÖ

SERIES EDITOR: K.C. CONDIE

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Advisory Editor Kent Condie

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KEY TO THE EVOLUTION OF THE FENNOSCANDIAN SHIELD

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PREFACE

The Fennoscandian (or Baltic) Shield represents the largest outcropping domain of Precambrian bedrock in Europe, covering more than a million km^2 throughout Norway, Sweden, Finland, and northwestern Russia. This book focuses on Finland, which occupies the central part of the shield and which, since the advent of modern geology in the 19th century, has been instrumental in a number of fundamental insights and advances in understanding Earth processes. Wilhelm Ramsay, who was the Professor of Geology and Mineralogy at the University of Helsinki in 1899–1928 and who introduced the term Fennoscandia, made an outstanding contribution to the understanding of alkaline rocks through his studies of the Devonian Kola province in the northeasternmost part of the shield. Meanwhile, J.J. Sederholm, Director of the Geological Survey of Finland in 1893–1933, pioneered the application of actualistic principles to Precambrian terrains and the systematic study of Precambrian granites, introducing the concepts of migmatites and anatexis in 1907, and published acclaimed monographs on orbicular textures and the rapakivi granite association. Pentti Eskola, who succeeded Ramsay in the Chair of Geology and Mineralogy at Helsinki in 1929–1953, is particularly renowned for defining the metamorphic facies concept, based initially on the Orijärvi district near Helsinki, and which now underpins studies in metamorphic petrology worldwide.

Further developments in analytical chemistry and elemental and isotope geochemistry, by Th.G. Sahama and Kalervo Rankama, paved the way for isotopic calibration of Precambrian rocks and events, which has been essential to attaining our present understanding of crustal evolution. Concurrent advances in geophysical techniques and instrumentation, while driven mainly by exploration applications, have played an equally significant role in mapping the country in recent decades, especially in poorly exposed areas, by providing detailed airborne survey as well as deep seismic sounding data. As a consequence, the Finnish part of the Fennoscandian Shield can rightfully be considered as one of the best-documented Precambrian terrains in the world.

This compilation provides the first modern account of the geology of Finland. The seventeen chapters of the book have been written by geologists and geophysicists who have actively contributed to the research in their respective fields. In addition to a general overview chapter on the Precambrian of Finland and an account of the history of Finnish bedrock research, the book contains twelve chapters on specific lithologic and crustal entities (the Archean in the eastern part of the country; Paleoproterozoic supracrustal belts, mafic and ultramafic intrusions, mafic dike swarms, ophiolites, and granitoid rocks; the rapakivi granites in their type terrain, and subsequent supracrustal successions and mafic magmatism; Neoproterozoic/Phanerozoic kimberlites, carbonatites, and alkaline rocks), as well as chapters on Paleoproterozoic tectonic evolution, carbon isotope stratigraphy, and the paleomagnetically defined drift history of the shield. The aim of the book is thus to provide the international geological community with an up-to-date account of the geologic framework and conceptual interpretation of the bedrock of Finland and to serve as a basis for future research. The book will also be a valuable reference for exploration activities, which at present are focused on gold, platinum-group metals, nickel, and diamonds in particular.

This book would not have been possible without the contribution from the Geological Society of Finland (the society published a precursor to this book in Finnish in 1998[1]), the commitment of the authors, and help from devoted reviewers (Andrey Bekker, Walter Boyd, Carl Ehlers, Sten-Åke Elming, Roland Gorbatschev, Eero Hanski, Yrjö Kähkönen, Jarmo Kohonen, Asko Kontinen, Raimo Lahtinen, Laura Lauri, Matti I. Lehtonen, Arto Luttinen, Hannu Makkonen, Satu Mertanen, Heikki Niini, Hugh O'Brien, Richard W. Ojakangas, Juhani Ojala, Heikki Papunen, Riku Raitala, Peter Sorjonen-Ward, Matti Vaasjoki, Pär Weihed, Alan Woolley). We would also like to thank Kent Condie, the Series Editor, for accepting this volume to be included in Elsevier's Developments in Precambrian Geology Series, and Patricia Massar and Friso Veenstra for excellent collaboration in technical and administrative matters. Our special thanks go to Sakari Haapaniemi, who patiently manufactured the final electronic manuscript of the book in the course of an overly long and tedious editorial process.

Martti Lehtinen Pekka A. Nurmi O. Tapani Rämö

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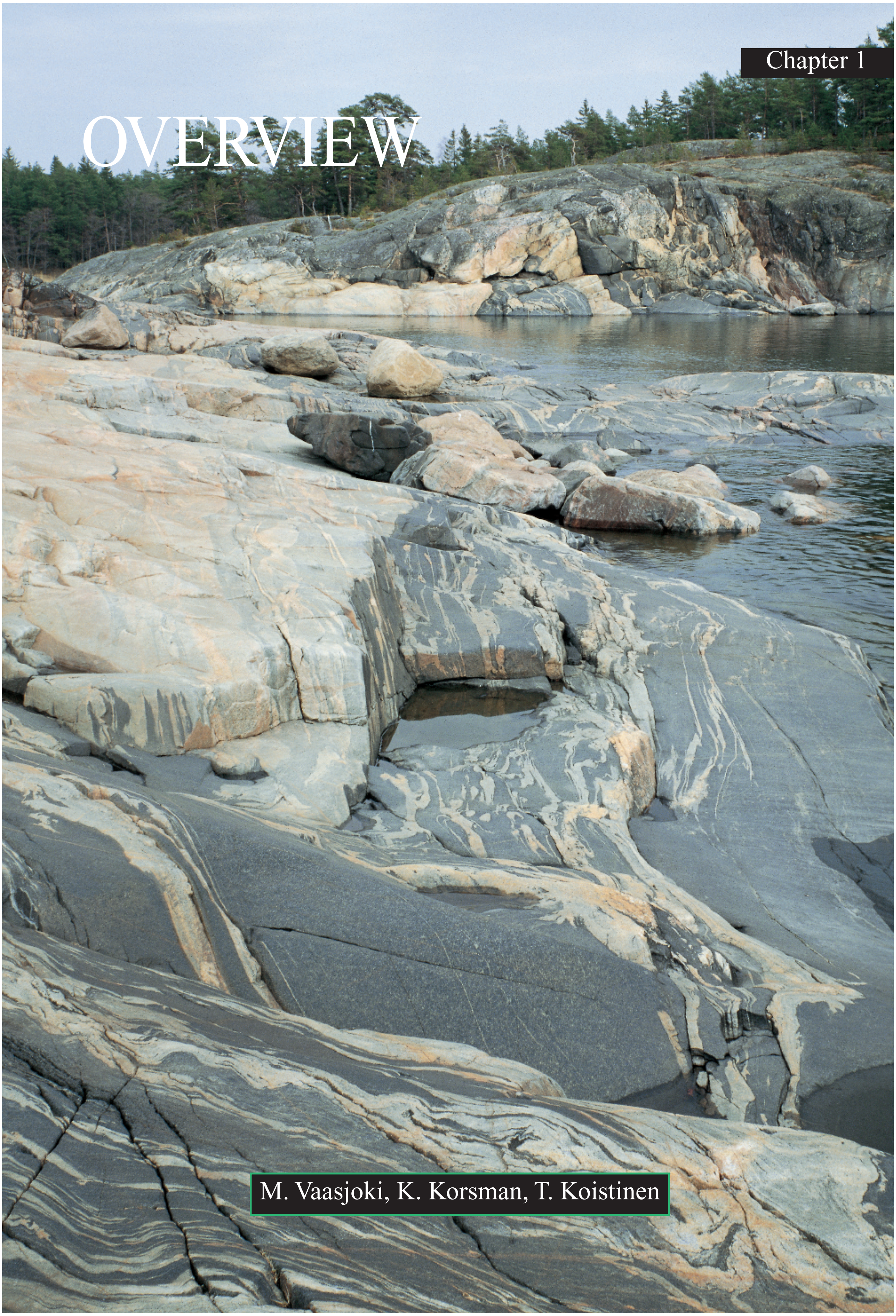
[1] Lehtinen, M., Nurmi, P., Rämö, T. (Eds.), 1998. Suomen kallioperä–3000 vuosimiljoonaa. Geological Society of Finland, Helsinki.



Chapter 1

OVERVIEW

M. Vaasjoki, K. Korsman, T. Koistinen

Cover page: Paleoproterozoic migmatic and gneissic granodiorite containing gabbro fragments crosscut by tiny granite pegmatite dikes (in the background). Porkkalanniemi, Kirkkonummi, ~30 km west of Helsinki. Photo: Jari Väätäinen.

Vaasjoki, M., Korsman, K., Koistinen, T., 2005. Overview. In:
Lehtinen, M., Nurmi, P.A., Rämö, O.T. (Eds.), The Precambrian
Geology of Finland – Key to the Evolution of the Fennoscandian
Shield. Elsevier B.V., Amsterdam, pp. 1–18.

The bedrock of Finland belongs to the Precambrian East European craton of northern and eastern Europe and northwestern Russia. Precambrian crystalline rocks crop out only in the northern and southwestern parts of the craton, in the Fennoscandian and Ukrainian shields, respectively; elsewhere they are covered by platform sediments. In Sweden and Norway, the Fennoscandian Shield is delimited by the Caledonides. In Estonia in the south and Russia in the southeast, the Precambrian bedrock plunges at a shallow angle under Phanerozoic sedimentary rocks.

The most important events during the evolution of the Finnish bedrock occurred at 2800–2700 Ma and 1900–1800 Ma. In those times, continental crust was segregated from the Earth's mantle in two major (probably multiphase) orogenies. The resultant Archean and Paleoproterozoic crust of Finland is divided into 25 areas with characteristic lithologic traits. This chapter gives an overview of Finland's bedrock and its evolution from the Mesoarchean to the present time.

1. Location, subdivision, timing, and general characteristics

Finland forms about one third of the *Fennoscandian Shield* which crops out among younger sedimentary rocks and the Caledonian mountain chain. It can be divided into four areas clearly deviating from each other: the Archean, the Svecofennian, and the Sveconorwegian domains, and the Transscandinavian igneous belt lying between the latter two (Figure 1.1). The northern and eastern parts of Finland belong to the >2.5 Ga *Archean* domain, divided usually into the Kola and Karelia blocks, while the central and southern parts comprise the *Svecofennian* Paleoproterozoic rocks, 1.93–1.80 Ga in age. Only a small part of the Finnish bedrock is younger than 1.8 Ga; the most significant of the younger formations are the 1.65–1.54 Ga *rapakivi granites*. After the intrusion of the rapakivi batholiths no major magmatism has occurred in Finland, but considerable graben formation took place during the Mesoproterozoic and at least southern Finland was covered by Paleozoic–Mesozoic sediments.

The first isotope datings from Finland were carried by Olavi Kouvo during his stay in the United States in the mid-1950's, and his doctoral thesis (1958) caused a fundamental change in the understanding of the Finnish Precambrian. It had been generally accepted that there were two great Precambrian orogenies in Finland: the older Svecofennian and the younger Karelian, but Kouvo's results showed that the lithologic units associated with these orogenies were in fact coeval and that the granite-gneiss domain northeast of Karelides was much older than the southwestern part of the country. The existence of an ancient plate boundary along the Raahe–Ladoga zone became an accepted fact, not a mere working hypothesis, during the 1960's (Simonen, 1971).

The laboratory for isotope geology at the Geological Survey of Finland was established in 1964, and since then the amount of age determinations and other isotope measurements has steadily increased. Figure 1.2 depicts the current data base for igneous rocks on chronograms, where the age results are plotted simply in an ascending order. On this kind of presentation, plateaus represent clusters in ages,

Mesoproterozoic, Neoproterozoic, and Phanerozoic rocks

🟩 Permo-Carboniferous igneous rocks including the Oslo rift

⬜ Vendian to Cambrian and Devonian alkaline igneous rocks

Caledonian orogenic belt

🟧 Lower Paleozoic intrusive rocks

⬜ Caledonian supracrustal rocks

Fennoscandian Shield
Mesoproterozoic to Paleoproterozoic rocks

⬜ Supracrustal rocks, predominantly metasedimentary

🟨 Sveconorwegian igneous and metamorphic rocks

🟥 Rapakivi granites and coeval igneous rocks

Paleoproterozoic rocks (1.96–1.75 Ga)

🟪 Migmatizing granites

🟥 TIB 1 and Revsund granites

🟧 Granitoids and metavolcanic rocks

🟦 Supracrustal rocks

Paleoproterozoic rocks in the Lapland–Kola orogen

🟦 Granulite, amphibolite, anorthosite

Paleoproterozoic rocks (2.50–1.96 Ga)

🟫 Intrusive rocks, mainly mafic and ultramafic

🟦 Supracrustal rocks

Archean rocks

⬜ TTG-complex

🟩 Greenstone belts

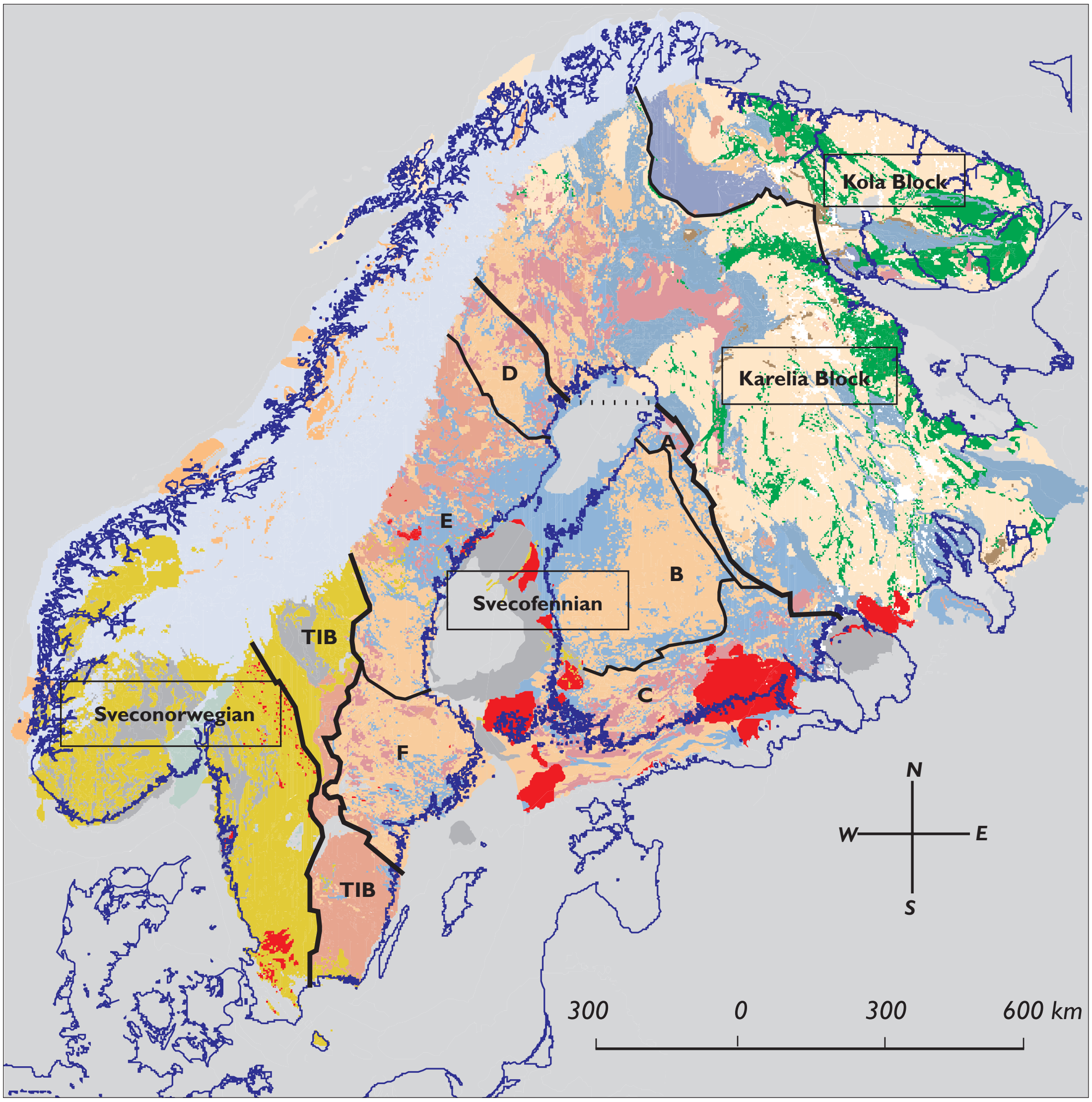


Fig. 1.1. Simplified geological map of the Fennoscandian Shield after Koistinen et al. (2001). TIB denotes the Transscandinavian igneous belt. The subdivisions of the Svecofennian are: (A) The Primitive arc complex of central Finland; (B) The Accretionary arc complex of central and western Finland; (C) The Accretionary arc complex of southern Finland; (D) The Skellefte district; (E) The Bothnian basin; and (F) The Bergslagen district.

while gaps indicate times with no significant igneous activity. The data are mainly based on U-Pb zircon analyses, but include also baddeleyite and columbite U-Pb data as well as some Sm-Nd results. Details of the data compilation can be obtained on request from the Geological Survey of Finland.

The border zone between the Archean and Paleoproterozoic rocks is sharp and has been accurately delineated by geological, isotope geological, and geophysical methods. Archean rocks are found in northern and eastern Finland, whereas the bedrock of central and southern Finland consists of rocks of the Svecofennian. The latter are divided on the current 1:1,000,000 bedrock map [Korsman et al., 1997; based on the 1:400,000 (whole country) and the 1:100,000 mapping (~2/3 of the country) as well as abundant special studies] into the primitive, central Finland and southern Finland arc complexes. Paleoproterozoic metasedimentary and metavolcanic rocks cover large areas of the Archean domain, which is also penetrated by 2.5–2.0 Ga, mainly mafic igneous rocks emplaced while the Archean crust was rifted and eroded. There is no sign of a major inherited Archean component within the igneous rocks of the Svecofennian domain, which has led to the conclusion that the Svecofennian bedrock represents new continental crust segregated from the mantle (Huhma, 1986). The Lapland granulite belt in northern Finland is a geologically significant formation, which has been thrusted from lower continental crust into its present environment.

In the early 1980's evidence on plate tectonic activity in early Precambrian times was insufficient. When the almost completely preserved 1950 Ma ophiolite at Jormua in east-central Finland was discovered in the 1980's, it constituted strong evidence for the operation of plate tectonic processes already in Paleoproterozoic times (Kontinen, 1987).

Within the Svecofennian island arc systems an unusually large amount of granites formed and the upper parts of the crust reached a high temperature. This caused an intense metamorphism of the volcanic and sedimentary rocks. In its course, the rocks partly melted and migmatites were formed. Thus migmatites and granites are the most widespread rocks in southern Finland. According to J.J. Sederholm, about 53% of the Finnish bedrock are granites and about 22% migmatites. Mafic igneous rocks, schists, quartzites, and limestones form a relatively small fraction. Metavolcanic rocks are more frequent in Lapland than in southern

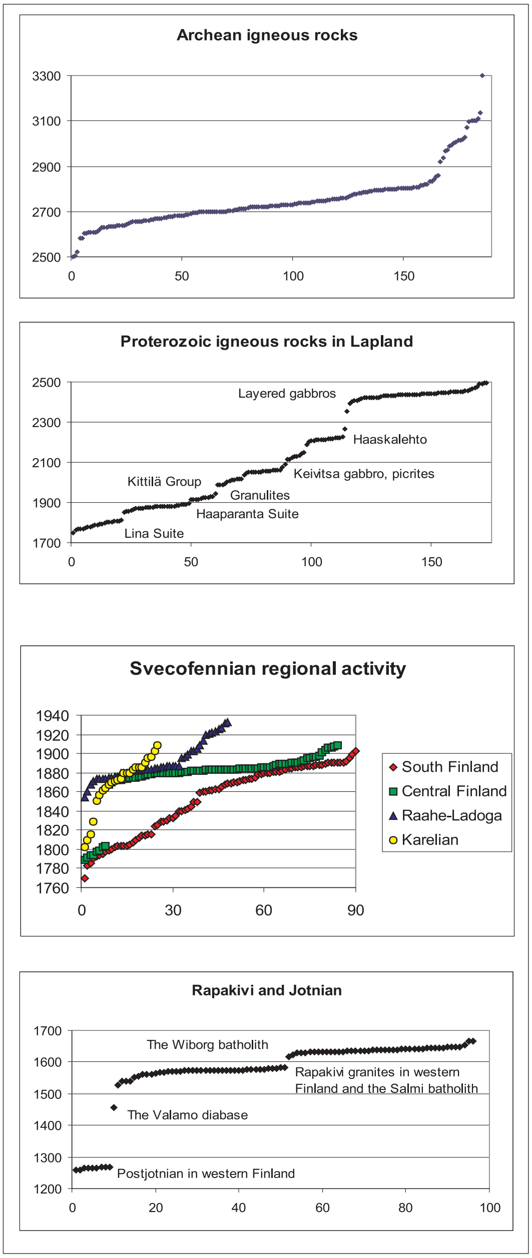


Fig. 1.2. Chronograms showing published U-Pb zircon and baddeleyite ages from igneous rocks in Finland (data compiled at the Geological Survey of Finland; details available from the Survey upon request). The results of these analyses are interpreted as indicating the times of intrusion or extrusion of the rocks.

Finland.

The Precambrian mountain chains of the Fennoscandian Shield have been leveled a long time ago and only ~3% of the bedrock is directly visible. Therefore, it has been difficult to delineate the continuity of rock formations and to obtain a three dimensional picture of the bedrock by geological methods alone. The mapping and study of the bedrock is assisted by high quality geophysical data (Figures 1.3 and 1.4) and has required close collaboration between geophysicist and bedrock geologists.

2. Regional geographic nomenclature

As probably in most other countries, Finnish geological literature is plagued by a multitude of regional names, often used for overlapping areas and sometimes with conflicting meanings. In this volume an attempt has been made towards consistency in this respect, and it has been chosen to apply the terminology proposed by an *ad hoc* working group (Nironen et al., 2002; Figure 1.5). It should be emphasized, that the names are lithological-geographical and do not have a genetic connotation, hence rocks of similar age and origin may be found in several areas. The names were given according to the oldest rocks, generally supracrustal ones, in each area. ‘Belt’ defines an area with linear shape and internal structures, and ‘complex’ means a fault-bounded part of bedrock, or an igneous complex. The areas cover the Archean and Paleoproterozoic bedrock; Mesoproterozoic and younger lithologic units are separated by broken lines in Figure 1.5. A short description of each area is given below.

1. Inari area. The area consists of para- and orthogneisses that are Archean (2.7–2.6 Ga) in the east and Proterozoic in the west. Greenstone belts are found among gneisses of both ages, and at lest some of these are Proterozoic and were deposited upon Archean crust. Gabbros and granodiorites of 1.95–1.93 Ga age are found as conformable bodies in the Proterozoic gneisses.

2. Lapland granulite belt. The rocks of the belt are felsic, generally intensely deformed garnet and pyroxene gneisses that have been metamorphosed at granulite facies. The gneisses are migmatitic especially in the center of the belt. Mafic, pyroxene-bearing 1.93–1.91 Ga igneous rocks of are found as elongate bodies among the gneisses.

3. Enontekiö area. The northwestern part, divided by a broken line, is covered by Caledonian assemblages. The Archean rocks in the northwest are granitoid gneisses with small greenstone belts and ultramafic bodies. The Proterozoic rocks in the southeast are mafic and felsic volcanic rocks as well as arkosic rocks and quartzites that are crosscut by ~1.88 Ga monzonites and granodiorites.

4. Central Lapland area. In the northeastern part of the belt there are felsic gneisses and amphibolites that are considered Archean. Moreover, Archean (3.1–2.7 Ga) gneisses are found as tectonic windows among the Proterozoic assemblages. In the eastern part, there are mafic–ultramafic layered intrusions with an age range of 2.44–2.05 Ga. Most of the Proterozoic supracrustal rocks were deposited upon Archean crust. Lowermost in the sequence are mafic volcanic rocks, overlain by arkosic rocks and mica schists. Two groups of mafic volcanic rocks, with an age range of 2.1–2.0 Ga, constitute the large greenstone belt in the western part of the belt: the first were erupted in a rift zone and the second upon oceanic crust. These rocks are crosscut by ~1.88 Ga monzonites and granodiorites. Quartz arenites and conglomerates were deposited after 1.88 Ga in the southern part of the belt.

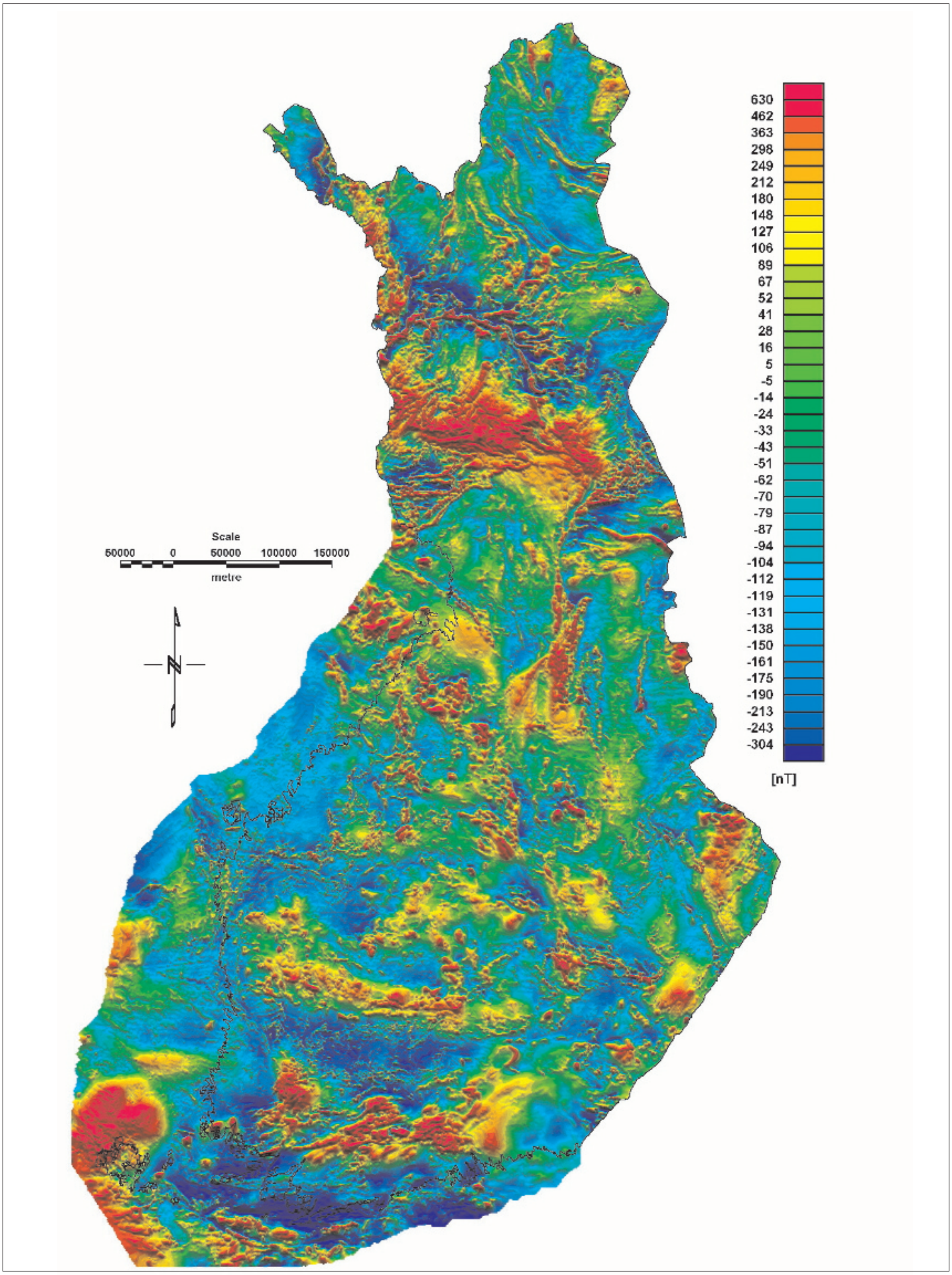


Fig. 1.3. Generalized aeromagnetic map of Finland after Ruotoistenmäki (1992).

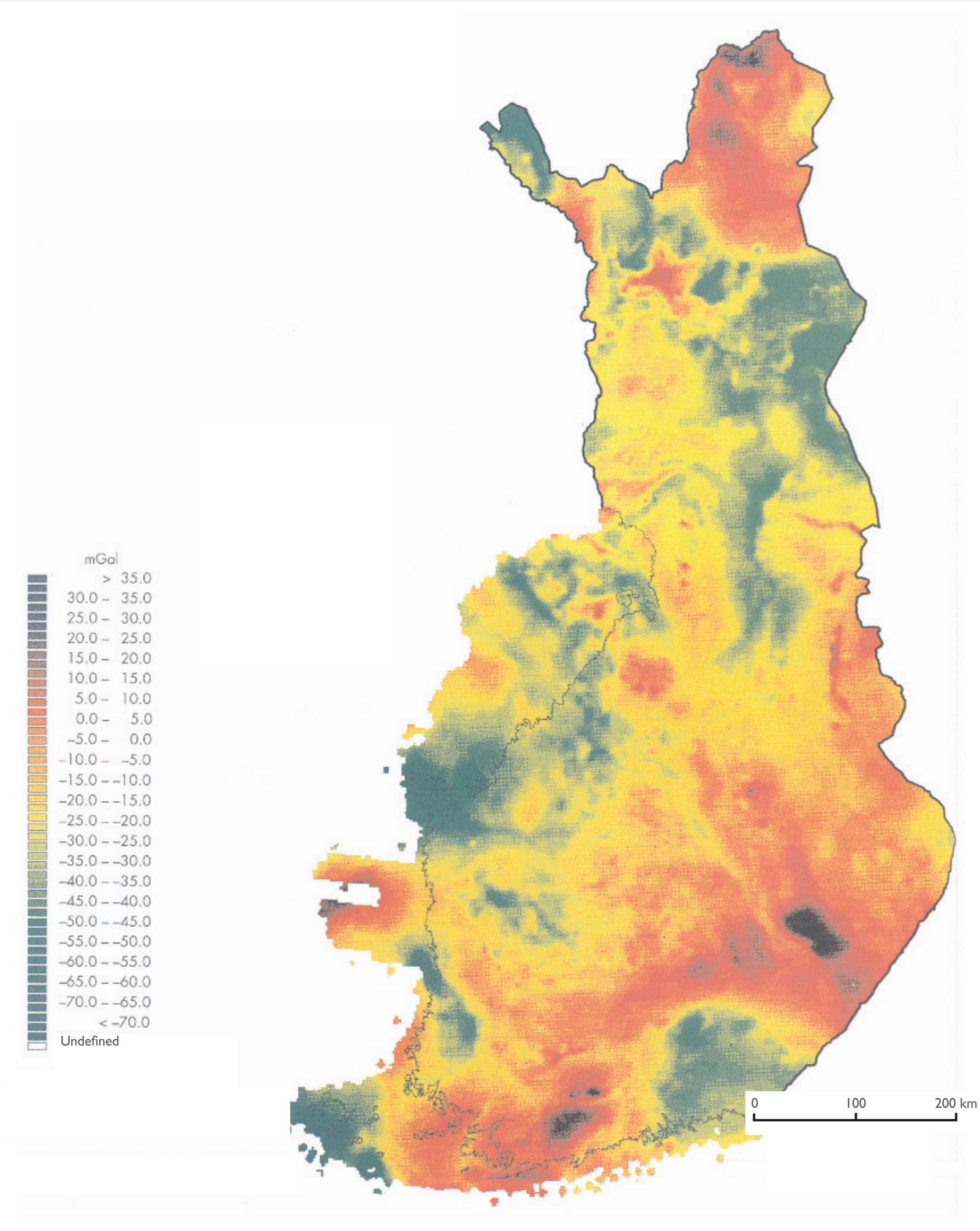


Fig. 1.4. Generalized gravity anomaly map of Finland after Elo (1992).

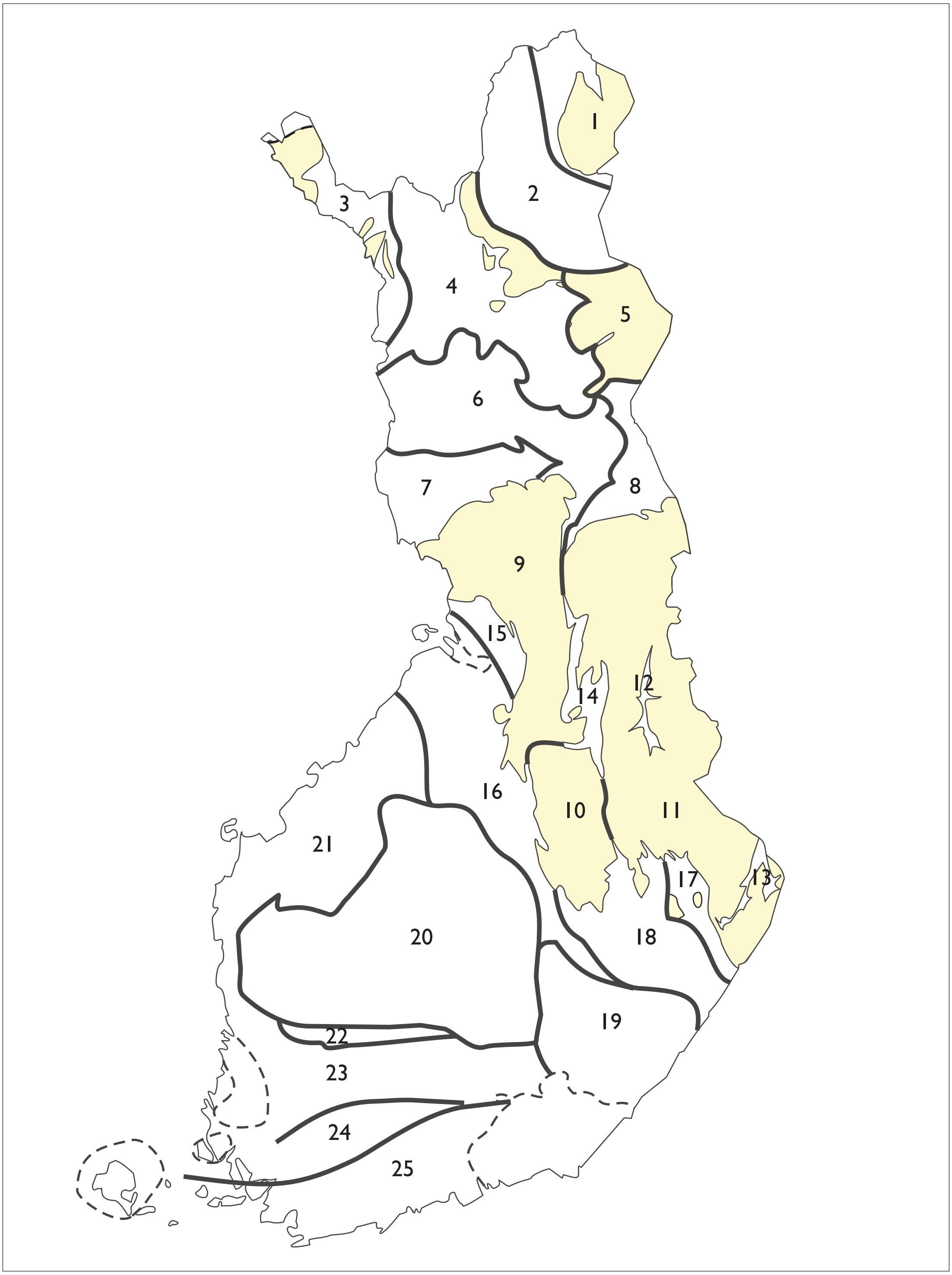


Fig. 1.5. The geographic distribution of various geological regions of Finland according to Nironen et al. (2002). Note that the divisions have been arrived at on lithological and geographic grounds only and bear no genetic connotations.

5. Eastern Lapland complex. The Archean complex mainly consists of 2.8–2.7 Ga tonalitic gneisses. In addition to these gneisses there is a belt of gneissic sedimentary rocks and several greenstone belts, consisting of ultramafic and mafic volcanic rocks as well as sedimentary rocks. Archean granitoid intrusions crosscut the gneisses.

6. Central Lapland granitoid complex. This poorly studied complex mainly consists of 1.8 Ga granites that migmatize and crosscut mica schists and arkosic gneisses. There are also Proterozoic mafic plutonic rocks and remnants of Archean gneisses within the complex.

7. Peräpohja belt. The rocks of this belt were deposited and extruded upon Archean crust. There is a swarm of 2.44 Ga mafic layered intrusions along the southern boundary. The rest of the belt consists of mica schists and quartzites with dolomites, metaconglomerates, black schists, and mafic volcanic rocks as interlayers. These rocks are crosscut by ~1.88 Ga monzonites.

8. Kuusamo belt. The central part of the belt is occupied by 2.44 Ga intermediate and felsic volcanic rocks, followed by mafic and ultramafic volcanic rocks. The mafic rocks in the southern part were deposited upon Archean crust. They contain sericite and mica schist as well as carbonate rocks as interlayers, and on top of the strata there are quartzites as a thick pile.

9. Pudasjärvi complex. This poorly known complex consists of Archean gneisses and granitoids as well as amphibolites that are presumably remnants of Archean greenstone belts. Proterozoic granites and diabase dikes have intruded the gneisses.

10. Iisalmi complex. The complex consists of 3.2–2.6 Ga tonalitic gneisses and amphibolitic migmatites metamorphosed at high grade in large areas. The complex also contains Archean paragneisses and an Archean carbonatite complex. Proterozoic granites and diabase dikes have intruded the gneisses, and Proterozoic deformation and alteration have locally strongly overprinted the gneisses.

11. Eastern Finland complex. This large complex mainly consists of 2.85–2.69 Ga granitoids and migmatites. In addition, there are paragneiss-dominated areas as well as several greenstone belts. Proterozoic granites and diabase dikes have intruded the gneisses, and Proterozoic deformation and alteration have locally caused strong overprinting especially in the western part of the complex.

12. Kuhmo belt. The greenstone belt consists mainly of volcanic rocks. The marginal parts consist of 2.97 Ga mafic and intermediate volcanic rocks, and 2.79 Ga mafic lavas with ultramafic parts and iron-formations as well as interlayers of mica schist are found in the central parts.

13. Ilomantsi belt. The greenstone belt is part of a larger belt that extends to Russia. The predominant and oldest rocks are 2.75–2.70 Ga old and of sedimentary origin. Iron-formations are found higher in the sequence, and mafic lavas are the youngest rocks of the belt.

14. Kainuu belt. The eastern part of the belt mainly consists of autochthonous mafic volcanic rocks and conglomerates overlain by quartzites. The latter are unconformably overlain by mica schists with metaconglomerates, iron-formations, and black schists as interlayers. Highest in the strata are homogeneous mica schists. Part of the mica schists as well as the 1.95 Ga Jormua ophiolite complex are allochthonous.

15. Kiiminki belt. The metasediment-dominated belt contains conglomerates and arkosic rocks lowermost in the sequence. These are followed by a thick pile of turbiditic graywackes, and on top there are mafic volcanic rocks with quartzites, black schists, dolomite rocks, and iron-formations as interlayers.

16. Savo belt. The belt is characterized by numerous shear zones. The predominant rocks are mica gneisses, which contain volcanic rocks, graphite schists, black schists, and carbonate rocks as interlayers. The volcanic rocks in the center of the belt consist of two groups: a 1.92 Ga bimodal group, and a 1.89–1.88 Ga mafic–intermediate group. 1.92 Ga gneissic tonalites and 1.89–1.88 Ga granitoids are also found within this belt.

17. Höytiäinen belt. The northeastern part of the belt consists of autochthonous or parautochthonous conglomerates, arkosic rocks, and quartzites. The main part is dominated by turbiditic mica schists with some interlayers of conglomerates and mafic volcanic rocks.

18. Outokumpu area. The predominant rocks are homogeneous, turbiditic mica schists that contain interlayers of black schists. The rocks are migmatitic mica gneisses in the southwestern part of the area. The 1.97 Ga Outokumpu association, consisting of lensoid serpentinite bodies, carbonates, skarns, and sulfide mineralization, is in the center of the area. The whole-rock sequence is allochthonous.

19. Saimaa area. The predominant rocks in the area are turbiditic mica schists that grade into migmatitic mica gneisses and garnet-cordierite gneisses toward south. Mafic volcanic rocks are found mainly in the northern part of the area. Crosscutting 1.89–1.88 Ga granitoids are found throughout the area. Moreover, 1.84–1.81 Ga granites migmatize and crosscut the supracrustal rocks in the southern part.

20. Central Finland granitoid complex. The complex consists of 1.89–1.88 Ga synkinematic tonalites, granodiorites, and granites, and 1.88–1.86 Ga postkinematic quartz monzonites and granites. In addition, there are minor areas of subvolcanic intermediate rocks, mafic igneous rocks, and remnants of supracrustal belts.

21. Pohjanmaa belt. The predominant rocks are turbiditic mica schists and gneisses, with mafic and intermediate volcanic rocks, black schists, metacherts, and carbonate rocks as interlayers. The conglomerates and arkosic rocks in the northern part represent the youngest sedimentation in the belt. Metamorphic grade increases in the center of the belt toward granulite facies. Granitoids of 1.88 Ga age crosscut the supracrustal rocks.

22. Tampere belt. The belt consists of 1.90–1.88 Ga intermediate and felsic volcanic rocks as well as turbiditic mica schists with conglomerate interlayers. Mafic volcanic rocks are found lowest and highest in the sequence. Granitoids of 1.88 Ga age crosscut the supracrustal rocks.

23. Pirkanmaa belt. The belt mainly consists of migmatitic, turbiditic mica gneisses with black schists and graphite-bearing schists as interlayers. Mafic and ultramafic plutonic rocks as well as 1.88 Ga granitoids crosscut the supracrustal rocks.

24. Häme belt. The belt is characterized by volcanic rocks which may be grouped into older, of intermediate and younger, of mafic–intermediate composition. The western part of the belt is dominated by metasedimentary rocks. 1.88 Ga granitoids of as well as 1.84–1.82 Ga granites crosscut and migmatize the supracrustal rocks.

25. Uusimaa belt. This sedimentary-dominated belt contains mica schists and gneisses with relatively common carbonate rock interlayers. Also felsic sedimentary rocks of volcanic provenance are typical of the belt. The volcanic rocks are generally mafic–intermediate in composition, but in the western part of the belt volcanism was bimodal. Granitoids of 1.88 Ga age as well as 1.84–1.82 Ga granites crosscut and migmatize the supracrustal rocks.

3. The Archean bedrock

The oldest rocks in Finland lie within the Archean domain in the eastern and northern parts of the country, and several occurrences of rocks older than 3 Ga are known. However, they are all of local nature and lie widely dispersed from each other with emplacement ages ranging from 3.1 to 3.5 Ga (Figure 1.2). The oldest known rock is trondhjemite gneiss found at Siurua, where ionprobe results from zircons, supported by conventional zircon data and Sm-Nd whole-rock data, indicate an intrusion age of ~3.5 Ga (Mutanen and Huhma, 2003). There are, however, indirect Sm-Nd and common lead indications suggesting that the 3.5 Ga crust in Finland may have been more wide-spread.

Greenstone belts formed by volcanic and sedimentary rocks are characteristic of all Archean terranes of the world. The mainly 2.8 Ga old greenstone belts especially in eastern Finland have been compressed into narrow sequences between Archean granitoid rocks, which are mainly ~2.7 Ga granodiorites and gneissose tonalites. This period of evolution is well evident in the isotope ages (Figure 1.2), although ion microprobe data suggest that some rocks both in the Suomussalmi and Ilomantsi areas contain also inherited zircons older than 3 Ga. A peculiarity of the Finnish Archean is the 2610 Ma carbonatite at Siilinjärvi, one of the oldest of its kind in the world.

4. Faulting of Archean crust and emplacement of Paleoproterozoic cover rocks

When the Archean orogenic movements ceased, there commenced a period of peneplanation, which lasted for several hundred million years. However, crustal scale faulting with associated volcanic activity and formation of sedimentary basins occurred within the eroding and peneplaning Archean crust. A characteristic feature are numerous 2.44 Ga layered mafic intrusions in northern Finland and northwestern Russia.

The faulting started to ease up about 2.4 Ga ago. At this time, weathering was well-advanced and the Archean bedrock was in many places covered by quartz sands, which later formed the so-called Jatulian quartzites. Volcanic activity occurred also during the Jatulian period, and is manifested as mafic lava flows and numerous diabase dikes that penetrated the Archean and its cover rocks 2.2–1.97 Ga ago. The cratonization of the Archean bedrock over a period of 500 Ma is especially diversely observable in Lapland.

Fundamental atmospheric changes occurred at the same time as the rifting phase of the Archean continent ended. For the evolution of life most important was the increase of the oxygen contents of the atmosphere almost to its present level about 2.1 Ga ago. This information, relevant to the evolution of the entire Earth, has been obtained by careful stratigraphic and isotope geological studies of the Finnish Karelian formations (Karhu, 1993).

5. The Svecofennian bedrock

The Jormua ophiolite demonstrates that oceanic mantle had formed and plate tectonics operated at least 1950 Ma ago, but, according to some interpretations, some kind of primitive Svecofennian continent may have formed already 2.1 Ga ago. However, so far no continental crust of that age has been found within the Fennoscandian Shield. The only indications are the zircon age distribution of younger metasedimentary rocks, Sm-Nd model ages, and some geochemical features suggesting that Svecofennian granites may have resulted from remelting of older crust, perhaps 2.1 Ga in age.

The oldest Svecofennian volcanic rocks of primitive island arc type and associated gneisses are 1930–1920 Ma old and occur along the Archean–Proterozoic boundary in central Finland. Observations from the Lapland granulite complex indicate, however, that subduction was already occurring in that area, as the ocean in the (present) north had already closed and the granulites were being thrust from lower crustal levels into their present geological environment. This belt, called the Lapland–Kola orogen, formed more or less simultaneously with the Svecofennian orogeny, and extends from the granulite belt in Finland to the southern part of the Kola Peninsula.

Evolved island arc volcanic rocks and associated metasediments in central and southern Finland are 1910–1890 Ma old. A particularly well-known volcano-sedimentary entity is the Tampere schist belt, where systematic studies have been carried out for over 100 years. Primary structures of the volcanic and sedimentary rocks have been preserved at many locations within the belt, facilitating conclusions on the origin of rock formations.

The Svecofennian crust is exceptionally thick, up to 65 km in the Paleoproterozoic–Archean boundary zone. The crust was thickened first during the collision when the newly created crustal plates were thrust upon each other. There is little reliable information on the incipient part of the collision and its beginning can be timed only indirectly at about 1910–1900 Ma. It had concluded 1870 Ma ago, because at that time the Svecofennian bedrock was already attached to the Archean continent. During the collision and the ensuing tectonic thickening, molten rock material was injected into the collision zone from the underlying mantle. The mantle-derived magma caused melting of the lower crust, which lead to the intrusion of magmas close to the then existing erosional level. Thus the temperature even in the upper parts of the crust was raised, leading to recrystallization and partial melting of rocks. The metamorphism and the magmatism generated from the lower crust are coeval at ~1885 Ma in the collision zone between the Archean and Svecofennian domains. After this strong pulse of magmatism and recrystallization, cooling commenced within the collision zone.

The collision of the Svecofennian island arc complex also affected the cratonized Archean continent. Easily observed evidence about the reactivation of the Archean continental crust during the Svecofennian orogeny are found up to 150 km from the collision zone: 1.9–1.86 Ga rocks with Archean Nd isotope signature, titanite and monazite U-Pb ages in the 1.9–1.8 Ga range, and reset biotite K-Ar ages in Archean granitoids.

The migmatite-forming lateorogenic microcline granites in southern Finland form large, sheet-like bodies with usually diffuse contacts. They are about 1.83 Ga old, and their emplacement was associated either with the extensional collapse of Svecofennian orogen or transpressional faulting. In any case, the migmatization of the Svecofennian bedrock in southern Finland is best regarded as a quite separate event from the main phase of the Svecofennian orogeny.

A special feature of the Svecofennian is also the survival of the 65 km thick crust, as the usual thickness of continental crust is about 40 km. Crust thickened during a collision of continents is in a disequilibrium. The light crust returns to equilibrium either by uplift or collapse, as is the case in the Phanerozoic mountain chains. There are signs of an incipient collapse within the Svecofennian, but the process was left incomplete, as the light crust thickened by the collision was quickly stabilized by magmatism originated in the mantle. Due to this unusually quick isostatic equilibration the thick crust became permanent. It is still thick, although erosion has removed the top 15 km!

The orogenic movements waned in southern Finland about 1.8 Ga ago. As the bedrock cooled, fissures opened and made way for deep-seated magmas, which crystallized in the upper crust as the so-called postorogenic (1.81–1.77 Ga) granites.

6. Rapakivi magmatism and the Jotnian period

A period of 150 Ma of geological quiescence followed after the emplacement of the postorogenic granites. There are very few signs of strong bedrock movements from this time, which indicates that the crust was being peneplaned through erosion. The quiescence terminated when the rapakivi granites intruded into the rigid bedrock 1650–1540 Ma ago.

More than ten rapakivi intrusions, often with associated gabbroic and anorthositic rocks, are known in southern Finland. The largest are the Wiborg, Åland, Laitila, and Vehmaa batholiths. Coeval with the rapakivi granites are tholeiitic (Subjotnian) diabase dikes.

Rapakivi granites are not limited to the Finnish bedrock. They are found in all Precambrian shield areas, but the origin of the rapakivi magmas as remelted lower continental crust has been successfully explained in Finland (Rämö, 1991). According to the prevailing view, the formation of rapakivi granites was not a direct consequence of the Svecofennian orogeny. Some scientists have, however, considered the formation of rapakivi granites to reflect the last phase of the stabilization of the Svecofennian crust.

Rapakivi granites intruded, at least partially, into a bedrock on which the so-called Jotnian sediments had started to deposit in topographic shallows. The deepening of basins and sedimentation continued still long after the rapakivi magmatism. The Jotnian sand- and claystones are preserved on the continent at Muhos and Satakunta, and the Satakunta sandstones continue into the Gulf of Bothnia covering large submerged areas. The Jotnian sedimentary rocks are cut by 1.26 Ga tholeiitic (Postjotnian) diabase dikes and sills. However, a recent result from the Valamo (Valaam) sill in the Ladoga basin, 1.46 Ga, suggests that this continental sedimentation at least in that area was well advanced much earlier on than belived so far. In Lapland, there are young dike rocks in local rifts: 1100 Ma at Salla and 1000 Ma at Laanila. These represent the youngest parts of the Finnish bedrock, because only rocks which were deposited or crystallized before the Vendian period (>650 Ma ago) are considered bedrock.

7. The Vendian period and the Paleozoic era

At the beginning of the Vendian period (~650 Ma ago) the Finnish bedrock had been eroded almost to its present level. Shallow-water sandstones were deposited on the continental peneplane. Cambrian sandstone is found in fissures in the southwest Finnish archipelago, at Lauhanvuori in northern Satakunta, and at Sulva (Söderfjärden) south of Vaasa. At Lumparn in the Åland Islands Ordovician limestones are known. At Muhos, the sedimentation, which had started in Jotnian times, lasted into the beginning of the Vendian period. Alkaline igneous rocks (e.g., kimberlites) were emplaced in eastern Finland at ~600 Ma.

The Paleozoic sediments deposited west of Fennoscandia were folded against the craton 450–400 Ma ago. An overthrusted nappe of the Caledonides has been found in Finland only in the far northwestern part of the country.

Other effects of the Caledonian orogeny on the Finnish bedrock are not well known. The 370–360 Ma alkaline intrusions at Iivaara and Sokli may have a causal relationship to the Caledonian orogeny, and faulting is likely to have occurred in the foreland of the Caledonides, i.e., in Finland.

8. Late events affecting the bedrock

Although movements strongly affecting the bedrock waned decisively already ~1.8 Ga ago, many shear zones remained active for hundreds of millions of years after the Svecofennian orogeny. Some of them are weakly active even today, although the amount of movement is relatively small.

The Svecofennian metasedimentary and metavolcanic rocks were deposited 1890 Ma ago, but subsided within a few million years to a depth of about 20 km within the crust, which demonstrates the rapidity of changes during ancient plate collisions. The present erosional level lay at a depth of 15 km even 1.8 Ga ago. The denudation which brought the Svecofennian metavolcanic and metasedimentary rocks back to surface lasted at least 200 Ma, as the intrusion of the rapakivi granites into the upper crust occurred at a depth of ~5 km. The present erosional level had been definitely reached at the onset of the Cambrian period about 600 Ma ago, as is demonstrated by the deposition of Cambrian sandstones and their preservation in bedrock cracks.

The Pleistocene continental glaciation eroded the bedrock mainly by polishing the weathering surfaces and sharpening the shear zones. Preglacial weathering surfaces formed before the glaciation have survived in a few places only, most notably in Lapland. The shallow Finnish lakes are found mainly in shear zones dredged deeper by the continental ice sheet.

The widening of the Atlantic Ocean and the postglacial isostatic uplift result in tensions within the bedrock which trigger earthquakes. The tremors are, however, so mild that they damage buildings or cause any alarm only in exceptional circumstances.

Generally, recognizable traces of asteroids have survived only locally. There are at least ten positively identified impact craters in Finland, of which Lappajärvi (impact at 75 Ma), Söderfjärden (~530–510 Ma), Sääksjärvi (~515 Ma), Lumparn, Karikkoselkä, Suvasvesi, and Paasselkä are the most widely known (e.g., Lehtinen, 1976; Pesonen et al., 2000).

The main features of the Finnish bedrock are ancient. As in many other Precambrian shield areas (e.g., Canada, Greenland, China) they were formed principally during late Archean and early Proterozoic times. Thus detailed results from the Fennoscandian Shield often have also a global bearing, which is one the reasons for the compilation of the present volume.

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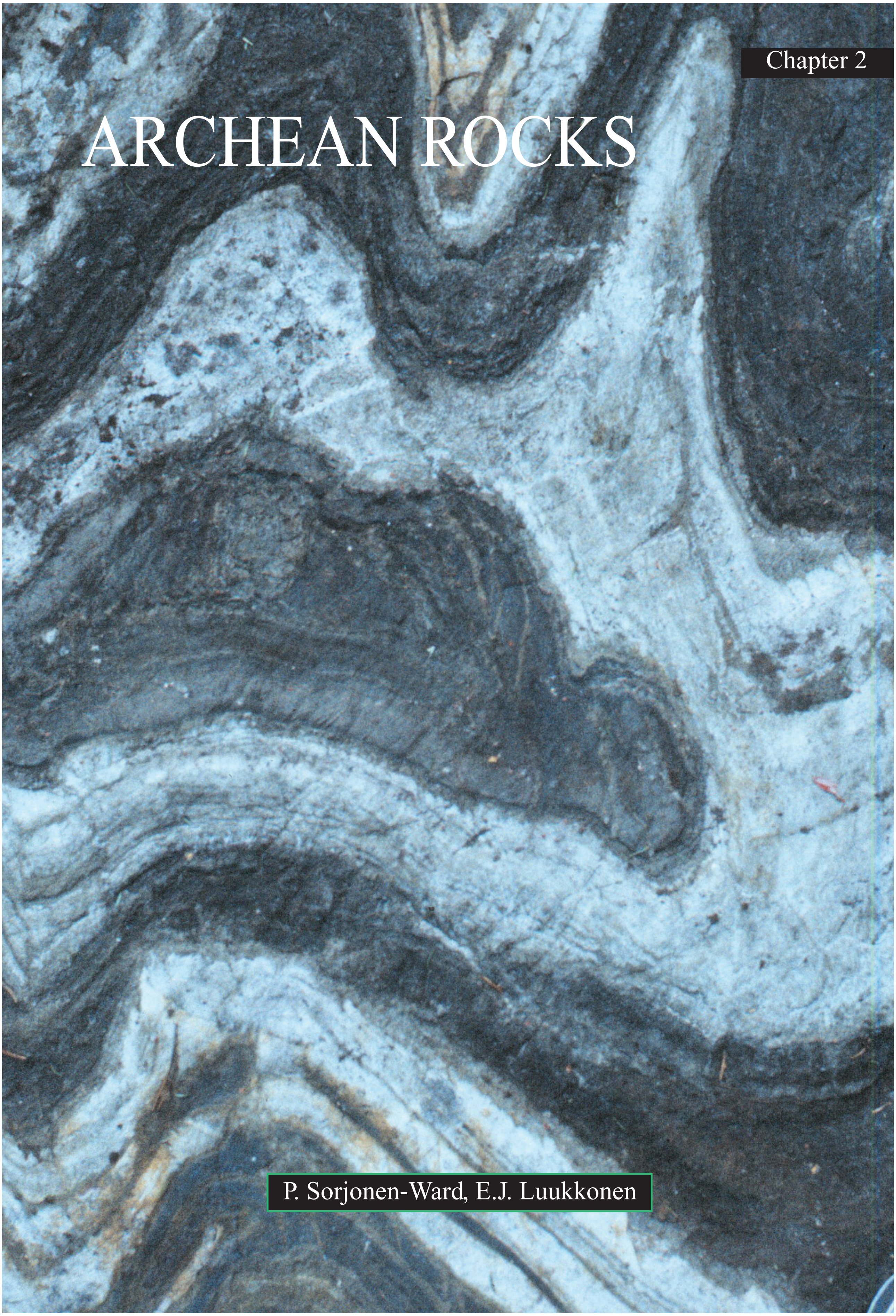

Chapter 2

ARCHEAN ROCKS

P. Sorjonen-Ward, E.J. Luukkonen

Cover page: Archean banded iron-formation. Ukkolanvaara, Ilomantsi.
Photo: Peter Sorjonen-Ward.

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There have been few attempts in recent years to synthesize the nature and evolution of the Archean geological record in Finland. Therefore, the main purpose of this review is to describe the principal features of the Archean bedrock in Finland as currently known, primarily in terms of lithological units and structures. Through comparisons with the Proterozoic record of Finland, we then briefly consider whether the Archean bedrock of Finland reflects a distinctive style of crustal evolution, related to secular variations in thermal regime and rates of crustal growth and recycling. We are therefore also concerned with attempting to discriminate between processes relating to crustal formation and those that rework existing crust. For example, is the evolution of high-grade terrains in the deep crust level necessarily coeval with and complementary to lower grade supracrustal units, as for example in paired metamorphic belts in modern convergent accretionary settings? Alternatively, does the pattern of metamorphic grade represent a direct consequence of vertical crustal differentiation related to thermal and gravitational instability? Does crustal zonation with depth differ from that of younger continental crust and to what extent has the existence of Archean lithosphere predetermined subsequent crustal development?

Although this review commences with brief descriptions of each of the various Archean rock units currently recognized, including a discussion of age relationships and possible correlations, we concentrate on those areas that are best known and which have begun to yield useful insights into Archean crustal processes. We conclude with a discussion of Archean thermal regimes and their tectonic consequences, the stabilization of the shield, and some regional scenarios and correlations, including a comparison between Archean and Paleoproterozoic crustal proceses in the Fennoscandian Shield.

1. Introduction to the Archean of Finland

1.1. The extent of the Archean in Finland

Although the distribution and nature of Archean rock types in Finland has been relatively well defined from regional reconnaissance scale mapping, a systematic framework for understanding Archean crustal evolution has yet to emerge. Indeed, in some cases there is still uncertainty over the age affinities of rock units. This applies particularly to extensive tracts of migmatitic gneisses intruded by Svecofennian potassic granite neosomes in the northern part of the country (Vaasjoki et al., 2001), as well as some metasedimentary complexes that contain exclusively Archean detrital zircons, but otherwise show evidence for reworking or partial melting during the Svecofennian orogeny (Huhma et al., 2000). Detailed studies addressing generic issues of crustal evolution are few and restricted largely to lower grade supracrustal greenstone belts which, by analogy with similar terrains elsewhere, are considered prospective for komatiite-hosted nickel and orogenic lode gold deposits. For example, a comprehensive commodity database for gold in Finland, prepared by Eilu (1999) includes attribute information for all known Archean occurrences and their geological context. In recent years attempts have also been made to understand the composition, thermal structure and evolution of the deeper crust and mantle lithosphere through seismic and other geophysical techniques and by studying exposed higher grade terrains (Hölttä, 1997; Hölttä and Paavola, 2000; Hölttä et al., 2000a,b) as well as xenolith suites sampled by Paleozoic kimberlites (Kukkonen and Peltonen, 1999; Hölttä et al., 2001).

It is convenient, as first suggested by Gaál and Gorbatschev (1987), to consider the Archean and Paleoproterozoic history of the Fennoscandian Shield in terms of three large crustal domains – the Kola, Karelian, and Svecofennian domains (Figure 2.1A). These three crustal units have shared a common history since amalgamation at about 1.8 Ga. The Karelian domain is the largest unit, forming a coherent late Archean (3.2–2.7 Ga) cratonic nucleus exceeding 200 000 km^2 in area in eastern Finland and adjacent Russia (Figure 2.1B and 2.2). The Karelian domain is flanked to the northeast by the Kola domain, which represents a complex tectonic collage of Archean and early Proterozoic terranes, and to the southwest by the essentially Paleoproterozoic Svecofennian domain (Figures 2.1A and B). The Karelian domain is characterized by a number of narrow northerly trending low-pressure greenstone and metasedimentary belts (Figures 2.1B and 2.2), intruded by discrete plutons of dominantly granodioritic to monzogranitic compositions. Higher grade medium-pressure metasedimentary gneiss complexes are also present, some of which represent older relict enclaves with younger migmatites, while others appear to be coeval with the greenstone sequences. The Archean of the Kola domain includes granitoid gneisses, migmatites, charnockites, aluminous metasedimentary rocks, and iron-formations (Meriläinen, 1976; Gaál et al., 1989; Rundquist and Mitrofanov, 1993), and also a distinctive suite of alkaline intrusions and gabbro–anorthosite intrusions (Zozulya et al., 2001).

The nature and age of the boundary zone between the Kola and Karelian domains in Russia has long been contentious, largely due to the presence of both Archean and Proterozoic isotope ages from medium- to high-pressure gneisses of the intervening Belomorian terrain (Figure 2.1A) (named from the Russian term for the White Sea). Intense deformation and medium-pressure metamorphism in unequivocally Proterozoic rocks, and widespread thermal resetting of U-Pb isotopes in titanites, demonstrate significant tectonic and thermal reworking of the Belomorian terrain between 1.9–1.8 Ga, which is attributed

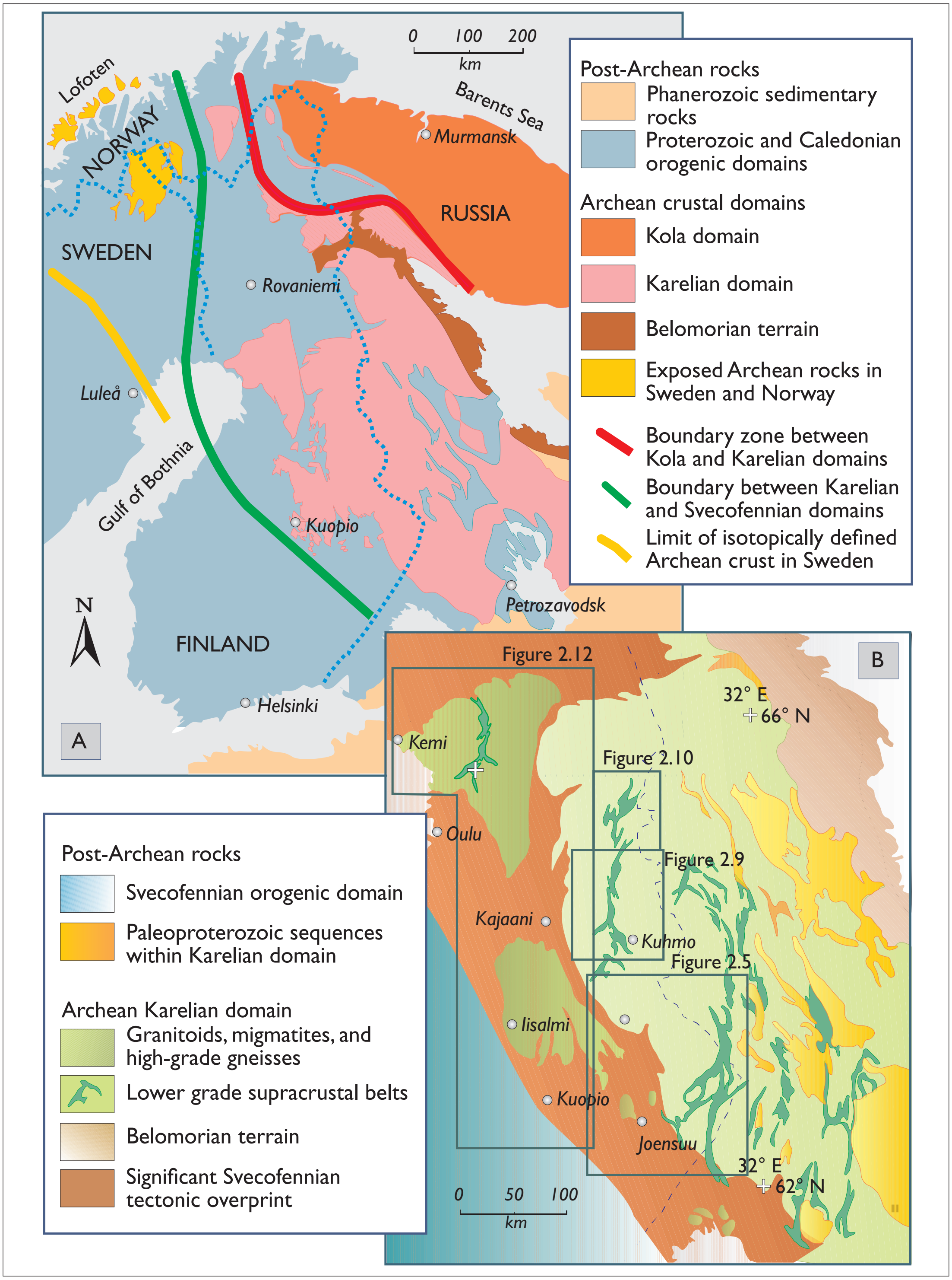

Fig. 2.1. Regional distribution of Archean rocks in the Fennoscandian Shield. (A) Principal crustal domains. (B) Distribution of greenstone belts and granitoid terrains within the Karelian domain in eastern Finland and adjacent Russia, showing locations of more detailed regional scale maps.