THE PRECAMBRIAN ROCKS OF SOUTHERN FINLAND AND ESTONIA

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Tallinn 2007

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MTÜ GEOGuide Baltoscandia. Tallinn, 2007.

ISBN 978-9985-9867-4-5

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Acknowledgements: Ari Linna, Ari Brozinski, Heikki Bauert, Olav Eklund and Arto Peltola supplied pictures to this booklet. Leena Laurila helped with the layout of the maps. Paul Reuter and Matti Wahlbäck are acknowledged for logistics during field trips in the archipelago of SW Finland. Jeremy Woodard edited the English version.

Edited: MTÜ GEOGuide Baltoscandia

Layout: Andres Abe

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Front page: Intensively folded granitic veins in a metavolcanite, southwest Finland. The structure was named ptygmatic by the Finnish geologist J.J. Sederholm in 1907. Ptygmatic is from the Greek, meaning "the folded". Photo A. Linna.

Back cover: Geologic map of southwest Finland.

Release of this booklet in English was co-financed by ERDF and by Estonian Ministry of the Interior under the INTERREG IIIA Southern Finland and Estonia programme.

The bedrock of southwestern Finland

By looking at any rock, you are looking at a piece of the history of the Earth. In Finland, if you draw a line between the town of Raahe and Lake Ladoga, then any rock (with a few exceptions) south of this line you look at formed between 1920 and 1575 million years ago. To the north of this line are Archaean rocks, which are rocks that formed more than 2500 million years ago. These rocks all formed either deep within the Earth's crust from crystallising magma or at the Earth's surface, either directly from material erupted from volcanoes or from sediments, for instance sand or clay, eroded, transported and redeposited at the sea floor. The majority of the rocks in southern Finland have, after formation, also been subjected to conditions of extreme heat and pressure, which resulted in mineralogical and textural changes in the rock. This process is called metamorphism, from the Greek *meta morphos* meaning change of form. The metamorphism in Southern Finland is related to orogenic (mountain building) processes, which affected all of the rocks in the region. Only the rapakivi granites, Jotnian Satakunta sandstone and diabases, which all formed after the metamorphic event, are unaffected.

By studying the texture, macroscopic and regional structures, mineralogy and mineral parageneses, chemical composition and isotope composition of rocks, geologists have been able to identify the environment where the rocks formed and when it happened. This allows geologists to reconstruct the geological history of our part of the Earth.

Why is there an archipelago in southwestern Finland?

Why do we have an archipelago in front of southwestern Finland? Why are there not archipelagos everywhere around the coast? To answer this, we first consider two major geological processes that have shaped (and continue to shape) the surface of the Earth in southwest Finland: those that affect the bedrock and those that affect the soil cover. The bedrock formed during a prolonged crust forming and mountain building event between 1900 and 1765 Ma (geologists report ages in *anno*, meaning years ago; Ma = *mega anno* = million years ago) that we call the Svecofennian orogeny. The soil cover is a mixture of glacial sediments, which were deposited on the top of this eroded mountain chain at the end of the last ice age, less than 10 000 years ago. Before this, the glaciers scraped away the Palaeozoic sedimentary cover plus the weathered surfaces of the crystalline bedrock. Remnants of the former Cambrian and Ordovician sedimentary rocks have only occasionally been preserved in deep depressions, for example within a meteorite crater or deep fractures in the bedrock.

The geological event that had the most profound effect on the modern Earth's surface was the last ice age, which ended about 10 000 years ago. Striking features include cliffs in the archipelago, rounded and polished on their northern (proximal; towards the advancing glacier) side, with grooves and lineation from the rocks in the bottom of the ice and fragmented on the southern (distal) side. This fragmentation on the distal side was caused by the freezing of water, derived from ice melting in the high-pressure conditions on the proximal side. Meltwater would seep into fractures and then refreeze, and the resulting expansion broke the rock. A huge volume of sediment was transported by the glacier and deposited in a variety of different sedimentary formations when the glaciers started to melt. Moraine fields, end formations, including sandurs and deltas, and eskers were formed (see the booklet about quaternary formations in Finland and Estonia).

We can agree that an archipelago is an area with a lot of islands with water between. However, when you travel from Turku towards the east, you see a lot of hills with fields between. Imagine if you were to change these fields to water, you would also have an archipelago there. As a matter of fact, these now-dry areas initially formed an archipelago, but as a consequence of land uplift after the end of the last ice age, parts of the archipelago are now situated on dry land. The hills (and islands) are usually made of granitoids, which are hard and resistant to erosion. The rocks beneath the fields (and the sea-sediments) are usually made of a softer rock, schist, which is less resistant to erosion. The granitic hills were formed from rocks melting in the roots of the Svecofennian mountains, 1880-1820 Ma ago. Very commonly in these rocks, you can see fragments of basic rocks, such as amphibolite, that have not melted, even though the other rock material was almost completely or completely melted.

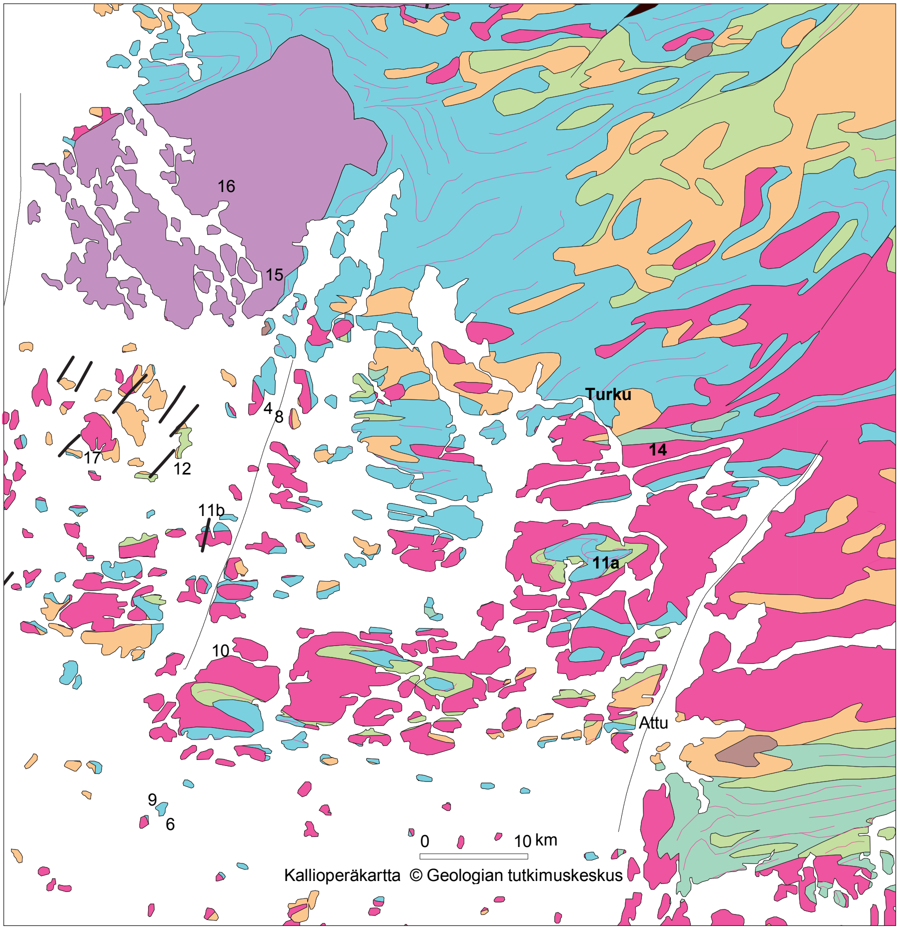
The formation of different rock types

To reconstruct the geological history, we need to know what mechanisms are active in the Earth today. The most important concept is Plate Tectonics.

Plate Tectonics

MeileThe Earth's crust is divided into eight major lithospheric plates, which drift around the Earth on a partly molten mantle. The plate Finland is situated on is currently moving towards the northeast at a rate of 2 cm/year (the same speed as your fingernails grow). The forces driving this motion are convection currents in the mantle, in which hot light material rises from deep within the Earth, cools and sinks down again, like boiling water in a kettle (Figure 1). Some of the plates are older, lighter continental plates and some of them are younger, heavier oceanic plates. The continents North and South America are drifting apart from Europe and Africa. As they drift apart, new oceanic crust is forming in the middle of the Atlantic Ocean. The volcanic activity in Iceland is also a consequence of this. Iceland is situated right on the mid-oceanic ridge, where two plates drift apart.

Since the Earth is a sphere, on which continents are drifting and new oceanic crust is formed all the time, oceanic crust must also be consumed somewhere and continents have to collide every now and then. These are geological events that have occurred throughout the history of the Earth. The Himalayas are a modern example of a continent-continent colli-



Fault systems

Diabase dykes (1590-1570 Ma) .... Figure 17

Rapakivi granite (1590-1570 Ma) ... Figure 15 ja 16

Microcline granite (1840-1820 Ma) ... Figure 14

Granodiorite, tonalite and quartz diorite (1890-1870 Ma) ... Figure 12

Gabbro and diorite (1890-1870 Ma) ... Figure 10

Mica schist and -gneisses (about 1900 Ma) ... Figures 5a & 13

Mafic metavolcanics and marble (about 1900-1885 Ma) ... Figures 3, 4, 8, 11a & 11b

Intermediate and felsic metavolcanics, metasedimets and marble (about 1900-1885 Ma) ... Figure 2 sion. The Himalayas formed when the Indian continental plate collided with the Asian continental plate. Previously, there was an ocean between Asia and India, and sediments from the sea floor were pushed upward during this collision. That's why we can find materials formed in oceans on the top of the mountains. We may say that where there are mountain chains, there has been a collision. The mountain chain in Norway and Sweden, the Caledonides, formed when the North American plate collided with Europe about 500 million years ago. The highest point in Finland, Halti, located in the westernmost part of the Finnish "arm", is a part of this extensive mountain chain.

When an oceanic plate collides with a continental plate, the heavier oceanic plate is pressed under the continental crust. This process consumes the old oceanic crust and is called subduction. The oceanic crust sinks down into the Earth's mantle, where, when the temperature rises high enough (at the distal end of

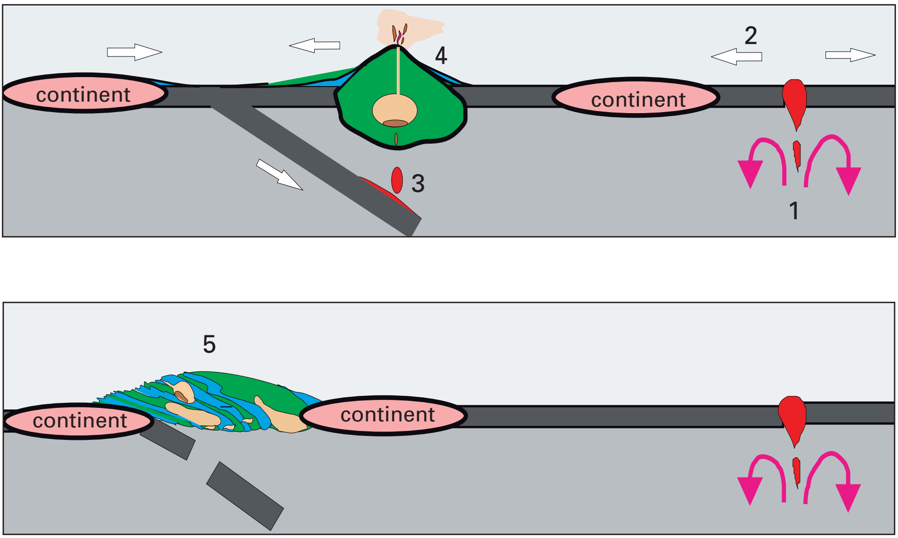


Figure 1. Principles of plate tectonics. 1. Due to convection currents in the deep mantle, hot material from the Earth's interior rises towards the surface and causes melting in the upper mantle. These magmas intrude the crust and crystallise forming new crust, such as in Iceland. 2. Arrows indicating the motion of crustal plates and their subduction into the mantle. 3. An oceanic plate subducting beneath another plate. 4. At depth, partial melting takes place above the subducting plate, resulting in the formation of a volcanic chain. 5. When two continents collide, the crust crumples to form a mountain chain. You can imagine that the two continents in the figure represent India and Asia and the mountain chain is the Himalayas.

the subducting plate), it starts to melt. The evolved hot magma rises up, causing melting also in the surrounding rocks of the continental plate. The magmas formed migrate towards the surface of the Earth (numbers 3 and 4 in Figure 1). Sometimes these magmas erupt at the surface, forming a chain of volcanoes; the "volcanic arc" is analogous to subduction zones. The earthquakes resulting from the readjustment of litospheric plates is an inseparable part in this complex of processes. At the moment, there is a lot of geological activity in Thailand, Indonesia and The Philippines, because several plates are fighting for space in that area.

If we go back in time 1900 million years, the geology of southern Finland was similar to what we see in southeast Asia today. Volcanic chains were moving towards today's north, producing volcanic rocks. Today, most of these have been metamorphosed and recrystallised to a rock type called amphibolite (Figure 2). The majority of these rocks were deformed and folded during orogenic processes (Figure 3). Still, some primary structures can be seen in these old volcanic rocks (Figure 4).

Before your tour into the geology of the archipelago, some geological terms must be explained.

Figure 2. Old volcanic rocks showing differences in their composition (black and grey areas). A younger, crosscutting granite is seen on the right side of the picture (Vekara island, west of Uusikaupunki). On a geological map, these rock types are marked in green (numbers 1 and 2 in the map legend). Photo A. Linna.

What are rocks made of?

A rock is a solid piece of the Earth's crust. A rock can be formed by a single geological process, or it may have undergone several processes. Usually, rocks are built up from silicate minerals. These can be roughly divided into two classes, based on the amount of iron-magnesium bearing minerals they contain. Felsic rocks, from **FEL**dspar and **S**ilica (quartz), have a low amount while mafic rocks, from **MA**gnesium and **F**errum (iron) have a high amount.

Typical felsic minerals are: (these are seen in Figure 15)

plagioclase feldspar $(Na,Ca)(Al,Si)AlSi_2O_8$ – usually white on weathered outcrops

alkali feldspar $(K,Na)AlSi_3O_8$ – usually red on weathered outcrops

quartz SiO_2 – usually transparent and pale greyish

The most common dark iron-magnesium bearing minerals in our rocks are:

olivine $(Fe,Mg)_2SiO_4$

clinopyroxene $Ca(Fe,Mg)Si_2O_6$

amphibole $Ca_3(Mg,Fe,Al)(Si,Al)_8O_{22}(OH)_2$

biotite $KAl_2(Al,Si_3O_{10})(OH)_2$ – black flakes

In Figure 5a, the black minerals are biotite, in Figure 5b amphibole. In Figure 5b there is a small amount of olivine, which is green when unaltered and brown when weathered.

The most common minerals of metamorphic origin in southern Finland are named below. They are formed in metamorphic reactions. Their composition and metamorphic reactions are related to the temperature and pressure in the rock.

garnet (almandine) $(Fe,Mg)_3(Al2(SiO_4)_3$ – red (Figures 5a, 6a, 13)

cordierite $(Mg,Fe)_2Al_3(AlSi_5O_{18})$ – dark blue (Figure13)

sillimanite Al_2SiO_5 – white and yellow, fibrous

There are also some common non-silicate minerals in the bedrock of southern Finland, like oxides and carbonates:

calcite $CaCO_3$ – (Figure 11)

magnetite Fe_3O_4 – (Figure 10)

Figure 3. Old volcanic rocks that have been folded in a mountain building process caused by a plate collision. (Vekara island, west of Uusikaupunki). Photo A. Linna.

Figure 4. Pillow lava from Velkua. Pillow lavas are formed when hot basaltic magma erupts underwater. Because of the temperature difference between the magma (1200°C) and the water, the magma is quenched, resulting in the pillow-like shape and the glassy texture at the contact. In this picture, you can see several pillows on top of each other. These pillows are between 30 and 50 cm across. Pillow lavas are marked with black semicircles on geological maps. Photo A. Linna.

Most of the minerals in the Finnish bedrock formed either via crystallisation from magma or in metamorphic reactions under a varied range of pressure-temperature conditions. When these are exposed the Earth's surface, they tend to react, albeit slowly, to form new minerals that are more stable under the new pressure-temperature conditions. Part of this alteration (or lack of it) is visible on the rock surface as weathering. Minerals have different capacities to resist weathering, such that, generally speaking, minerals that formed at higher temperatures weather more quickly. The hills in southern Finland are mostly of granitic composition, and they consist of minerals resistant to weathering like alkali feldspar, plagioclase feldspar and quartz.

Rocks

Rocks are divided into three major groups:

1. Igneous rocks

An igneous rock is a rock that has crystallised directly from magma. Rocks that crystallise deep within the crust, where the minerals have been able to grow to a size that they are easily distinguishable with the naked eye, are called plutonic rocks (Figures 10, 12, 15, 16). If the magmas crystallise close to the surface in dykes, they form dyke rocks (Figures 10, 17). If magma erupts onto the Earth's surface as lava, it crystallises as volcanic rocks (Figures 2, 3 and 4).

Magma. Molten rock below the surface of the Earth is called magma, and erupted magma is called lava. Depending on the composition, the temperature can vary between 700° and 1200°C. Granitic magma, which contains high amount of silica and gases (usually steam), is quite viscous and tends to erupt explosively. These eruptions produce a variety of different materials, such as rock fragments (resulting in the formation of agglomerates), volcanic ash (resulting in the accumulation of tuffs and tuffites) and tephra, which can accumulate rather far away from the volcano. Basaltic magma, on the other hand, contains less silica and therefore flows more easily and rarely erupts explosively.

Partial melting. Partial melting is a process that takes place when any rock starts to melt as the temperature rises above its crystallisation temperature (Figure 5). Partial melting is the process by which magmas are produced. If partial melting takes place in the Earth's mantle, magmas rich in iron and magnesium and with low amounts of silica, potassium and sodium form. These magmas produce dark rocks (like basalt) because of the high amount of iron-magnesium bearing minerals (olivine, pyroxene). Partial melting of the crust, however, generates magmas with high amounts of silica, potassium and sodium, but low amounts of iron and magnesium (minerals like alkali feldspar and quartz form). A partially melted rock containing both melted and not melted material is called migmatite (Figures 5, 6 and 13.

2. Sedimentary rocks

Rocks on the surface of the Earth are continuously exposed to the direct and indirect effects of the Earth's atmosphere and hydrosphere, topographic gradient and vegetation. Weathering (both physical and chemical breakdown of rocks) and erosion (transport of weathered material) of the bedrock are the most obvious consequences of these phenomena. The weathering of bedrock produces rocks, gravel, sand and clay, which are transported and redeposited as sediments. The sediment lithology and transport distance depend on several prevailing factors: the lithology and provenance of the host rocks, mixing or non-mixing, the gradient and the transporting medium (i.e. air, water, etc…). Sediments accumulate in sedimentary basins, which vary from mountain gorges to alluvial plains to water basins. Sediments can be transported over great distances; for example, sediments derived from Finnish bedrock are encountered as far away as the North Sea near Holland. Sedimentary rocks form when soft sediment, such as sand (Figure 18) or clay, hardens. This process is called diagenesis, which happens as a result of the pressure from the overlying sediment load combined with dissolution of minerals and their reprecipitation as cement. Limestones (Figure 11) and evaporites also have a sedimentary origin. For example, the salt we use in everyday cooking is, geologically speaking, a chemical sediment derived from the evaporation of sea water.

3. Metamorphic rocks

Metamorphic rocks are formed when igneous or sedimentary rocks change form due to changes in pressure and temperature. Metamorphic reactions convert the mineralogy of the rock in response to the changed conditions. Most of the bedrock in southern Finland is composed of metamorphosed igneous and sedimentary rocks. During metamorphism, when the temperature rises above around 700°C, rocks start to melt. Figures 5 and 6 show examples of migmatites from southwest Finland, which formed as a consequence of partial melting.

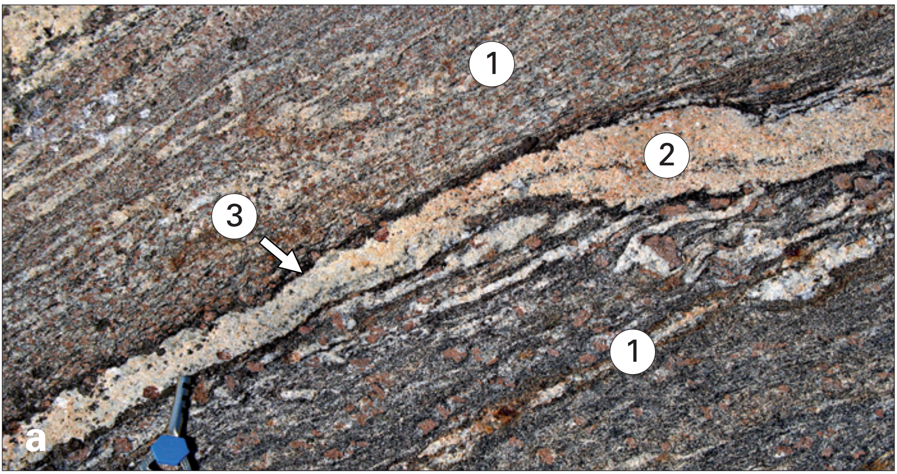
These three rock types are part of a gigantic rock cycle. Temperature and changes in temperature, water and wind erode continents, and the eroded sediment material is transported into sedimentary basins (e.g. the sea), where they are compacted at the sea bottom and form sedimentary rocks. Sedimentary and igneous rocks are metamorphosed in collision zones where Earth's litospheric plates collide. If they are transported into the mantle in subduction zones, they melt and again become magmas that crystallise as igneous rocks.

How do we know the age of a rock?

The relative age of two different rock types occurring together can be determined by looking at which one cuts the primary structures in the other; the younger rocks always cuts the older. The stratigraphy, or order of deposition, gives the relative age in the case of sedimentary rocks. Even in some metamorphosed sedimentary rocks, sedimentary structures, and sometimes the order of deposition, are still recognizable.

To get the absolute age of the rock, isotopes are used. Isotopes are atoms of the same element that have different numbers of neutrons in the nucleus. For example, the simplest atom, hydrogen, always has one proton in its nucleus, but may have zero, one or two neutrons (the more neutrons, the heavier the isotope). It is still the same element, since it is the amount of protons in the nucleus that determine what element it is, but the element hydrogen has three different isotopes. Some isotopes are radioactive, meaning that they spontaneously change into new elements or isotopes at a constant rate. Most people have heard of radiocarbon dating, which is based on the decay of the radioactive isotope of carbon. In geology, other, longer-lived radioactive isotopes such as uranium are used. Over time, uranium isotopes decay to lead isotopes. The mineral zircon ($ZrSiO_4$), a mineral commonly found in granitic rocks, is often used in determining the age of a rock. When zircon crystallises, trace amounts of uranium enter the crystal lattice, while lead is excluded. Since we know the decay rate, and we can assume that any lead is the result of the radioactive decay, we can analyse the amount of uranium and lead isotopes in the mineral today and calculate back in time to when the mineral formed. The rocks in Finland are amongst the best-dated rocks in the world, which is why

Figure. 5. An example of the partial melting that took place during the metamorphism in southern Finland about 1830 million years ago. **a**) Partial melting of an old sedimentary rock. **b**) Partial melting of an old volcanic rock. 1 - the old rock, 2 - the melt produced because of the high temperature, 3 - material not melted. Photo A. Linna.



we are able to reconstruct the evolution of our part of the world in such detail. The rocks of southern Finland, as well as in Estonia, formed during the early part of the Proterozoic Eon, between 1900 and 1575 million years ago, through a series of geological processes.

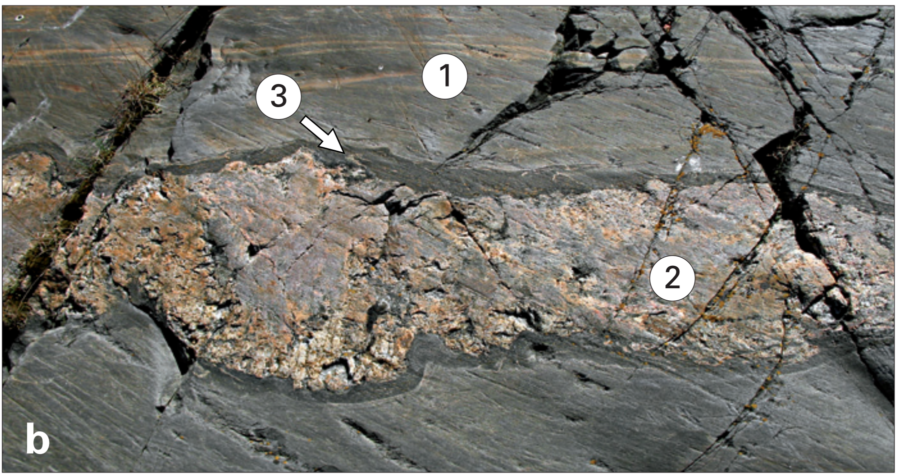
The geological history of southern Finland, focusing on the archipelago in SW Finland

Southern Finland was exposed to intense metamorphism about 1830 Ma. At this time, the rocks we see now at the surface were situated about 18 km deep within the Earth's crust, where the temperature was as high as 800°C. At such high temperatures, rocks start to melt. Old sediments and volcanic rocks underwent partial melting and the melts crystallised as granites and tonalites (Figure 5 a, b). This fact makes it difficult to trace the history older than 1830 million years. However, here and there you may see traces of only slightly deformed rocks that tell us the older history of the rocks.

Let's look at the geological evolution in southwestern Finland in chronological order:

1900-1880 Ma

A volcanic chain above a subduction zone, similar to modern Japan, produced volcanic rocks (Figure 1 and 7a). When the lava from the volcanoes erupted underwater, it was quenched by the cold sea water, forming pillow shapes and tubes, through which the lava was subsequently transported. Figure 4 shows pillow lavas on the northwest shore of Iso-Humasluoto in Velkua. On the southern side of the island, there is an example where lava intruded wet carbonate sediments. Here, the limestone (carbonate rock) is eroded and the lava produces the relief of the rock (Figure 8).



Other signs of this volcanic activity appearing in the Archipelago include the amphibolites and some of the acid gneisses. Amphibolite is a metamorphosed volcanic rock and is easy to recognise on a slightly weathered surface. It principally contains only two minerals, amphibole and plagioclase. On a weathered surface, the amphibole is black and the plagioclase is white. The texture is reminiscent of a mixture of black and white sugars.

Acid gneiss of volcanic origin is fine-grained (grain size less than 1 mm) and light in colour. Usually it also contains varying amounts of black amphiboles. Figure 9 is an example of this rock type from Brunskär, Korpo (Korppoo). The mafic rocks of volcanic origin are marked in green on the geological maps (amfibolite, tuff, other mafic volcanics). The felsic volcanic rocks and other quartz-feldspar gneisses are marked in yellow, while the mica schists and -gneisses are in blue.

In the magma chamber beneath the volcanoes, plutonic rocks like gabbros, diorites and tonalities formed. A good example of such magma chamber is the diorite found in Korppoo (Korpo) at the Galtby harbour (Figure 10).

At the same time as all of this volcanic activity, erosion also occurred. The volcanoclastic material accumulated on the sea bottom, together with other material coming from the continent. In addition, carbonate sediments also accumulated.

Figure 6. Examples of typical metamorphic rocks in southern Finland. The picture shows a sequence of alternating sedimentary and volcanic rocks. Brunskär, Korpo (Korppoo). Photo A. Linna.

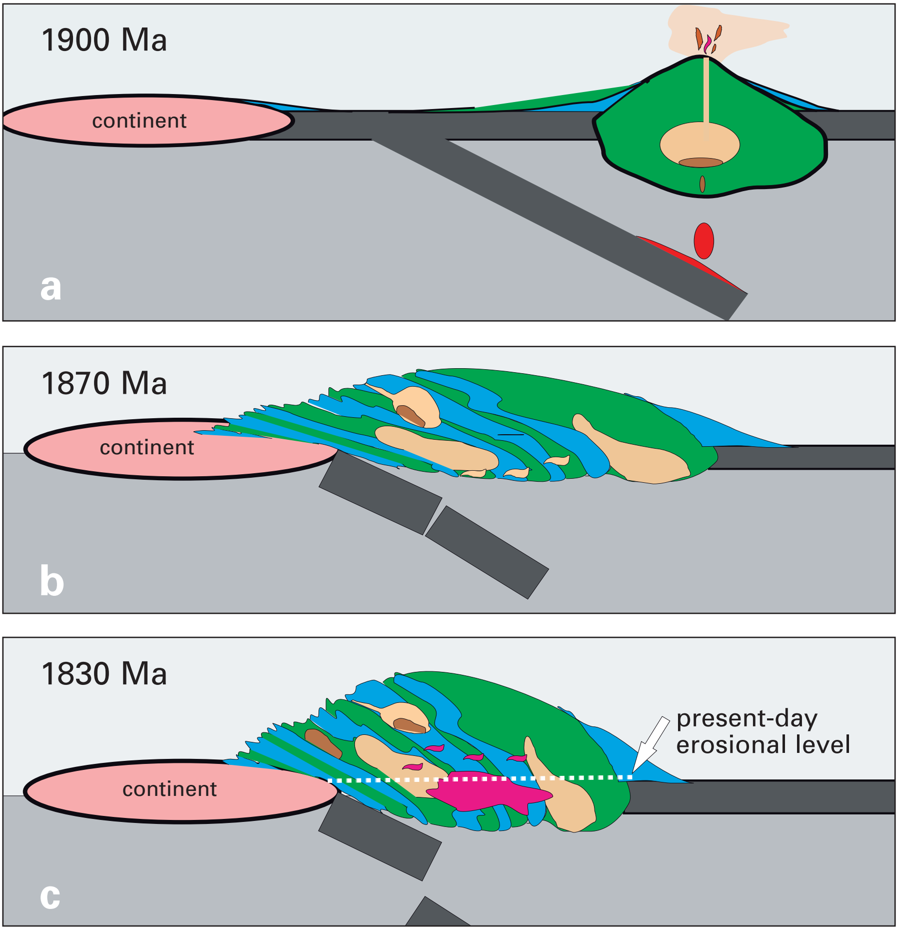


Figure 7. Schematic cross-sections of the tectonic evolution of southern Finland. North is to the left and south to the right. **a.** The situation 1900 million years ago. To the left in the figure, there is a microcontinent, coloured pink. This microcontinent is now situated in central Finland. Green represents the volcanic rocks that formed in the volcanic chain above the subduction zone. The red blob represents partial melting in the mantle. The brown colours are representative of magmas in deep magma chambers. Sediments, formed as the volcanic chain and the continent eroded are shown in blue. **b.** 1870 million years ago. The volcanic chain and the microcontinent collide. The volcanic rocks, sediments and plutonic rocks are deformed in the collision (the Svecofennian orogeny). **c.** 1830 million years ago. The collision is intensified (probably due to the collision of another continent). This increases the metamorphic grade in the crust, which starts to melt at deeper levels (marked in red).

Figure 8. Lava intruded into wet carbonate sediments. On the right side of the picture, the limestone is reddish and the lava dark. In the central part of the picture is a more extensive area of lava, and around it the limestone has been eroded, giving the rock its particular relief, Velkua. Photo A. Linna.

Figure 9. Acid gneiss, Korppoo (Korpo), Brunskär. Photo A. Linna.

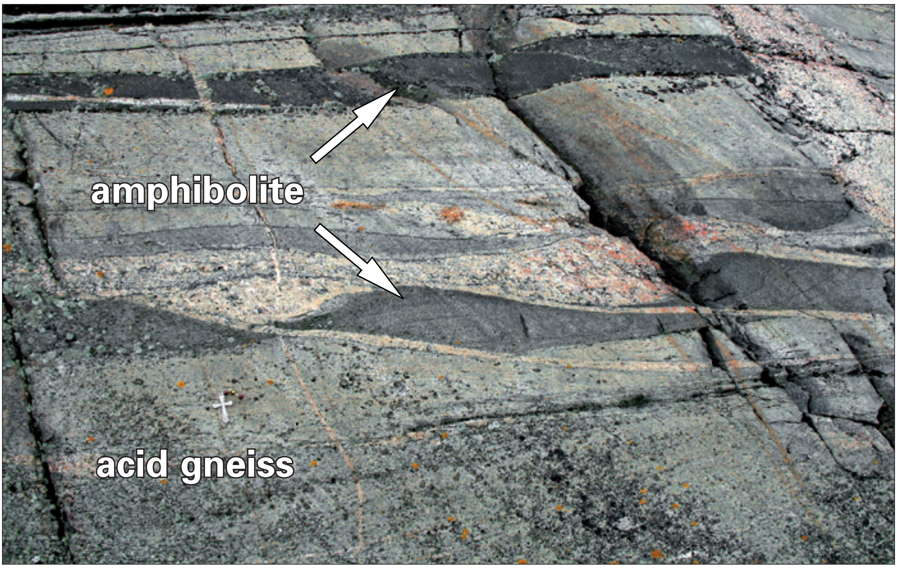


Figure 10. A former magma chamber at Galtby, Korppoo (Korpo). The dark rock is diorite, which crystallised deep within the young crust about 1885 million years ago. This magma chamber was probably located beneath a volcano. This rock type is shown in dark brown on the geological map. The red rocks cross-cutting the diorite are coarse-grained granitic dykes called pegmatites. These formed during the post-collisional uplift in the area around 1800 million years ago. These rocks contain large crystals of the magnetic mineral magnetite. Photo H. Bauert.

As the volcanic arc weathered, calcium was released. Simultaneously, the CO_2 content of both the atmosphere and the sea were elevated because of the volcanic activity. The calcium and CO_2 reacted, resulting in the accumulation of calcium carbonate in the sea. Algae may have played a role in the deposition process, for example at Tervola in northern Finland, the 2000 Ma year old stromatolite structures were formed by blue-green algae. The carbonate rocks formed at an active continental margin, in relatively deep water at the basin margin in pelagic environment. During the regional metamorphism, these carbonate rocks recrystallised as marble. Marble is rather common in southern Finland. The marble quarry in Parainen (Pargas) is the best place to see this rock type (it is the metamorphic equivalent to limestone, which is abundant in Estonia). Figure 11a is a picture of the marble quarry at Parainen (Pargas), where limestone raw material has been produced since 1898. Figure 11b is from Ahvensaari (Åvensor), Korppoo (Korpo), where it is seen how the soft marble is eroded while the surrounding volcanic rock forms the relief of the rock.

Figure 11. **a**. Carbonate sediments accumulated in the sea near volcanoes around 1900 million years ago. Later, these were deformed and recrystallised during the orogeny, forming marble (metamorphic limestone). In places such as Parainen (Pargas), pictured here, the marble became concentrated in the crust. Photo A. Brozinski.

b. Relief formed by erosion of the softer marble around harder volcanic rocks. Note the deformation structures in the volcanic rock. Åvensor, Korppoo (Korpo). Photo A. Linna.

Figure 12. A polished slab of tonalite from an islet south of Perkala, Iniö. This rock type is shown in light brown on the geological map. Photo A. Linna.

1880-1860 Ma

The volcanic chain moved toward and collided with a microcontinent, located in today's north (Figure 7b). During the collision, slices of the volcanic chain and sediments from the sea floor were folded and thrusted on top of each other, forming a mountain chain. The roots of the chain were pushed downward into the hot mantle, where they melted, forming tonalitic magmas. Figure 12 shows light-coloured tonalite from an islet in Perkala fjärden, Iniö.

1850-1810 Ma

This was the time of high-grade metamorphism in southern Finland. At this time, rocks now exposed at the surface were situated at about 18 km depth in the Earth's crust, where the temperature was between 700 and 800°C. In this environment, rocks change a lot. Clay-rich (pelitic) former sediments recrystallise, resulting in argillites, slates, schists, gneisses and finally in the formation of pelitic migmatites. Minerals that are stable at lower pressures and temperatures react and new minerals form. Red garnet and dark blue cordierite, encountered all over southern Finland, form when biotite (a black mica) reacts with quartz. Figure 13 shows an example of a metamorphic, partially molten rock containing recrystallised garnets and cordierites.

Partial melting of rocks begins with the melting of pelitic material at around 700°C. The first magmas produced are granitic in composition. These magmas

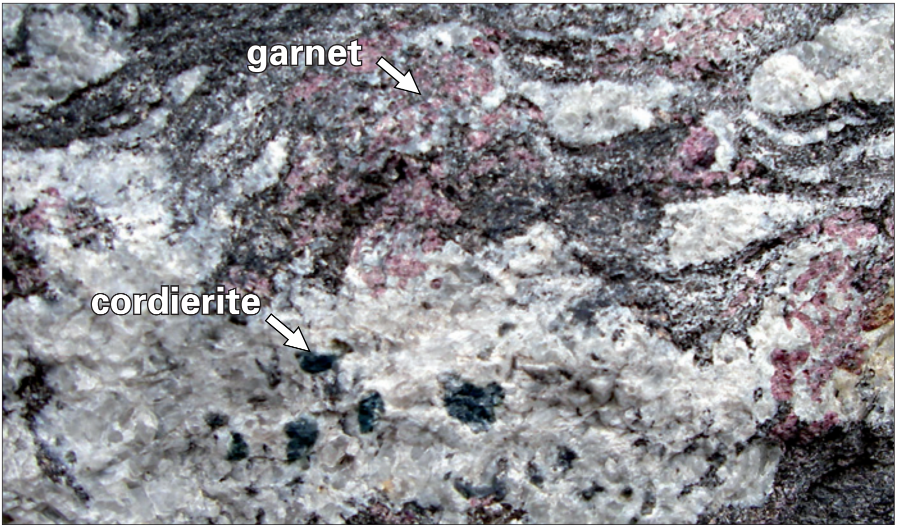


Figure 13. Garnet-cordierite mica gneiss, a typical rock in southern Finland. The red minerals are garnet and the dark blue minerals are cordierite. This rock type is shown in blue on the geological map.

Figure 14. S-type granite, Kaarina. The majority of the hills in southern Finland as well as the islands in the archipelago are made of this type of granite, which formed via the partial melting of old rocks, particularly old sediments, during the metamorphic peak 1830 million years ago. Photo O. Eklund.

form veins in the host rock, which results in the formation of different types of migmatites, such as vein gneisses (Figure 5a, 13). In addition to the migmatites formed from partial melting, in southern Finland there are also granitoids, which result from the complete or near-complete melting and recrystallisation of the host rocks. The bedrock of many islands in the archipelago and many of the hills along the Turku-Helsinki highway formed in this manner. In the flat area between the hills, softer rocks have been eroded to deeper level than the more resistant granitoids and granitic migmatites. Figure 14 shows an example of the typical red granite, formed during this intensive phase of melting and recrystallisation 1830 Ma.

1800-1760 Ma

This was the time of post-collisional uplift. At this time, the crust rose rapidly from depth, cooled and became brittle. When the crust was brittle, magmas with a complicated origin were able to rise rapidly through cracks in it. Some were generated in the crust and others deep within the Earth's mantle. Among the rocks formed at this time are the magnetite-bearing pegmatites (coarse grained granite dykes) in the archipelago (Figure 10), and carbonatites, which are rare rocks made of calcite that crystallised from carbonate magma. A carbonatite dyke can be seen on the southeastern side (before the tunnel) of the Ukko-Pekka Bridge in Naantali. The red colour of the rocks at Kuparivuori hill in Naantali is a result of fluids derived from the carbonatite magma.

1575 Ma

A heat pulse of unknown origin caused extensive melting in the mantle. Hot magma from the mantle rose into the crust, causing melting over extensive areas. This is how the famous rapakivi granites were formed. Rapakivi granites cover extensive areas in southwestern Finland. The main Åland Island, an area south of Kökar, the Fjälskär bay, Vehmaa and Laitila are covered by rapakivi (see back cover). Rapakivi granite is a general name for granites of different texture, which occur together in the same batholith (an extensive area of magmatic rocks). Examples from the Vehmaa rapakivi granite are a wiborgitic variety from the quarry in Marjuksenranta, Taivassalo (Figure 15), and a porphyritic variety from the quarry in Helsinginranta (Figure 16).

At the same time that the rapakivi granites formed, magmas from the mantle intruded the crust through cracks (figure 17a), forming black dykes of an igneous rock called diabase (figure 17b,c). Diabase is ideally suited for use as sauna rocks, as it contains iron-magnesium bearing minerals such as olivine and pyroxene, which have a high heat capacity. These minerals fill the space in a three dimensional network made of plagioclase that makes the rocks resistant to alteration (figure 17a).

Some younger Precambrian formations are found a short distance to the north, in Satakunta. The topography around Pori is flat, as the bedrock here is made of Jotunian sandstone. This sandstone was deposited in a shallow sea after the emplacement of the rapakivi granites. The sandstone can be seen in the river-

Figure 15. Wiborgite rapakivi granite, Marjuksenranta, Vehmaa. On the left of the picture is a fresh surface and on the right is a slightly weathered surface. The different major minerals stand out on the slightly weathered surface. This rock contains the plagioclase-mantled, egg shaped alkali feldspars called *ovoids,* typical of rapakivi granites. Rapakivi granites are shown in magenta on the geological map. Photo O. Eklund.

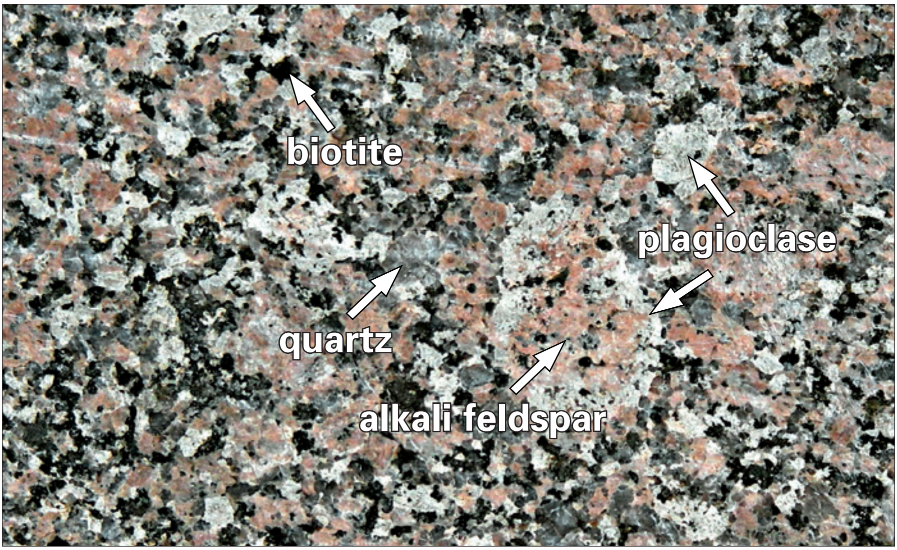


Figure 16. Porphyritic rapakivi granite, Helsinginranta, Vehmaa. A view of a quarry that produces dimension stones found in buildings all over the world (above). Close-ups of porphyritic rocks (below). Photo O. Eklund.

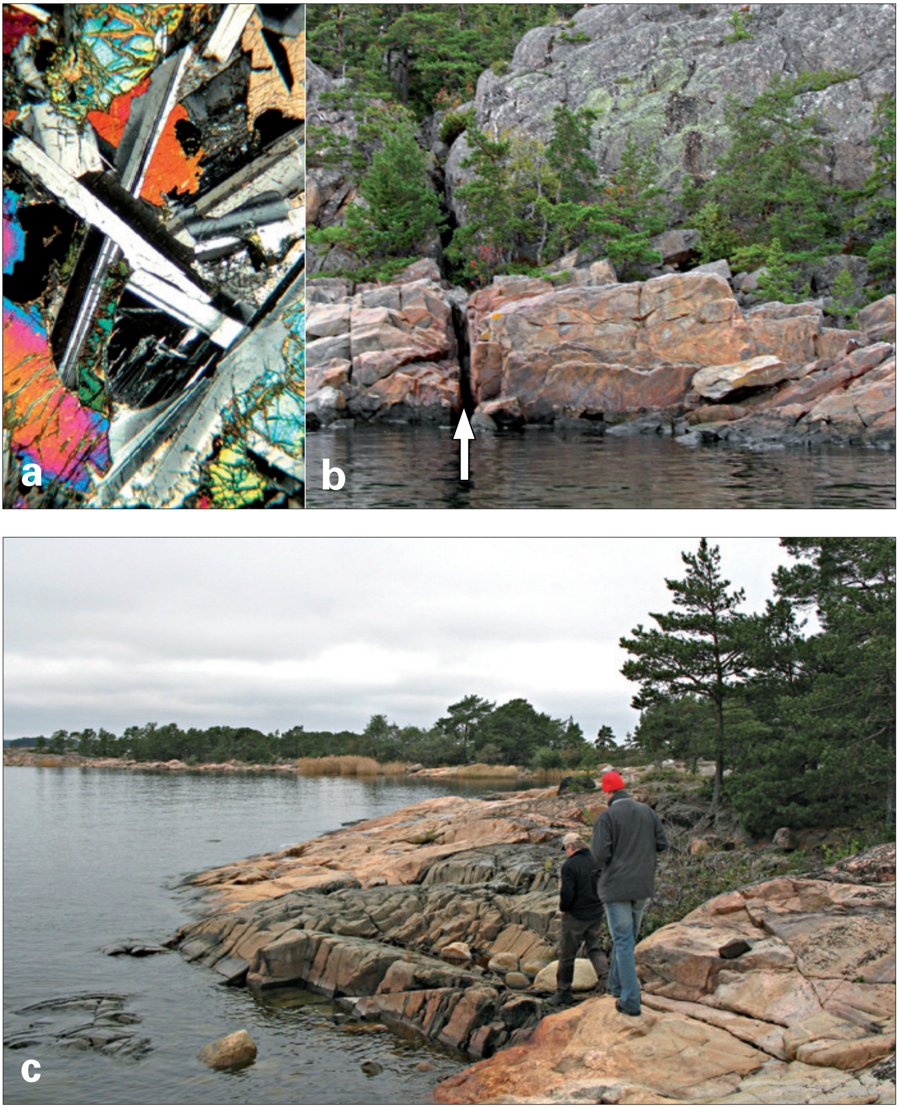


Figure 17. Diabase dykes from southern Keistiö, Iniö.
a. Microscope picture of a diabase. White and grey laths of plagioclase form a three-dimensional network, wherein crystallises the colourful iron-magnesium rich olivine. Photo A. Peltola, **b**. A thin, 30-cm-wide diabase dyke cutting the surrounding rock. Photo A. Linna, **c**. A 2.5-m-wide diabase dyke. These rocks are shown on the geological map as heavy black lines. Photo A. Linna.

bed of Kokemäenjoki at the Harjavalta power station. Within this sandstone, traces of ancient ripple marks have been preserved (Figure 18). When you walk in shallow water on a sandy beach on a sunny day, you can feel the ripple marks in the soft sand beneath your feet. The ripples in the Jotnian sandstone were formed in the same way as the ripples are formed today. This is a good way to understand that the geological processes at work today have been active over the whole evolution of the Earth.

1275 million years ago, the crust was again intruded by magma from the mantle that crystallised as olivine diabase. This diabase can be seen, for example, at the Siikaranta camping area at Reposaari, near Pori. In addition, the island of Säppi, southwest of Pori, is wholly composed of coarse-grained diabase. These rocks are similar to the 1585 Ma diabase shown in figure 17. On the geological map on the back cover, these rocks are marked in dark green in the Satakunta area.

Figure 18. The feet of a four-year-old child, standing on a 1300-1500 million year old Jotnian sandstone with ripple marks. Jotnian sandstones are marked in blue on the geological map, and are found in the vicinity of Pori. Photo O. Eklund.

Metallic ore

A fluid, in geological sense, is hot water containing ions like chlorine, fluorine and sulphur. Hot fluids that circulate in the Earth's crust during the rock forming stage have the capacity to leech elements, particularly metals, from the surrounding rock. These elements may then be transported and precipitated elsewhere, where the temperature is lower. This is how some of the most important ore minerals are formed. The fluids tend to follow cracks in the crust, which is why ore mineralization are often thin and elongated. On Attu island, 12 km south of Parainen (Pargas), there is an orebody that has been mined off and on since the 17th century. Zinc, lead, copper and silver have been produced here. The major ore minerals in the Attu ore are pyrrhotite, sphalerite, galena, pyrite and chalcopyrite. Minor ore minerals include arsenopyrite, magnetite, marcasite, löllingite, tetrahedrite, boulangerite, tennantite, bournonite, pyrargyrite, kesterite, sinnerite, ilmenite, mackinawite, hessite, breithauptite, rutile, molybdenite, electrum, silver, gold and bismuth.

The younger evolution of the crust

The crystalline basement of Finland was once covered by younger, Palaeozoic formations, just as Estonia is today. Although most of these have been eroded away, small traces of these younger rocks are found, for example, in the Lumparn

Figure 19. Sulphide ore from collections of Museum of Geology at Tartu University. Photo M. Isakar.

meteor crater in Åland. Sometimes, these younger rocks can be found filling cracks in the bedrock, like the dyke of Cambrian sandstone from Korppoo (Korpo) shown in Figure 20. In addition, erratic boulders of Ordovician mud- and limestone, as well as some Cambrian sandstone, can be found in the archipelago. These boulders, many of them fossil-bearing, originate from sedimentary rock deposits beneath the Bay of Bothnia.

The crystalline Precambrian rocks of Estonia

There are no Precambrian rock outcrops in Estonia. The only crystalline rocks available on the surface are erratic boulders – the messengers of crystalline rocks from Finland carried by continental ice during the ice age. The crystalline rocks of the Estonian basement consist of early Proterozoic metamorphic and igneous rocks and are covered by a deposit of Palaeozoic sedimentary rocks 100-780 m thick. Since there are no outcrops, only drill core material (Figure 21) and geophysical/geochemical methods have been used for the geological study of these rocks. In the uppermost section of the Estonian Precambrian rocks, there is an ancient, dominantly kaolinitic (clay) weathering crust with a thickness ranging from a few meters up to 150 meters. Due to intense denudation during the late Proterozoic, the surface of the basement has turned into a peneplain, which dips gently southward (2–3.5 m/km). For example, the crystalline basement lies at the depth of 67.5 m on Vaindloo

Figure 20. Dykes filled with Cambrian sandstone. On the left is a close-up picture of the same dyke. Photos A. Linna & O. Eklund.

Island (Gulf of Finland), 629.0 m in Häädemeeste (southwest Estonia), and 784.1 m on Ruhnu Island (Gulf of Riga) (Figure 21).

The Estonian Precambrian basement is divided into two major geological units: the North Estonian amphibolite facies and the South Estonian granulite facies complexes. These are separated from each other by a tectonic boundary, the Paldiski-Pskov shear zone, and include six smaller rock zones. These zones are: South-Estonian, West-Estonian, Tapa, Jõhvi, Tallinn and Alutaguse zones (Figure 22). These zones differ by rock type (metasediments or metavolcanites/igneous intrusions), degree of metamorphism and other chemical-physical properties.

The Estonian-Australian geologist Armin Öpik was the first to propose, in 1942, that the Estonian basement rocks are an extension of the same Svecofennian orogenic system as the rocks in Finland. We know today that at least the northern Estonian rocks are very similar to those we see in southern Finland, and can conclude the regions have a shared geological history during the early Proterozoic, 1920 - 1575 Ma.

The rock formations

From the 1960's to the 1980's, most geologists believed that the Estonian basement rocks formed both during the early Proterozoic (1920 - 1575 Ma) and the Archean (more than 2500 Ma). Later, radioactive isotope geochronological studies have shown that our basement is mostly early Proterozoic, and there is no direct evidence for older, Archean crust in Estonia.

The South Estonian Zone is the northern part of the ca.1000-km-long Belarus-Baltic Granulite Belt, containing predominantly metamorphosed igneous rocks with minor metasedimentary rocks. These rocks have experienced relatively high pressure (up to 6-7 kilobars) and temperature (700-800°C), corresponding to a depth of 18-20 km. The main rock types in the West Estonian Zone are amphibolites and different gneisses. The Tapa Zone comprises amphibole gneisses/amphibolites and intercalated pyroxene gneisses in addition to biotite-plagioclase gneisses and quartz-feldspar gneisses. The narrow Jõhvi Zone consists of interlayered pyroxene gneisses and quartz-feldspathic gneisses, biotite-plagioclase gneisses, amphibole gneisses, garnet-cordierite gneisses, and magnetite-quartzites (Jõhvi magnetic anomaly). The Tallinn zone in northern Estonia is comprised of mafic amphibolite facies metavolcanites to metasediments. The Alutaguse zone, also in northern Estonia, lies in between the Jõhvi and South Estonian Zones and is dominated by metasedimentary rock types. The Tallinn and Alutaguse zones experienced lower temperature and pressure conditions than the other zones.

Although the majority of the Estonian Precambrian rocks are metamorphic in nature, there are also some occurrences of younger, igneous rocks. These rocks are mostly granites, forming small intrusive bodies, which are the products of the

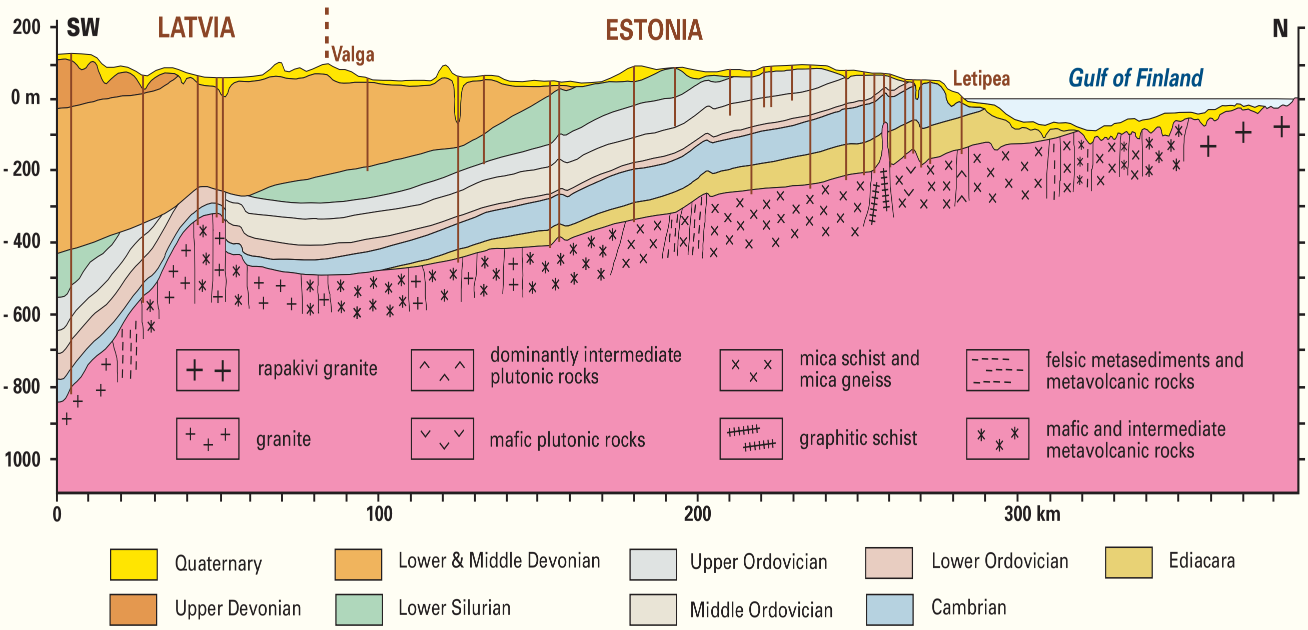


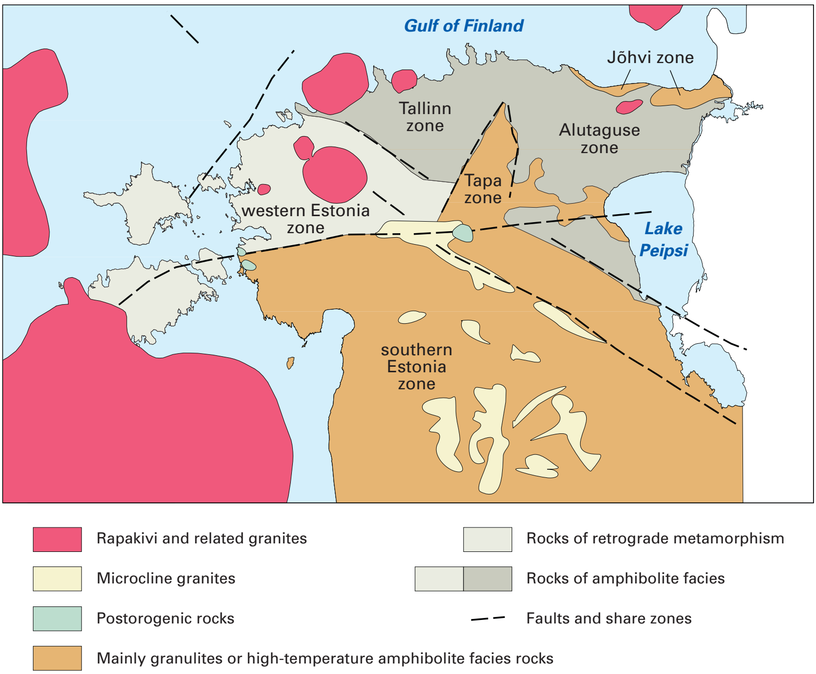
Figure 21. A schematic cross-section of the Estonian basement from southern Finland to Mõniste on the Latvian border (modified after Puura & Vaher, 1997).

partial melting of the surrounding rocks or deeper ones. The largest granitic intrusions in the Estonian basement belong to the large-scale rapakivi magmatic event, around 1600 Ma. The largest of these is known as the Riga batholith. There are also at least five minor potassic, porphyritic granite intrusions: Naissaare, Märjamaa, Taebla, Neeme, Ereda as well as the Abja quartz-diorite intrusion in southwest Estonia. A few smaller intrusions are known, which are basic to intermediate in chemical composition (containing less than 60% SiO_2). All these plutons intruded after the main metamorphic event, so they have preserved their original crystallisation features and textures.

Figure 22. The major rock units of the Estonian basement.

Metals in Estonian basement

During the Soviet times, the Estonian basement rocks were extensively drilled and studied in a search for metal ore. From the metal resources point of view, the Jõhvi area in northeast Estonia contains good occurrences of iron ore (in magnetite quartzites) and sulphides. The Jõhvi iron ore was discovered nearly a century ago and occurs as subvertical beds within gneisses. The thickness of the iron bed is about 100 m, and the reserve of iron ore (Fe over 25%) is about 355 million tonnes (calculated to 500 m depth) and 629 million tonnes (calculated to 700 m depth). Many other occurrences of metals exist within the crystalline rocks of Estonian basement, however these have no economic value at the moment.



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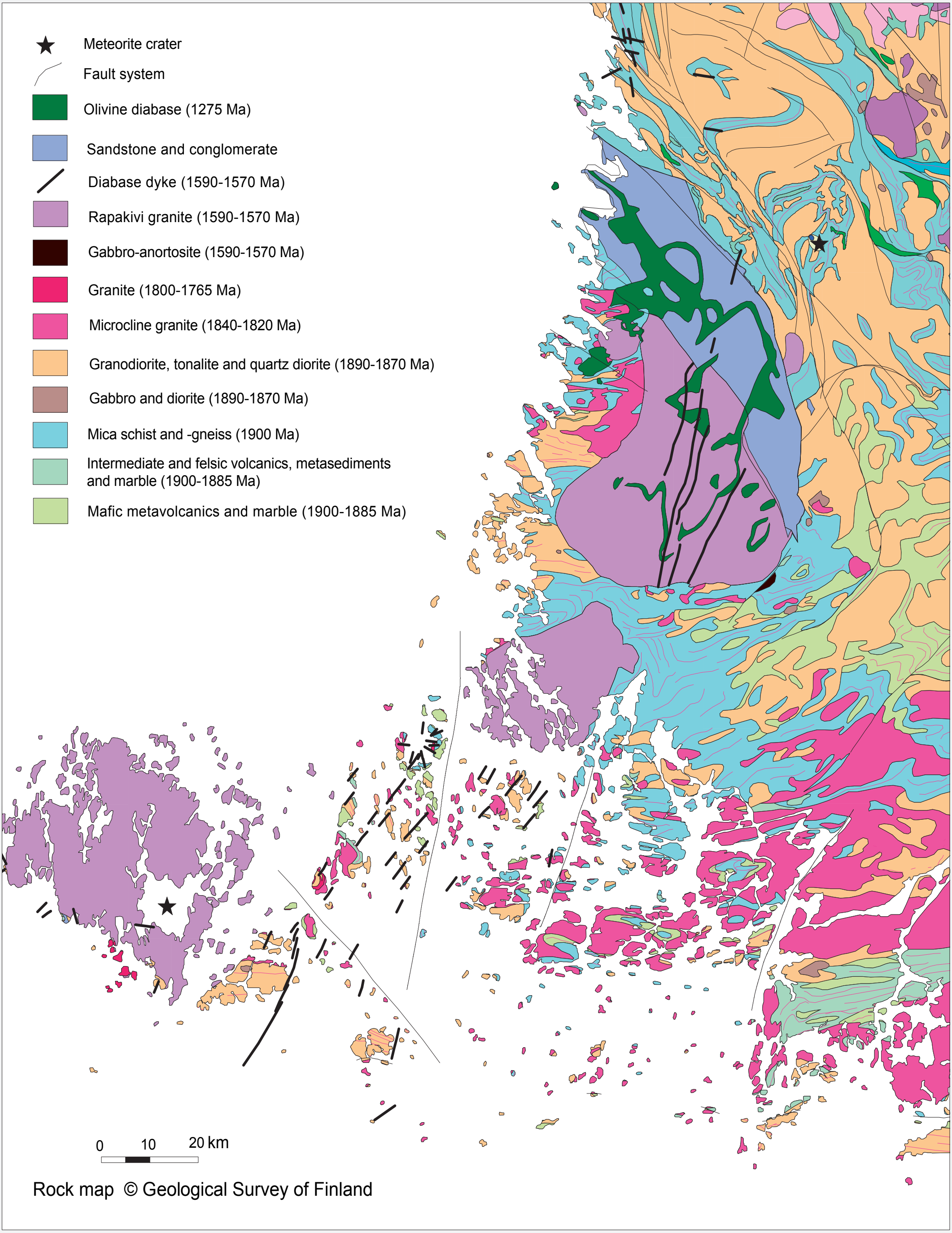

ISBN 978-9985-9867-4-5