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THE PRECAMBRIAN IN FINLAND

BY

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with 35 figures and 3 tables in the text

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The Precambrian crust of Finland forms the central part of the Baltic Shield, which is the most extensive Shield area in Europe. The geological evolution of the Baltic Shield has been outlined to show the structural setting of the Finnish Precambrian.

The main geological and structural outlines of the Finnish Precambrian crust are based on lithological, structural, geochronological, seismological, gravimetric and aeromagnetic data. The petrographical, structural, stratigraphical and geochronological data on the principal geological units are presented in chronological order from the oldest to the youngest complexes; and the concluding remarks summarize the geological evolution of the Precambrian in Finland.

The most important events in the geological evolution of the Finnish Precambrian were the revolutions that produced the Presvecokarelidic and Svecokarelidic folded areas 2 800—2 600 Ma and 1 900—1 800 Ma ago, respectively. Most of the Finnish Precambrian rocks received their present form during these ancient events. Both of the orogenic revolutions were followed by periods of cratonization connected with lively igneous activity taking place on a stable platform in the time intervals 2 400—2 500 Ma and 1 550—1 700 Ma ago, respectively. The oldest nonmetamorphic sedimentary cover of the Finnish Precambrian is represented by the Jotnian sediments (1 300—1 400 Ma).

Key words: treatise, evolution, igneous rocks, metamorphic rocks, stratigraphy, geochronology, structure, Baltic Shield, Svecokarelidic orogeny, Precambrian, Finland

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»Prove all things;
hold fast that which is good».
1 Thes 5.21

INTRODUCTION

This paper on the Precambrian in Finland is based on the geological studies of many generations of geologists. The pioneers and great masters of Precambrian geology, J. J. Sederholm (1863—1934) and P. Eskola (1883—1964), blazed the trail for research on the oldest geological history of the globe. New geological studies, geological re-mapping, and geophysical and geochronological data have increased our knowledge about the Finnish Precambrian to a fundamental extent. In particular, age determinations and many new studies on the structure and stratigraphy of certain key areas have contributed many provocative new ideas regarding the evolution of the Precambrian in Finland. An abundance of new material has been registered and published.

The motto quoted above served as a guiding principle in the preparation of this paper, which is intended to be a short synthetic review of the main characteristics of the Precambrian in Finland. Furthermore, this paper will provide as an explanatory text to a new geological map of the Finnish Precambrian (1 : 1 000 000, under preparation), and it is offered as a guide through the rocky labyrinth of the Finnish crust.

THE BALTIC SHIELD

The Precambrian rock crust in Finland is a typical and central part of the Baltic or Fennoscandian Shield, which is the broadest Shield area on the European continent. The Baltic Shield is an uplifted part of the wide basement area upon which the sediments of the North- and East-European platform have been deposited. The Precambrian basement of this so-called Fennosarmatian platform is exposed only in the Baltic and Ukrainian Shields.

The boundaries and main structural features of the Baltic Shield are represented in Fig. 1. The northern and western parts of the Shield are bordered by the Paleozoic Caledonidic mountain chain, which in many places has overthrust upon the Baltic Shield. The southwestern margin of the Shield is characterized by Paleozoic and younger faults. In the east and south, the surface of the Baltic Shield dips gently under the sedimentary cover of the East-European platform. The platform cover is composed of the Late Precambrian, Paleozoic and younger sediments that have not undergone metamorphism.

The Precambrian age of the Baltic Shield can be determined from the fact that the metamorphic and plutonic complexes of the Shield underlie nonmetamorphic Late Precambrian (Jotnian and Eocambrian) and Cambrian sediments. The bedrock of the Baltic Shield represents a deeply denuded section of Precambrian mobile belts of different ages, and studying it has proved a fruitful exercise toward the development of ideas needed to understand

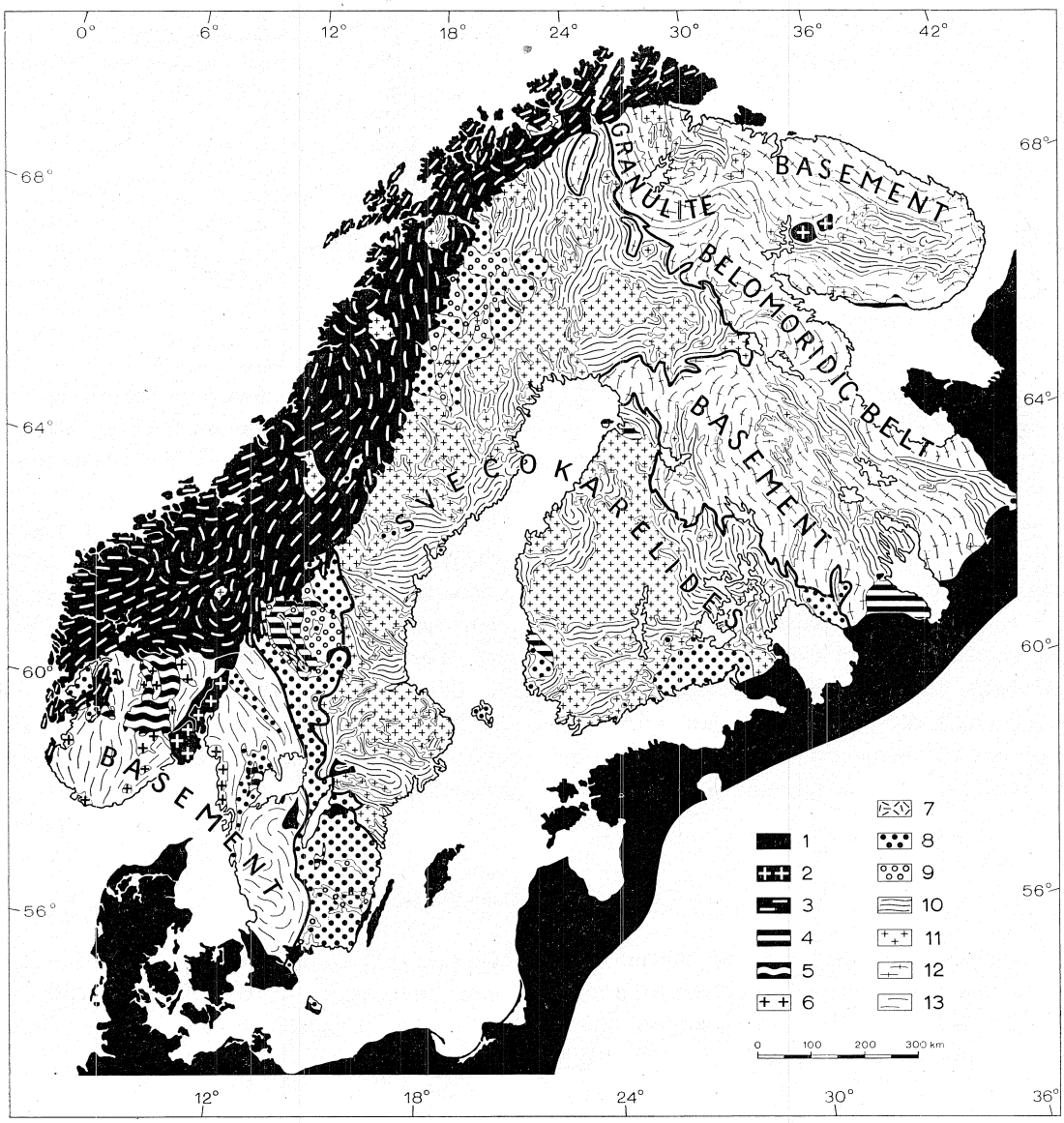

Fig. 1. Main structural units of the Baltic Shield. 1, Paleozoic and younger sedimentary rocks; 2, Paleozoic igneous rocks; 3, Caledonides. *Precambrian unmetamorphic sediments:* 4, Jotnian formations. *Dalslandian folded area:* 5, gently folded Dalslandian formations; 6, Dalslandian granites. *Precambrian igneous rocks, representing the time of cratonization after the Svecokarelidic orogeny:* 7, diabases; 8, Gothian granites and rapakivi granites; 9, volcanic rocks. *Svecokarelidic folded area:* 10, schists and gneisses; 11, plutonic rocks. *Basement complexes:* 12, Presvecokarelidic basement; 13, basement of unknown age (rejuvenated by the Dalslandian movements). Compiled by A. Simonen.

the Precambrian geology in general. Furthermore, many fundamental ideas on the petrology of metamorphic and granitic rocks are based on the studies carried out in different parts of the Baltic Shield.

The oldest part of the Baltic Shield comprises the broad basement area in the east. Monotonous, cataclastic basement gneisses of quartz dioritic and granodioritic composition are the most abundant rocks of the basement area, where

there occur only certain narrow schist zones, composed mainly of mafic metavolcanics, metasediments and quartz-banded iron ores. The Belomoridic gneiss belt and the granulite arch of Lapland represent high-grade metamorphic parts of the basement complex, which became intensely reworked and recrystallized during the younger Svecokarelidic orogenic movements. The age of the basement gneisses is in most cases 2 600—2 800 Ma. However, even older ages, 3 000—3 500 Ma, have been sporadically recorded expecially in the Kola Peninsula.

In the southwestern part of the Baltic Shield, there occurs a basement complex of unknown age which was thoroughly reworked by Dalslandian tectonic movements about 1 000 Ma ago. Some authors have correlated this basement to that of the eastern part of the Baltic Shield.

The main and central part of the Baltic Shield belongs to the area characterized by Svecokarelidic folding. The geological evolution of the Svecokarelides has been a long one, and it shows many features similar to younger orogenic belts.

The Svecokarelian sedimentation started with an evolutionary, transgressive Jatulian group composed of basal beds, quartzites, dolomites and sapropelic pelites. The Jatulian group of sediments was deposited about 2 200—2 000 Ma ago upon the stabilized and deeply eroded basement in the eastern part of the Baltic Shield. The Jatulian sedimentation is connected with lively initial mafic volcanism, which took place at least in three different phases between 2 200 and 2 000 Ma. The Jatulian rocks, which were metamorphosed in the Svecokarelidic movements, either occur along the western rand of the ancient craton or they form many separate basins upon the old basement.

West of the ancient craton, mobile geosynclinal belts developed and deposition of the eugeosynclinal graywacke-basalt association took place. The total thickness of the eugeosynclinal, Svecofennian strata is many kilometers (at least 8 kilometers in the Tampere field). No valid evidence of a sedimentation floor or basement for Svecofennian sedimentation has been found.

The main phase of the Svecokarelidic orogeny, which was connected with folding, regional metamorphism and plutonism, occurred about 1 900—1 800 Ma ago. The synorogenic plutonic rocks, emplaced during the main deformation phase of the Svecokarelides, are mainly quartz diorites, granodiorites and trondhjemites with minor amounts of associated mafic rocks. The late orogenic plutonic rocks are mostly potash-rich granites forming migmatites with the older rocks. Some small postorogenic plutons (~ 1 800 Ma) mark the final stage of the Svecokarelidic orogeny.

The Svecokarelidic orogeny was followed by a long period of erosion and cratonization. Numerous joints, faults and shear zones of highly varying ages produced a mosaic structure in the crust. Vertical block movements took place and enormous masses of granites and associated porphyries intruded into the stable platform and sharply penetrated the Svecokarelidic folded belt. To the platform intrusions, representing the time of cratonization after the Svecokarelidic orogeny, belong the rapakivi granites, the so-called Gothian granites (e.g., the Småland, Värmland, Sorsele and Lina granites in Sweden), their volcanic equivalents and diabases. The ages of the rapakivi granites and Gothian granites vary between 1 550 and 1 700 Ma.

The deposition of the oldest red Jotnian sediments, about 1 300—1 400 Ma ago, occurred upon the deeply eroded Svecokarelidic rock crust. The Jotnian sediments are red arkose sandstones and siltstones and they form the oldest nonmetamorphic sedimentary cover of the Baltic Shield. The remains of the Jotnian sediments are preserved only in deep downfaults or grabens of the Svecokarelidic rock crust. Diabase dikes and sills occur abundantly in many Jotnian deposits, and they represent

hypabyssal eruption channels for basaltic magma intrusions into the stable platform.

So-called Dalslandian or Sveco-Norwegian tectonic movements took place about 900—1 000 Ma ago in the southwestern corner of the Shield. The Dalslandian formations, deposited on the ancient basement of unknown age, are of the platform type and no geosynclinal strata are present. They have undergone a gentle folding, and intrusions of granite plutons and pegmatites have taken place. The Dalslandian tectonic movements, connected with intrusions of granites, have caused a regional rejuvenation of the ancient basement in the southwestern corner of the Baltic Shield.

The youngest Precambrian of Scandinavia consist of so-called Eocambrian sediments, which occur along the eastern rand zone of the Caledonides and are connected with the evolution of the Caledonides.

Remnants of the Paleozoic, Cambro-Silurian platform cover of the Baltic Shield are found especially in the southern part of the Shield. These sediments were deposited on the ancient Sub-Cambrian peneplain, and were preserved mostly in graben-like structures, which were formed in connection with Caledonian and Hercynian movements. The afore-mentioned tectonic movements caused deep fractures in the Shield area, along which alkaline magmas intruded. The largest occurrences of Paleozoic igneous rocks are in the Kola Peninsula and the Oslo graben.

The Baltic Shield has been undergoing erosion for a long time, and the ancient Sub-Cambrian peneplain, on which the oldest Paleozoic sediments were deposited, was situated only slightly above the present surface. The Shield has had a tendency to lift, and the sediments of the platform cover are mostly eroded away or are preserved in the downfaulted grabens. The transgressions of younger geological times have taken place only in the rand areas of the Shield. The Baltic Shield was an uplifted peneplained land area — approximately within its present boundaries — until the Quaternary glaciation.

The Pleistocene ice sheet covered the whole Baltic Shield and its movements swept the old peneplain clean, removing the loose material and polishing the surfaces of the hard rocks. The Pleistocene glacial deposits consist mainly of till. However, stratified drift in ice marginal and radial deposits are found all over the Baltic Shield. Pleistocene silt and clay deposits occur in the areas formerly submerged by various stages of the Baltic Sea.

The deglaciation of the Baltic Shield took place about 11 000—8 000 years ago, after which extensive parts of the Shield were covered by the Sea. The upheaval of the Shield area started and continues at present, being about one meter per century in the central part of the Shield.

The glaciation left clear marks on the geomorphology of the Baltic Shield, which is characterized by the old peneplain with young glaciation. Ice-polished outcrops of the Precambrian rocks, moraine landscapes, eskers, deltas, glaciofluvial erosion forms, and thousands of lakes have created a landscape of changing character and special beauty.

THE PRECAMBRIAN IN FINLAND

In the following chapters, an attempt will be made to give a short description of the main characteristics of the Precambrian in Finland. The geological and structural outlines, obtained by different methods of geoscience, are presented first, followed by a description of the geological units and, in conclusion, remarks on their evolution. The economic geology of the country is also briefly summarized.

GEOLOGICAL AND STRUCTURAL OUTLINES

Our knowledge about the Precambrian in Finland is based on investigations made by several generations of geologists. The results of systematic geological mapping and many regional geological studies are of fundamental importance in reconstructing a general picture of the evolution of the bedrock in Finland. Systematic geological mapping of the country has been carried on for about a hundred years by the Geological Survey of Finland, which was established in 1886. The entire country has been surveyed: geological maps on the scales of 1 : 200 000 (southern Finland) and 1 : 400 000 cover the total area. Geological mapping in more detail was begun at the end of the 1940s. The field investigations are recorded on 1 : 20 000 maps and the results are published as map sheets on the scale 1 : 100 000. Today, about 1/3 of the country has been mapped on this scale. In addition to the geological studies, especially the geochronological and geophysical investigations have substantially added to our knowledge about the evolution and structure of the Precambrian crust in Finland. The following geological and structural outlines have been prepared to summarize the existing lithological, structural, geochronological, seismological, gravimetric, and aeromagnetic data on the Precambrian in Finland.

Lithological data

The lithological features of the Finnish bedrock are represented in Fig. 2, which shows that the crust consists mainly of plutonic and metamorphic rocks. Broad areas of orthogneisses in eastern and northern Finland belong to the Early Precambrian or Archean basement.

The rocks included in the so-called Svecokarelidic folding are, however, most extensively spread. The schist zones, which are characterized by a rich abundance of quartzites, occur along the borders of the old basement. These schist zones form the so-called Karelidic schist belt of the Svecokarelides which extends from southeastern Finland to Lapland. The so-called Svecofennidic schist belt of southern and western Finland consists mainly of micaceous schists. Both the Karelidic and Svecofennidic schists belong to the Svecokarelides and represent different types of sedimentary associations of the same orogenic cycle. The Svecokarelidic plutonic rocks, consisting mainly of granodiorites and granites, are widely distributed and penetrate both the Karelidic and Svecofennidic schists.

The youngest Finnish Precambrian granitoids are represented by many platform-type rapakivi intrusions in southern Finland. The unmetamorphic, Precambrian sediments consist of so-called Jotnian arkose sandstones and shales. So far as is known, the youngest Precambrian of Finland is represented by diabase dikes cutting the Jotnian sediments.

Structural data

The main structural units of the Finnish Precambrian are given in Fig. 3. These units differ from each other in age, lithology, metamorphism and structure.

The oldest part (2 600—2 800 Ma) is the so-called Presvecokarelidic basement, which consists of some schist and gneiss zones, a granulite arch, and wide areas of granitoid orthogneisses. The schists in this complex are penetrated by granitoid rocks of the age group 2 600—2 800 Ma. The granulite arch, a high-grade metamorphic part of the basement complex, was thoroughly reworked by younger, Svecokarelidic movements.

The main part of the Finnish Precambrian belongs to the Svecokarelidic orogenic belt, the folding of which took place in connection with regional metamorphism and plutonism

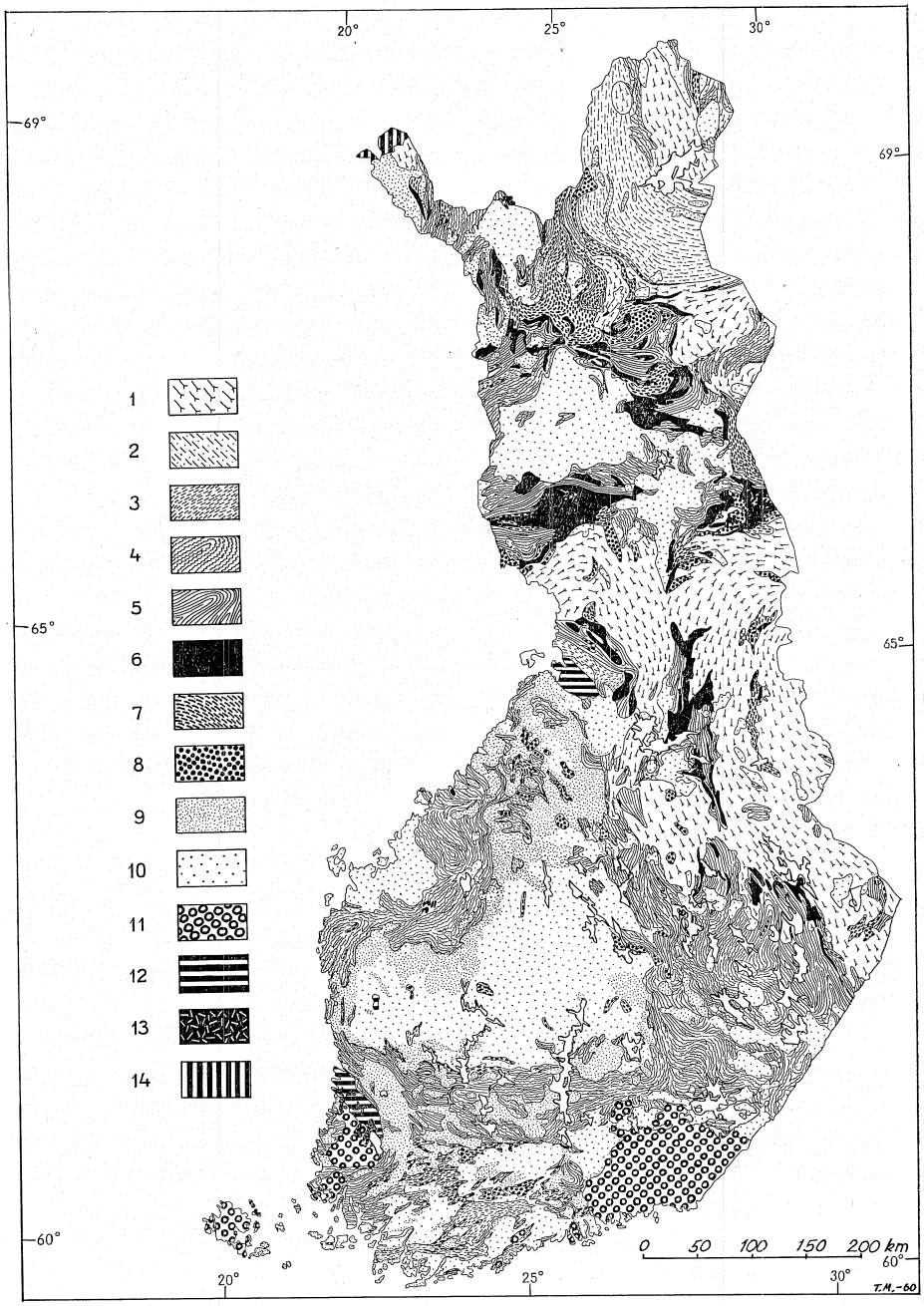

Fig. 2. Lithological map of the Precambrian in Finland. 1, orthogneiss; 2, granulite; 3, quartz-feldspar schist; 4, mica gneiss and migmatite; 5, phyllite and mica schist; 6, quartzite; 7, metabasalt and amphibolite; 8, gabbro, anorthosite and ultramafic rocks; 9, granodiorite and quartz diorite; 10, granite; 11, rapakivi granite; 12, nonmetamorphic sedimentary rocks; 13, diabase; 14, Caledonidic schists. Drawn by Toini Mikkola after the map compiled by A. Simonen.

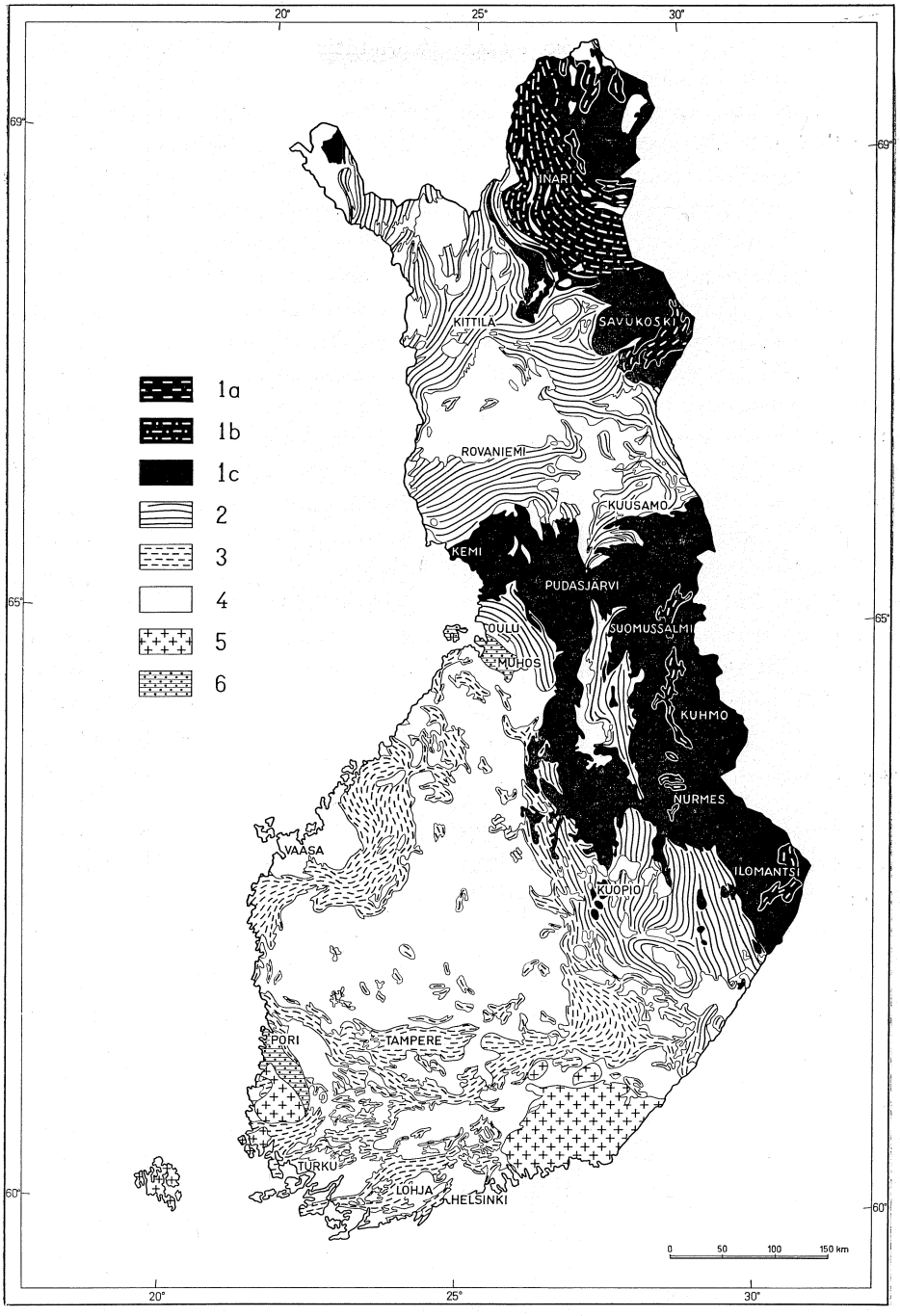

Fig. 3. Main structural units of the Precambrian in Finland. *Presvecokarelidic:* la, schist and paragneiss; lb, granulite; lc, orthogneiss. *Svecokarelidic:* 2, Karelidic schist belt; 3, Svecofennidic schist belt; 4, orogenic plutonic rocks. *Postsvecokarelian:* 5, rapakivi granites; 6, Jotnian sediments. After A. Simonen.

about 1 900—1 800 Ma ago. The Svecokarelidic schists are divided into the Karelidic and Svecofennidic schist belts, which deviate from each other mainly in their lithological features, as described in the foregoing. The Karelidic schists, with their rich abundance of quartzites, are formations deposited upon or along the rands of the ancient basement. The Svecofennidic schist belt consists mainly of micaceous schists and amphibolites, which produce a graywacke-basalt association of the geosynclinal sequence. Great masses of orogenic plutonic rocks were emplaced into the schist belts during the Svecokarelidic orogenic movements.

The Postsvecokarelian evolution of the Finnish Precambrian is represented by the intrusions of rapakivi granites (1 700—1 550 Ma) and the sedimentation of nonmetamorphic, Jotnian sediments (1 300—1 400 Ma). Furthermore, to this evolution belong the intrusions of diabase dikes, which are partly connected with the rapakivi intrusions or are to some extent younger than the Jotnian sediments.

Geochronological data

The frequency diagram of the age determinations, reproduced in Fig. 4, gives an idea of the main phases of the long geological history of the Finnish Precambrian. The ten age groups marked on the diagram are listed in the following with their geological interpretations:

Group 1 (2 800—3 000 Ma). The zircons of this oldest age group have been found sporadically in Presvecokarelidic rocks. The oldest zircons (~ 3 000 Ma) occur as detrital particles in the Presvecokarelidic quartzite.

Group 2 (2 600—2 800 Ma) comprises the Presvecokarelidic rocks in the broad areas of the orthogneisses or so-called basement gneisses in eastern and northern Finland. The basement gneisses, which occur as mantled gneiss domes in the Svecokarelidic folded area, have been intensely reworked by later movements, and their zircons give younger ages (~2 400—2 500 Ma).

Group 3 (~ 2 500 Ma) consists of Presvecokarelidic orthogneisses in northern Finland.

Group 4 (2 430—2 450 Ma) comprises layered mafic intrusions, connected with acid porphyries, in northern Finland. These differentiated, sill- or lopolith-like intrusions penetrate the Presvecokarelidic basement gneisses, but they are older than the basal beds of the Svecokarelides.

Group 5 (2 000—2 300 Ma) represents the evolutionary phase of the Svecokarelidic orogeny during which the deposition of an epicontinental, transgressive Jatulian group of sediments took

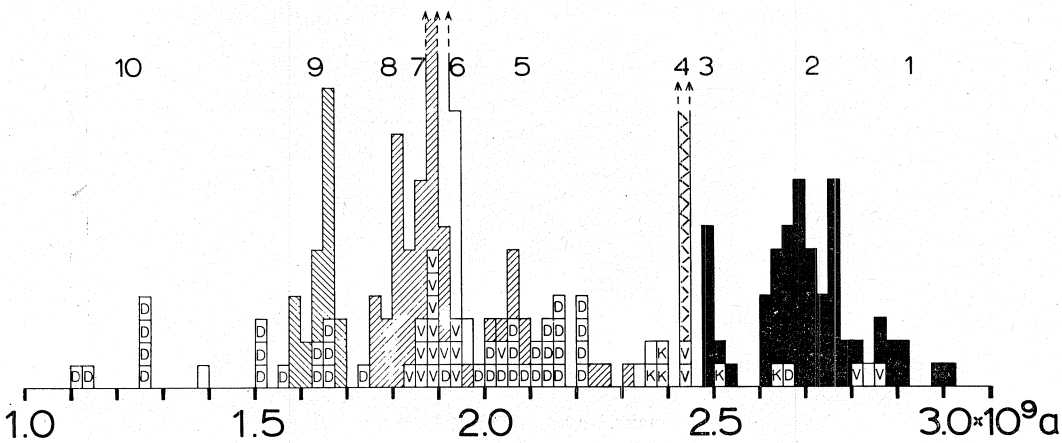

Fig. 4. Frequency diagram of the U-Pb age determinations on the Precambrian rocks of Finland. Compiled by O. Kouvo.

place upon the Presvecokarelidic basement. The dating of this group has been done mainly by using mafic volcanics and diabases (2 200—2 000 Ma) connected with the Jatulian sedimentation.

Group 6 (1 900—2 000 Ma) is based mainly on the mineral ages of the old rocks from northern Finland that were intensely recrystallized during the granulite metamorphism. Furthermore, certain Svecofennidic metavolcanics and plutonic rocks (trondhjemites) belong to this group.

Group 7 (1 850—1 900 Ma) comprises the Svecofennidic metavolcanics and synorogenic plutonic rocks, mainly quartz diorites and granodiorites. The time involved represents the main phase of the Svecokarelidic folding and regional metamorphism.

Group 8 (1 750—1 850 Ma) consists of late-orogenic and postorogenic intrusions of the Svecokarelidic orogeny.

Group 9 (1 550—1 700 Ma) comprises the intrusions of rapakivi granites and gabbro-anorthosites as well as the diabases connected with them.

Group 10 (< 1 500 Ma), the youngest group of the Precambrian in Finland, is represented by the Jotnian sediments (1 300—1 400 Ma) and the Postjotnian diabases (1 270 Ma).

Seismological data

The crustal structure in Finland is studied mainly by the Institute of Seismology at the University of Helsinki. Explosion-seismic and earthquake studies carried out in different northern countries have given a rough general idea about the structure of the Earth's crust in the Baltic Shield. The sketch maps, based on refraction-seismic methods, are presented in Fig. 5, and they show schematically the thickness of the sublayers and Earth's crust in different parts of Fennoscandia.

The granitic layer (Fig. 5, I) in Finland and in the area of the Baltic Shield is usually 15—20 km thick. Thicknesses slightly over 20 km are found in southeastern Finland and less than 15 km in the area around the Gulf of Bothnia and in the Caledonidic folded belt.

The basaltic layer (Fig. 5, II) is in most places 15—20 km. Thicknesses over 20 km are found in the area around the Gulf of Bothnia and measurements of less than 15 km have been mostly made locally in southeastern Finland.

The depth of Moho (Fig. 5, III) in the Baltic Shield is commonly 35—40 km. Values over 40 km are found in the area of the Gulf of Bothnia and the thickness of the crust in southeastern Finland may be locally less than 30 km. The average thickness of the Earth's crust in Finland is 39 km.

Gravimetric data

Gravity anomaly maps of Finland have been compiled by the Geodetic Institute and new maps are under preparation. A simplified free air gravity anomaly map of Finland is presented in Fig. 6.

The original map published in 1962 on the scale 1 : 1 000 000 is based on measurements made more than 10 000 stations. In southern Finland, the distribution of stations is fairly even, with an average spacing of 5 km. In northern Finland, the measurements represent mainly profiles along the roads, and there are wide areas without gravimetric data between them. Mainly Worden-type gravimeters have been used. The interval between the isoanomaly curves in the original map is 5 mgal.

Certain of the major geological units of the Precambrian in Finland are clearly seen in the gravity anomaly map. A wide area, showing a negative anomaly, occurs around the region of the Gulf of Bothnia where the thickness of the Earth's crust is greater than in the surroundings. Marked 20—60 mgal, negative anomalies are characteristic of the rapakivi granite areas in southeastern and southwestern Finland. Furthermore, areas of Jotnian sediments

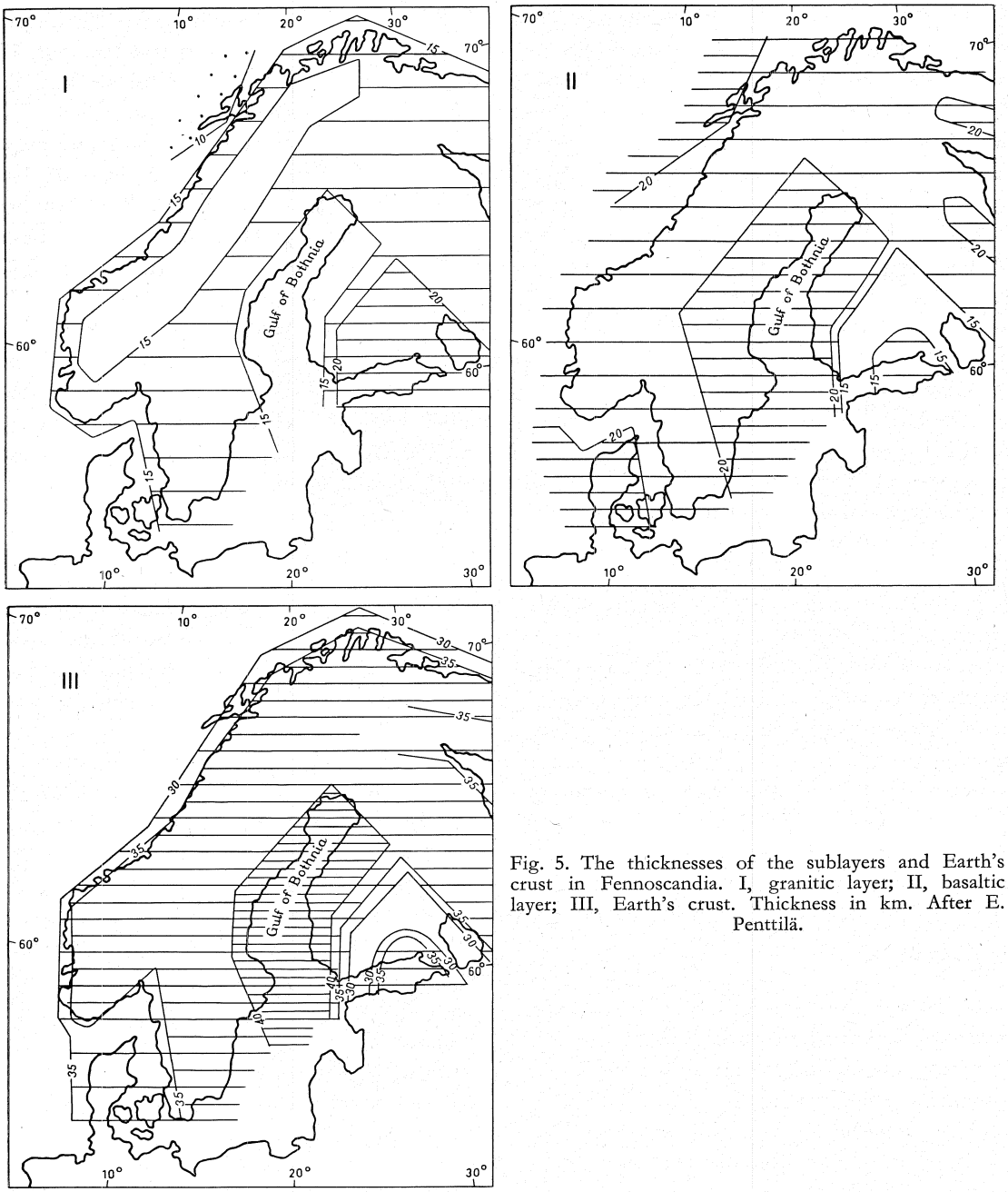

Fig. 5. The thicknesses of the sublayers and Earth's crust in Fennoscandia. I, granitic layer; II, basaltic layer; III, Earth's crust. Thickness in km. After E. Penttilä.

are characterized by a 20—30 mgal negative anomaly. Positive anomalies seem to be a typical feature of the areas of the old Presvecokarelidic basement in eastern and northern Finland.

Aeromagnetic data

A systematic aerogeophysical mapping of the whole country (including the magnetic, electromagnetic and radiometric measurements) was

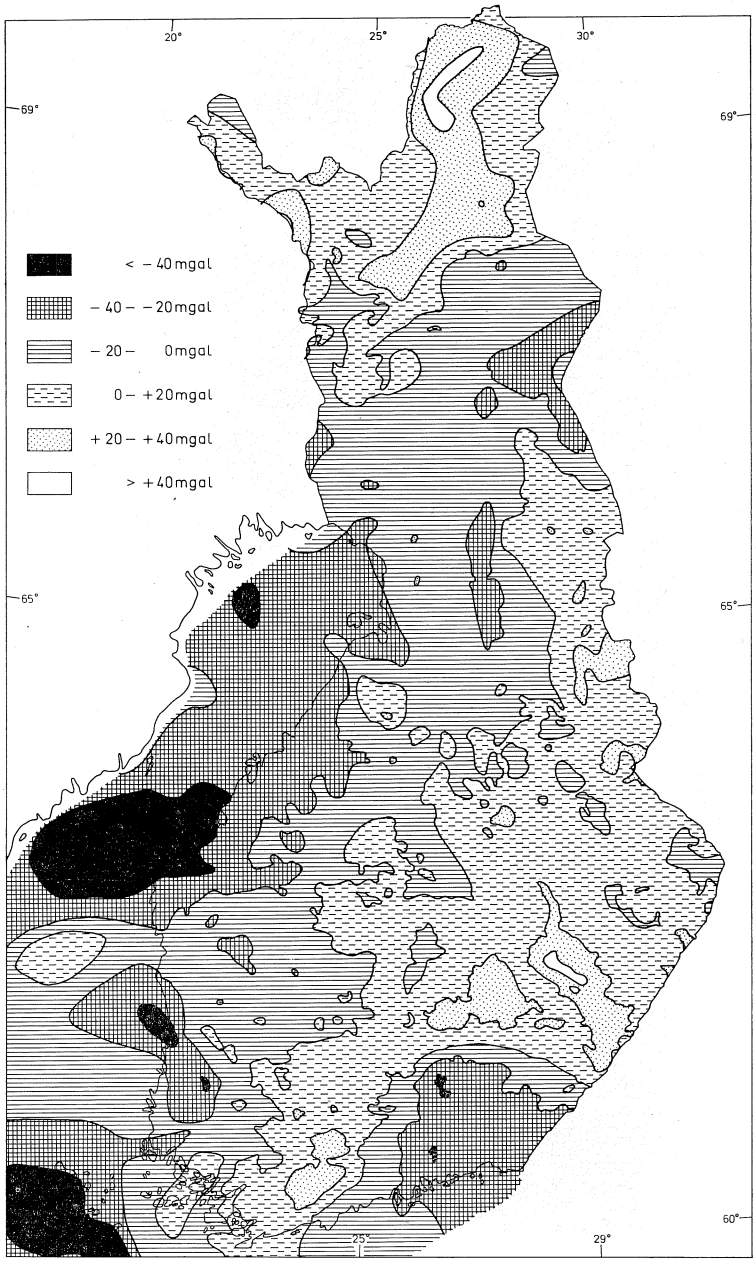

Fig. 6. Free air gravity anomalies in Finland. Simplified from the original map (1 : 1 000 000) published by the Finnish Geodetic Institute.

carried out in the years 1951—1972 by the Geological Survey of Finland. Flights for this survey were made at an altitude of 150 meters along parallel lines spaced 400 meters apart. The measurement of the Earth's total magnetic field was made with a fluxgate magnetometer.

The results of the aeromagnetic survey are summarized on maps drawn on the scale 1 :

Fig. 7. Aeromagnetic anomaly map of Finland. Geological Survey of Finland, Geophysics Department.

20 000. The interval between the isoanomaly curves for the magnetic total intensity is 20 γ on these original maps, of which the aeromagnetic map of Finland presented in Fig. 7 is a photographic reduction. In many cases, owing to the reduction, the isoanomaly curves of the original maps meet to form coherent and dark anomaly areas.

Most of the schist zones are characterized by coherent anomaly areas, the form of which yields information about the structural features of the crust. Small and rounded anomaly areas are usually produced by mafic and ultramafic bodies of plutonic rocks. The massifs of granitoid rocks are usually observed to lack marked magnetic anomalies, and they appear as white areas in Fig. 7. Furthermore, the Jotnian sediments are characterized by lack of magnetic anomalies.

CHARACTERISTICS OF THE GEOLOGICAL UNITS

The characteristics of the geological units of the Finnish Precambrian will be given in chronological order from the oldest to the youngest complexes. The description begins with the oldest, Presvecokarelidic crust, which acted as a floor for the deposition of the Svecokarelian sediments. The main part of the description is devoted to the Svecokarelides, which form the largest and the most essential part of the Precambrian in Finland. The Postsvecokarelian igneous and sedimentary rocks, which did not take part in the orogenic movements, are treated last.

Presvecokarelidic basement

The Presvecokarelidic basement complexes occur in eastern and northern Finland and they have a broad extension in Soviet Karelia and the Kola Peninsula. An abundance of cataclastic granitoid rocks of quartz dioritic, granodioritic and granitic composition is characteristic of these basement areas. Originally, these gneissose, granitoid rocks of the basement areas were known as granite gneiss or gneissose granite. However, the composition of most of these gneisses is not granitic, and hence the neutral term »basement gneiss» has been suggested. Some separate, narrow schist zones occur penetrated and surrounded by granitoid rocks. The granulite complex of Lapland forms a unique part of the Presvecokarelidic crust, recrystallized in the Svecokarelidic movements.

Basement area in eastern Finland

The oldest rocks are schists and paragneisses penetrated by orthogneisses. The ancient schists form the isoclinally folded schist zones of Suomussalmi, Kuhmo and Ilomantsi, which are pressed between the surrounding blocks of the basement gneisses. New geological reports show that the schist zones consist mainly of mafic metavolcanic rocks associated with small lenses of ultramafics (serpentinites, soapstones and talc-chlorite schists) and with minor beds of a quartz-banded iron formation. Silicic metavolcanics occur only sporadically. The metavolcanics have been originally both lavas and pyroclastics, and they contain relics of a porphyritic and amygdaloidal texture and agglomeratic and pillow lava structure. The metamorphism of the mafic metavolcanics grades from the conditions of the greenschist facies into the amphibolite facies. Metasediments are represented by impure meta-arkoses, phyllites and mica schists. Graphite-bearing black schists occur as thin intercalations in the metasediments as well as in the metavolcanics.

The majority of the basement gneisses are considered to be orthogneisses, which had been primarily silicic plutonic rocks ranging in composition from quartz diorites to granites. Orthogneisses are even-grained or porphyritic

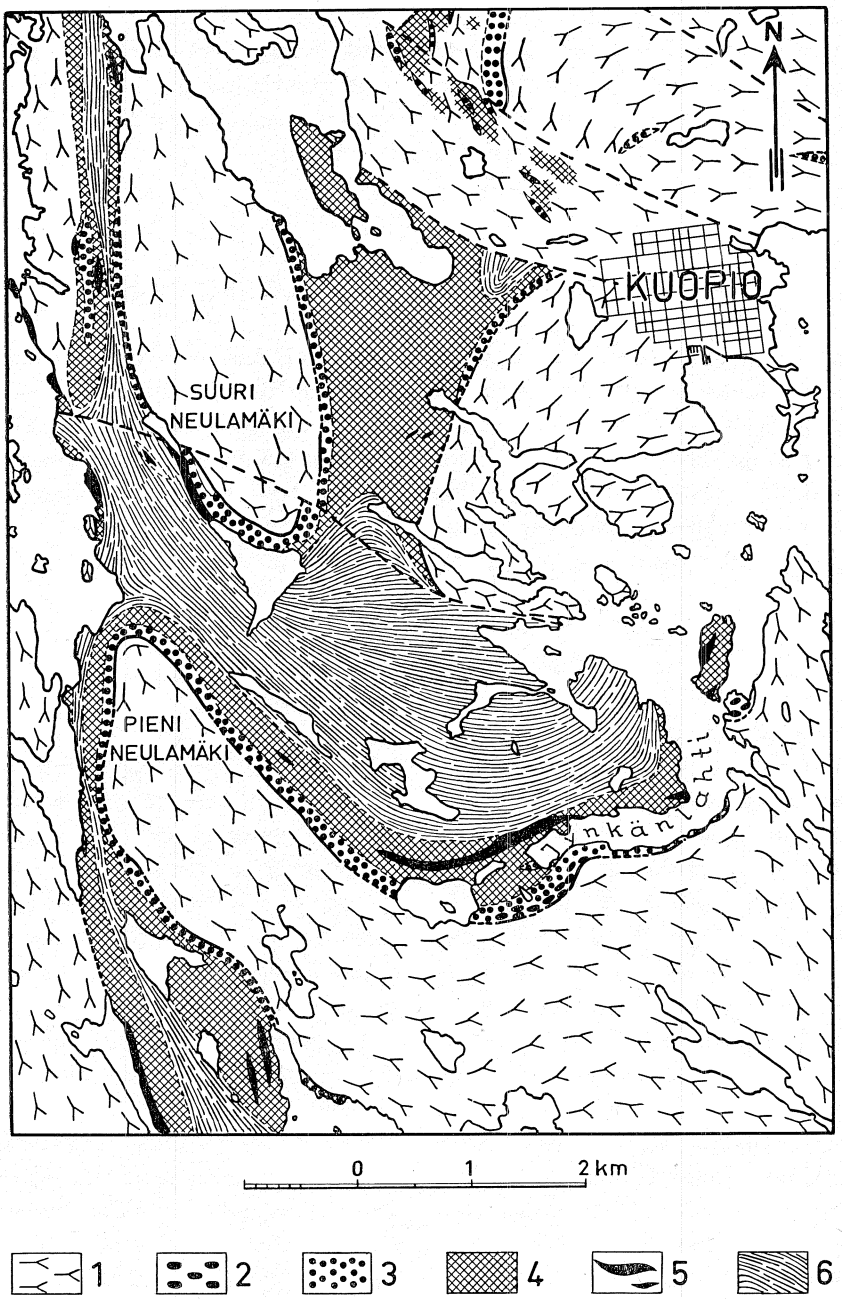

Fig. 8. Mantled gneiss domes in the Kuopio area. 1, basement gneiss; 2, conglomerate; 3, quartzite; 4, amphibolite; 5, dolomite; 6, mica schist. After W. Wilkman and J. Preston.

rocks, which are usually clearly foliated. However, weakly orientated and massive varieties also occur. A characteristic feature of many orthogneisses is their cataclastic texture. The quartz and feldspar grains of cataclastic rocks are crushed and the fine cracks are filled with mica. Some basement gneisses are banded and granoblastic in texture. They may be either

ortho- or paragneisses. Basement gneisses are often migmatitic and contain schlieren of ortho- and paragneisses.

Basement gneisses occur in the Karelidic schist belt as domes mantled by Karelidic schists (Fig. 8). Cores of these so-called mantled gneiss domes were reworked during the Svecokarelidic orogeny.

Field evidence shows that the Presvecokarelidic basement is separated from the Svecokarelidic schists, bordering the basement, by a first-order unconformity, an interval of deep erosion and peneplanation. This ancient basement, so-called Jatulian continent, acted as a floor of deposition for the evolutionary Jatulian group of the Svecokarelian sediments and it formed the resistance area during the Svecokarelidic folding that took place against the ancient craton.

The zircon ages of all the granitoid rocks of the basement area fall within an age group of 2 600—2 800 Ma. Both cataclastic and massive granitoid rocks of the basement area, as well as granitoids penetrating the Presvecokarelidic schists belong to this age group. It should be mentioned that the K-Ar age of the biotite in the basement gneisses is only 1 750—1 800 Ma. This indicates that the rocks of the basement complex underwent partial recrystallization during the later Svecokarelidic orogeny. Furthermore, the zircon ages of the basement gneisses from the cores of the mantled gneiss domes are lower (2 400—2 500 Ma) than those from the coherent basement area. This is probably due to partial recrystallization of the zircon during the later Svecokarelidic metamorphism.

Basement area in northern Finland

The basement complex of northern Finland contains both para- and orthogneisses. The paragneisses are represented by quartz-feldspar gneisses, mica gneisses, hornblende gneisses and amphibolites. The orthogneisses are gneissose quartz diorites, granodiorites and granites. Migmatitic gneisses are common.

The gneiss complex of Tuntsa-Savukoski in eastern Lapland consists mainly of mica

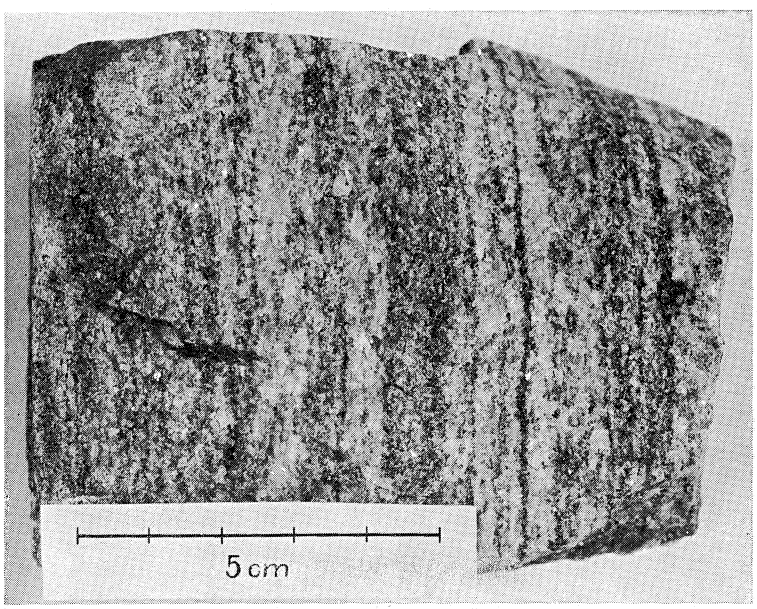

Fig. 9. Basement gneiss. Inarinjärvi, Kotkavuono. Photo E. Halme.

gneisses, which are penetrated by orthogneisses. The mica gneisses are highly metamorphic and aluminous gneisses containing garnet, staurolite, kyanite and cordierite. Glassy quartzites, hornblende gneisses and amphibolites occur, too.

Many Presvecokarelidic schist and gneiss zones from the most northern part of Finnish Lapland occur as steep synclines between the basement gneiss blocks or as a marginal zone of the granulite belt. The schist zones with an abundance of amphibolites are related to those in the basement area of eastern Finland. The stratigraphical sequence from youngest to oldest for the schists seems to be as follows:

— amphibolites, with some black schist in their upper part;

— mica gneisses, or locally quartz-feldspar gneisses, mica gneisses, hornblende-gneisses and amphibolites as randomly alternating beds and bands, magnetite-banded quartzites and calc-silicate gneisses:

— quartzites and quartz-feldspar gneisses.

The orthogneisses of the basement area (Fig. 9) are highly similar to those met with in eastern Finland. The gneissose, mostly granodioritic, and in many cases cataclastic orthogneisses and migmatitic gneisses are common. The zircon ages of the orthogneisses range between the limits 2 500—2 800 Ma.

Granulite arch

A special part of the basement area of Finnish Lapland is the so-called granulite complex, which is composed of para- and orthogneisses that were metamorphosed under higher PT-conditions than the surrounding rock crust. Typomorphic minerals of Finnish granulites are: sillimanite, almandine-pyrope, hypersthene plagioclase, orthoclase and quartz.

The most common rocks of the granulite arch are garnet gneisses (Fig. 10), the mineral associations of which are: garnet-quartz-feldspar gneisses, garnet-cordierite gneisses, garnet-biotite gneisses and garnet-biotite-plagioclase gneisses. The chemical composition, varying

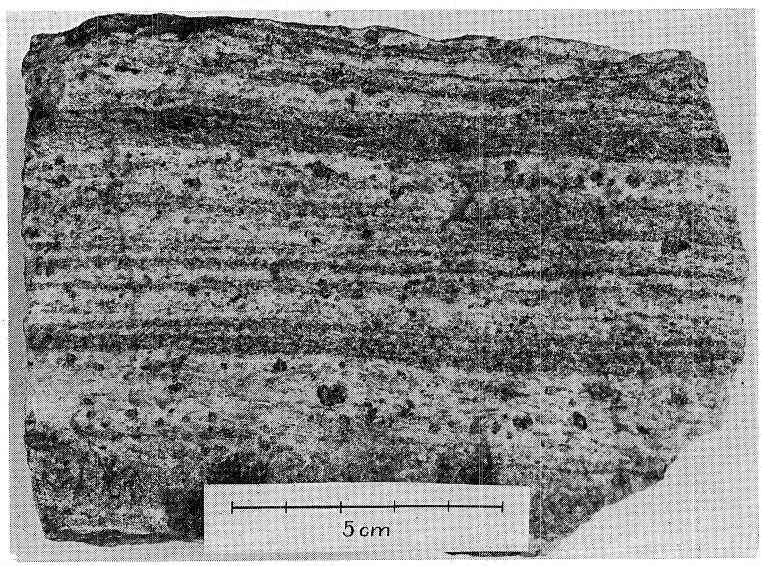

Fig. 10. Fine-grained garnet-quartz-feldspar gneiss of the granulite complex. Utsjoki, Rittatshobma. Photo E. Halme.

from arenaceous to argillaceous, the indistinct banding of different layers and the presence of quartzitic and graphite-bearing bands suggest that these garnet gneisses are of a sedimentary origin.

Hypersthene gneisses occur sporadically as thin intercalations in the garnet gneisses. The plutonic rocks of the granulite area are mainly charnockitic quartz diorites associated with minor bodies of pyroxene-bearing mafic and ultramafic rocks. There are also occurrences of garnet-biotite quartz diorites and garnet-bearing porphyritic granites.

The metamorphic and tectonic evolution of the granulite complex is highly complicated and characterized by quite a thorough reworking, which occurred during the Svecokarelidic orogeny. The gneisses of the granulite arch are polymetamorphic rocks, which formed stable structures as a result of the Presvecokarelidic movements; but they took part in later tectonic movements of the Svecokarelides. The granulites were formed from ancient Presvecokarelidic amphibolite-facies rocks by kinetic metamorphism in the shear zones. The granulite metamorphism (~ 2 150 Ma) was followed about 1 900 Ma ago by later metamorphism under conditions of low-grade granulite facies and high-grade amphibolite facies. As a consequence of the Svecokarelidic movements, the granulite massif was uplifted and overthrust towards the southwest, causing the Svecokarelidic schists to follow the tectonics of the granulite arch.

The zircon ages of the fine-grained garnet-quartz-feldspar gneisses of the granulite complex are ~ 2 150 Ma and the zircons of the garnet-cordierite gneisses are about 2 000—2 040 Ma. The Presvecokarelidic rocks recrystallized by the granulite metamorphism have a new generation of zircon and only remnants of the old zircon generation have been met with. Evidence of the earliest event of the granulite metomorphism (~ 2 150 Ma) is preserved only in the southwestern part of the granulite arch. The later high-grade metamorphism (~ 1 900 Ma) laid its stamp on the entire area. It is noteworthy that the isotope composition of the total lead of the whole rock corresponds, however, to that of the ancient Presvecokarelidic age group ~ 2 500 Ma. For example, the ages of the granulites in the Koppelo area (south of Lake Inari), influenced by a later phase of metamorphism, are as follows:

zircon	1 940 Ma
monazite	1 915 Ma
total lead of the whole rock (isochron)	2 465 Ma

and the age data of the pyroxene quartz diorites in the granulite area as follows:

zircon	1 925 Ma
total lead of the whole rock (isochron)	2 535 Ma.

Presvecokarelian igneous rocks younger than the folded basement

Penetrating the Presvecokarelidic folded basement, layered mafic intrusions represent the Presvecokarelian igneous rocks older than the Svecokarelides. Furthermore, the intrusions of this croup seem to include a unique carbonatite complex in Siilijärvi, which is one of the oldest carbonatite occurrences in the world.

Mafic igneous rocks

Many differentiated and layered mafic intrusions in northern Finland, which are usually considered as Svecokarelian rocks, seem, however, to be older than the Svecokarelides. These mafic rocks occur as sheets or lopolith-like bodies

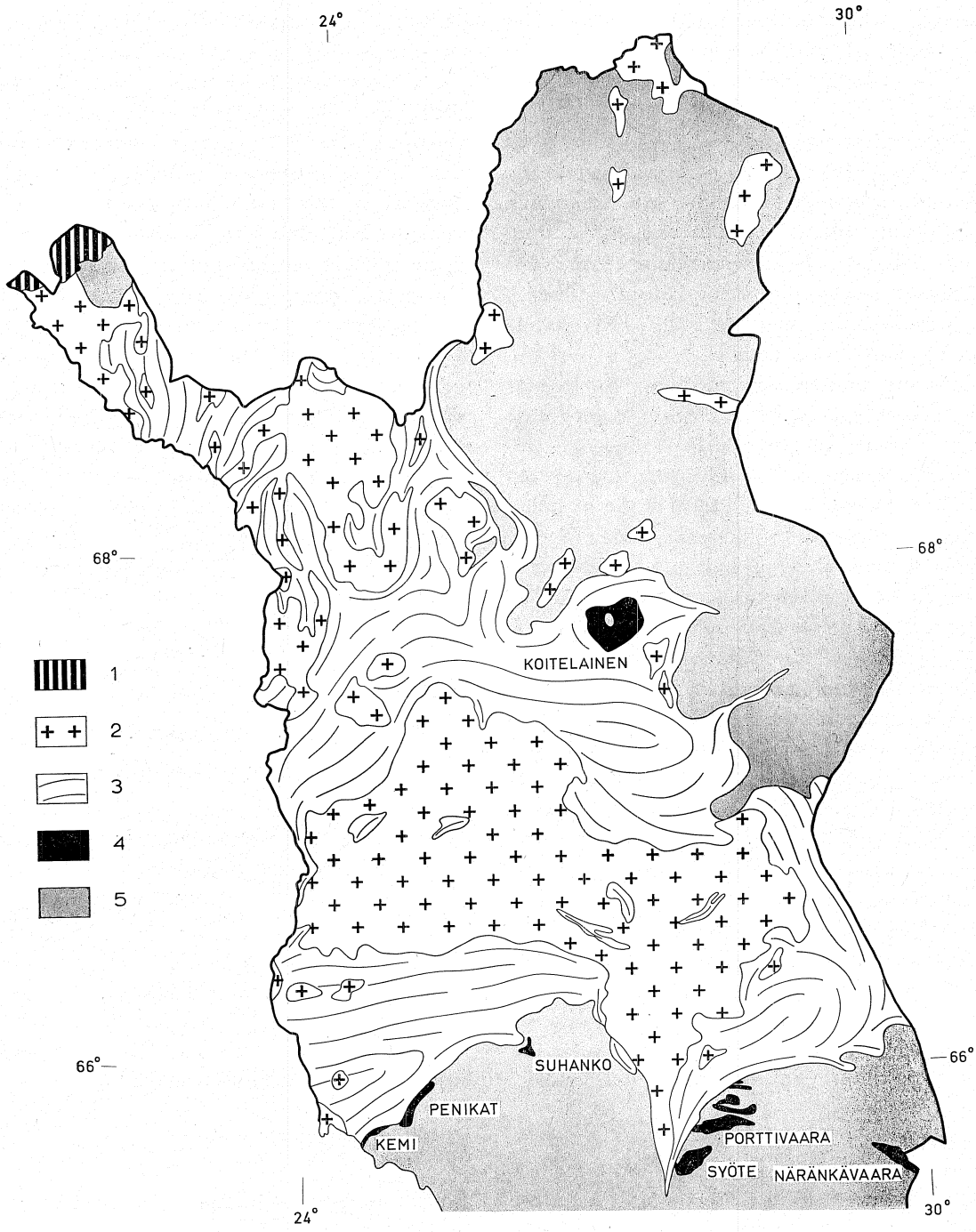

Fig. 11. Presvecokarelian, layered mafic intrusions in northern Finland. 1, Caledonidic rocks; 2, Svecokarelidic plutonic rocks; 3, Svecokarelidic schists; 4, Presvecokarelian, layered mafic intrusions; 5, Presvecokarelidic basement (schists, basement gneisses and granulites).

in the Presvecokarelidic basement area or along the contact zones between the ancient basement and the Karelidic schist zones (Fig. 11). The mode of occurrence and age data show that the mafic intrusions had emplaced the stabilized Presvecokarelidic basement before the evolutionary phase of the Svecokarelides. The differentiated mafic bodies may have originated as platform-type intrusions in the ancient crust between the Presvecokarelidic and Svecokarelidic folding movements. Study of these layered mafic intrusions is still in progress and their geological position and importance in the geological evolution of Finland are still an open question.

The chemical composition of the magma was basaltic, tholeitic or ossipitic. High contents of alumina and lime and very low contents of alkalies are characteristic. The differentiation of the magma produced mainly peridotites, gabbros, anorthositic gabbros and anorthosites. The ultramafic differentiates form the lower parts and the anorthositic types the upper parts of the differentiated bodies. Common features are gradual transitions between different varieties and rhythmic layering. Some of the mafic bodies are associated with granophyres and silicic porphyries in the uppermost parts of the layered intrusions.

The most common primary minerals of these mafic rocks are olivine, orthopyroxene, augite and plagioclase. Owing to autometamorphism after magmatic crystallization and to reworking caused by the Svecokarelidic movements, the mafic minerals have been altered into serpentine, talc, uralite and chlorite, etc. Remnants and relics of the original minerals are, however, present. Furthermore, the reworking produced a crushed texture and the contacts of the mafic bodies were tectonized.

The ages of the layered mafic intrusions were determined by the U-Pb method for zircon. Zircon occurs in the coarse-grained, pegmatoidic parts of the gabbros. The age determinations show that the layered mafic rocks form a coherent age group of 2 430—2 450 Ma.

Carbonatite complex

In addition to the afore-mentioned mafic intrusions, the peculiar carbonatite complex of Siilinjärvi may also belong to the group of Presvecokarelian igneous rocks. This complex forms an elongated, vertical sheet-like body, which penetrates the Presvecokarelidic basement gneiss. The main rock types, in succession to the intrusions, are: glimmerite (phlogopite rock), syenite and carbonatite. The fenitic margins around the carbonatite complex are weakly developed.

Carbonatite was intruded into glimmerite, producing mixed rocks. Most common are glimmerite—carbonatite rocks, the carbonatite content of which varies from 5 to 25 %. The main minerals of the glimmerite are phlogopite, alkali amphibole (richterite) and apatite. The trace elements enriched in the carbonatite complex are P, F, Sr, Ba, RE (especially Ce group), Zr and Nb. The age of the complex is about 2 500 Ma, as determined by the K-Ar method for richterite.

Svecokarelides

The Svecokarelides cover most of the Finnish Precambrian area, and the Svecokarelidic folded zone is composed of the following major geological units (cf., Figs. 2—3):

— Karelidic schist belt in eastern and northern Finland, characterized especially by an abundance of quartzites.

— Svecofennidic schist belt in western and southern Finland, characterized by an abundance of micaceous schists.

— Orogenic Svecokarelidic plutonic rocks, emplaced during the Svecokarelidic movements and penetrating the Karelidic and Svecofennidic schists.

Karelidic schist belt

The main rock types in the Karelidic schist belt, the trend of which is from southeastern to northern Finland, occur in the following proportions:

micaceous schists	45.2 %
quartz-feldspar schists	2.8 %
quartzites	26.4 %
limestones	0.3 %
metabasalts and amphibolites	25.3 %

Originally, the Karelidic schists were mainly argillaceous sediments and true quartz sandstones, which metamorphosed into phyllites or mica schists, and quartzites. Metavolcanics — originally mafic lavas, tuffs and diabases — are also common. The widely distributed metavolcanics of northern Finland are associated with ultramafic, picritic bodies and with beds of jaspilites. The limestones are mainly dolomitic. Further, there are minor occurrences of many other rock types, including conglomerates, kaoline deposits, arkosites, carbonaceous black schists, etc.

The metasediments and metavolcanics of the Karelidic schist belt show, as a relic fabric, many primary textures and structures. Well-preserved sedimentary structures, such as ripple marks, cross bedding, and mud cracks, are found in low-metamorphic, blastoclastic quartzites. The micaceous schists show graded bedding and stratification. Porphyritic, amygdaloidal, pillow lava and agglomerate textures and structures are common in metavolcanics.

The metamorphism of the Karelidic schists took place in the conditions of the greenschist, epidote-amphibolite or amphibolite facies. Micaceous schists grade from phyllites into mica schists and mica gneisses. The mica schists contain porphyroblasts of andalusite, cordierite or staurolite. Migmatic mica gneisses contain garnet, cordierite and sillimanite. The metabasalts of northern Finland are commonly greenstones, consisting of albite, epidote, and chlorite. The greenstones grade into amphibolites, especially along the contact of plutonic masses.

The folding of the Karelidic belt took place against the Presvecokarelidic basement blocks, and gentle synclines and anticlines developed. The fold axes are gentle and linear structures commonly run parallel to them. Axial culminations and depressions are typical of the Karelidic belt of eastern Finland, where the ancient basement or the floor of the Karelides appears in the culminations and anticlines of the folded belt. Sections through the Karelides, showing some examples of the folding, are presented in Figs. 12—13.

The standard stratigraphical section of the Karelidic metasediments, especially in eastern

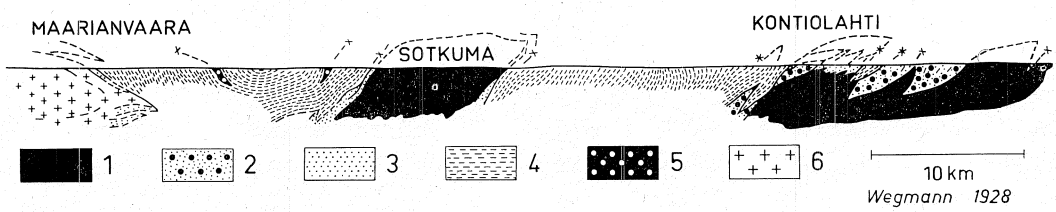

Fig. 12. Section through the Karelides in North Karelia, E-Finland. 1, Presvecokarelidic basement gneiss; 2, basal quartzite; 3, quartzite; 4, phyllite and mica schist; 5, ophiolite (serpentinite); 6, granitoid. After E. Wegmann.

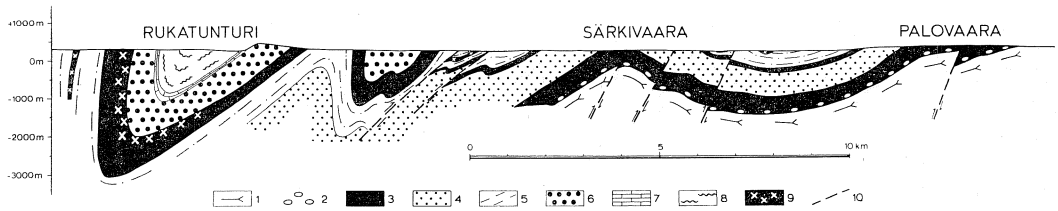

Fig. 13. Section through the Karelidic schist zone in the Rukatunturi area, Kuusamo. 1, Presvecokarelidic basement; 2, basal beds of the Karelian strata; 3, greenstone; 4, sericite quartzite, sericite schist and quartzite; 5, siltsized argillaceous and dolomitic schist; 6, sericite quartzite and orthoquartzite; 7, dolomite; 8, amphibole schist with black schist intercalations; 9, subsilicic intrusives, mainly sills; 10, fault. Compiled by A. Silvennoinen.

Finland, which has been a key area in the interpretation and classification of the Finnish Karelides, is as follows:

Kalevian group: phyllites and mica schists

Jatulian group:
- carbonaceous slates
- dolomites
- quartzites
- basal conglomerates and arkoses

——— Great unconformity ———

Presvecokarelidic basement

The Karelidic schists are separated by a marked unconformity from the Presvecokarelidic basement (Fig. 14). The Jatulian sedimentation started with basal arkoses and conglomerates lying upon the Presvecokarelidic basement, which sometimes shows relicts of the crust weathered in situ, to a depth of some ten meters. The basal arkose, with intercalations of siltstone, calcareous and quartzitic beds, overlies the weathered surface of the basement gneiss. The basal polymict conglomerates (Fig. 15), which contain pebbles of Presvecokarelidic gneisses, occur only sporadically as basal beds of the Karelian strata. This basal formation has been called the Sariolian formation.

The pure quartzites associated with quartz conglomerates, sericite quartzites, kaoline and uranium deposits rest upon the Sariolian basal beds or directly upon the Presvecokarelidic basement. This widely distributed quartzite formation has been called the Kainuian or Jatulian quartzite formation and it serves as an excellent key bed for stratigraphical correlations. The quartzites are overlain by so-called marine Jatulian metasediments: dolomites and carbonaceous slates, associated in some cases with hematite-bearing iron formation. The metasediments of the Jatulian group represent a transgressive epicontinental sequence upon the peneplained Presvecokarelidic basement. The time of the Jatulian sedimentation is associated with contemporaneous volcanism represented by metabasalts and metadiabases, which are present in all the areas consisting of the metasediments of the Jatulian group. Metadiabases penetrate both the basement and the Jatulian sediments, but not the Kalevian rocks overlying the Jatulian. The mafic volcanism interrupted the Jatulian sedimentation. Usually, one or more interbeds of mafic metavolcanics are found in the Jatulian strata. The beds of metavolcanics in some cases directly overlie the ancient basement.

The Jatulian transgressive group, the total thickness of which is usually some hundreds of meters, is overlain by many kilometers of thickly accumalated, so-called Kalevian graywacke-like geosynclinal sediments, which have been metamorphosed into phyllites and mica schists. In some places, the Kalevian group overlies the Jatulian sediments unconformably and conglomerates, containing pebbles of the basement gneisses and Jatulian metasediments

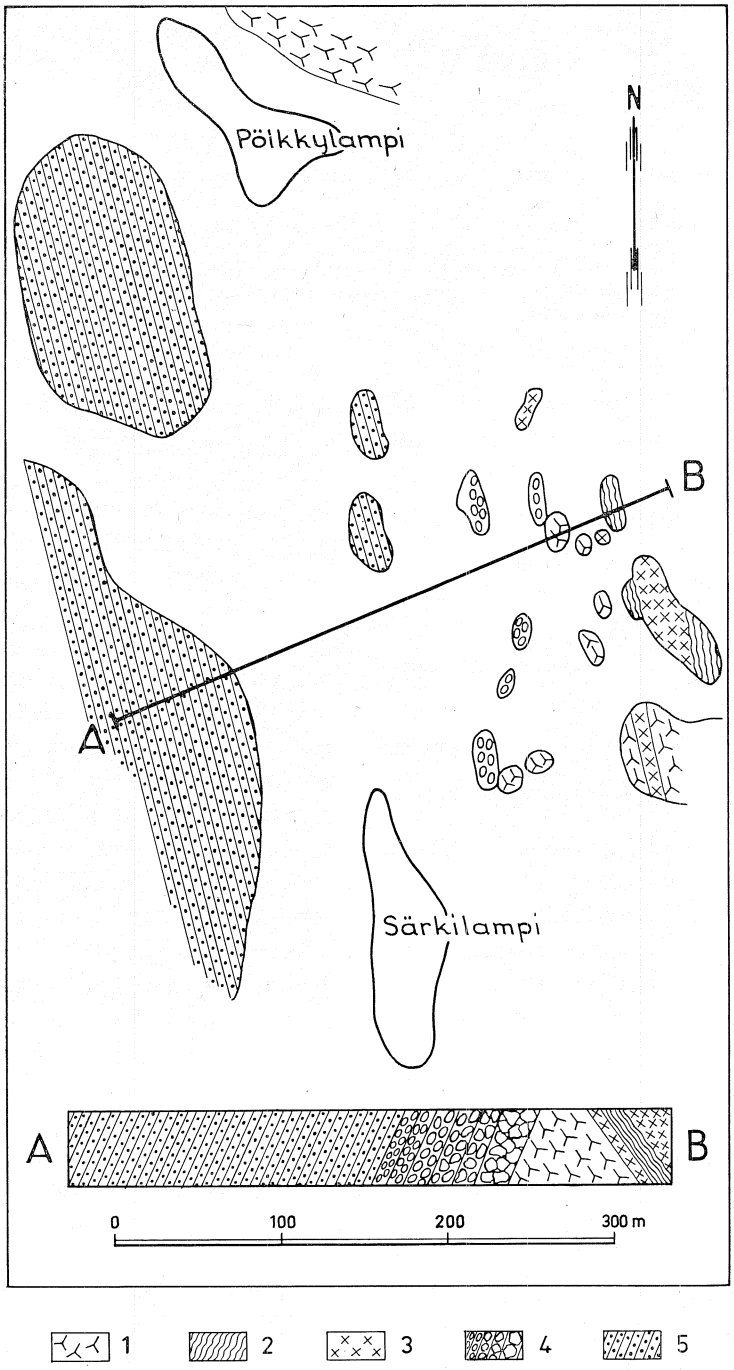

Fig. 14. Basal conglomerate in Pölkkylampi, Kiihtelysvaara, E-Finland. 1, Presvecokarelidic orthogneiss; 2, Presvecokarelidic paragneiss; 3, tourmaline-bearing granite; 4, polymict conglomerate (containing pebbles of the rocks 1—3); 5, quartzite. After B. Frosterus and W. Wilkman.

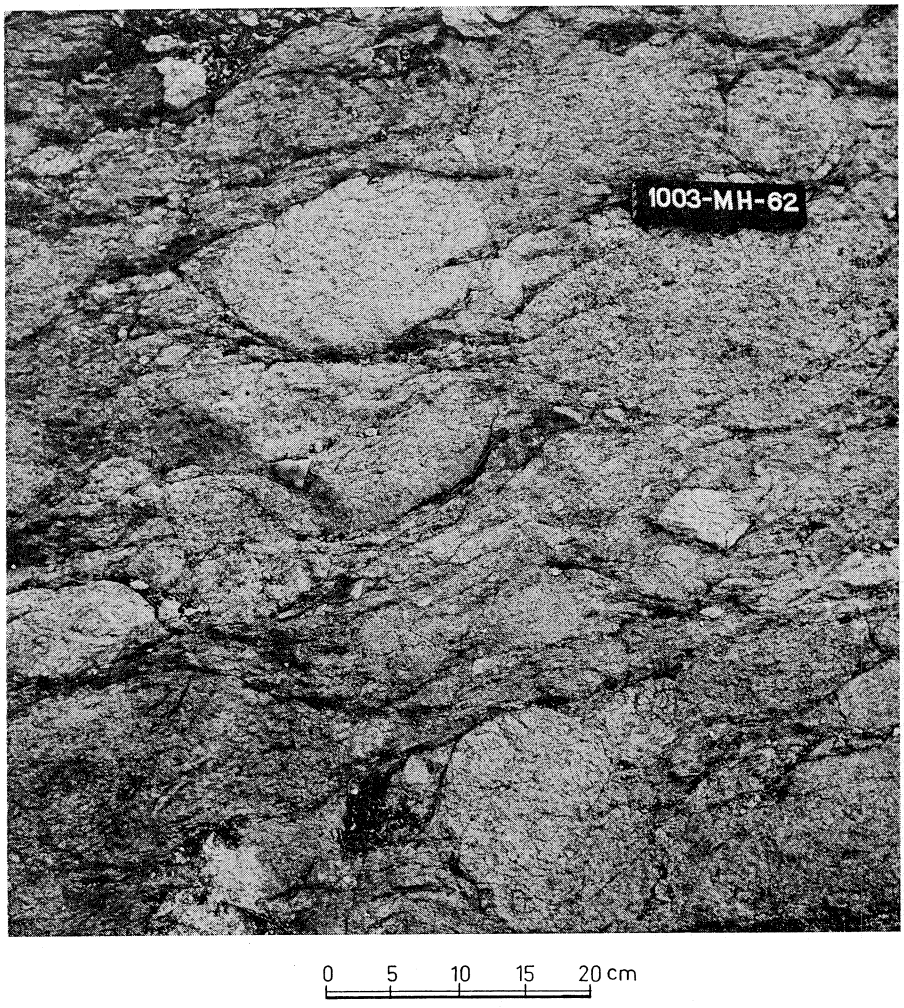

Fig. 15. Basal conglomerate, Viesimonjoki, Kiihtelysvaara. Photo M. Härme.

and metavolcanics, separate the groups from each other. The marked unconformity between the Jatulian and Kalevian successions does not, however, exist in all sections of the Karelian sedimentation area.

An extremely thick sequence of the Jatulian strata occurs in the Kuusamo area, where the Jatulian transgression is interrupted by three stages of basic volcanism and slight regression after the second phase of volcanism. The stratigraphy of the Rukatunturi area in Kuusamo is given in Table 1.

Table 1. Stratigraphy of the Rukatunturi area, after A. Silvennoinen.

Formations	Thickness in meters	
	S-part	N-part
amphibole schist	> 250	
dolomite	?	50—100
Rukatunturi quartzite	800	?600
greenstone III	200	200
siltstone	200	200
greenstone II	50	0
quartzite schist	50	0
sericite schist	130	
sericite quartzite	200	?100
greenstone I	?500	
basal conglomerate	0—20	?
—— unconformity ——		
Presvecokarelidic crust		

The Karelidic schists in Finnish Lapland consist mainly of quartzites, mica schists and mafic metavolcanics, but the stratigraphical succession of the strata is still under investigation. A special feature seems to be that some of the Karelidic schists are overlain by coarse-grained, arkosic quartzites and conglomerates, which contain pebbles deriving from the Karelidic schists. This younger sedimentary formation is called the Kumpu formation, which has been considered as a molasse-like accumulation after the main phase of the Svecokarelidic folding.

Taken as a whole, the stratigraphical units of the Karelidic metasediments represent different stages and types of the sediments of an orogenic cycle. The Jatulian group is an evolutionary phase of sedimentation upon a stable platform and along the border of the ancient Presvecokarelidic craton. The Kalevian micaceous schists are products of geosynclinal sedimentation and the arkoses and conglomerates of the Kumpu formation may be sediments of the molasse type. The metavolcanics and associated metadiabases represent initial volcanism of the Svecokarelides, and their rich occurrence as intercalations and sills in the Jatulian group indicates marked tectonic activity, characterized by deep fractures, along the border zone between the stable Presvecokarelidic craton and the developing geosyncline.

The age of the Jatulian magmatism (metavolcanics and metadiabases) ranges between the limits of 2 200—2 000 Ma, dated by the U-Pb method on zircons. The Pb-Pb age of the dolomite and the age (total lead of the whole rock, isochron) of the iron formation, both of which rocks belong to the upper part of the Jatulian group, are ~ 2 050 Ma and ~ 2 080 Ma, respectively. On the basis of these ages, it may be concluded that the time of the Jatulian sedimentation extended over 200 Ma (~ 2 200—2 000 Ma ago). The Kalevian sediments, which overlie the Jatulian, are younger than ~ 2 000 Ma, but older than the synorogenic Svecokarelidic plutonic rocks (~ 1 900 Ma), which penetrate the Karelidic schists.

Svecofennidic schist belt

The abundance of the main rock types in the Svecofennidic schist belt, trending from western to southern Finland is as follows:

micaceous schists and gneisses	79.9 %
quartz-feldspar schists	6.5 %
quartzites	0.3 %
limestones	0.3 %
metabasalts and amphibolites	13.0 %

The Svecofennidic metasediments were originally mainly graywackes and impure arkoses, metamorphosed into slates, mica schists, mica gneisses and quartz-feldspar schists. The scarcity of true quartzites and limestones, associated mainly with quartz-feldspar schists, is a characteristic feature. The limestones are mainly calcitic. Metavolcanics and amphibolites, originally mainly mafic lavas and pyroclastics, are common in some Svecofennidic schist areas. Furthermore, there are small quantities of many other rock types, such as, for example intraformational conglomerates, calcareous schists, black schists, etc. Relics of the primary textures and structures of the Svecofennidic metasediments and metavolcanics have been found only in certain of the best-preserved parts of the schist belt; but in wide areas of markedly recrystallized gneisses and migmatites, they have been destroyed.

Micaceous schists are represented by graywacke slates, mica schists and mica gneisses. The graywacke slates show graded bedding (Fig. 16) and a blastoclastic texture. They pass gradually into granoblastic mica schists, which show only sporadically relics of graded bedding. The intensely recrystallized mica gneisses, which are widely distributed, show only indistinct banding of different layers, owing to the primary variation in the sedimentary strata. The aforementioned micaceous schists, which are the

Fig. 16. Graywacke-slate with graded bedding. Siivikkala, Ylöjärvi. Photo M. Härme.

most abundant metamorphites of the Svecofennidic belt, have been interpreted as products of incomplete weathering; and they contain both argillaceous and arenaceous material. They are similar to the graywackes of younger orogenic belts.

The quartz-feldspar schists are by and large layered, and relics of cross-bedding have been found. Most of the quartz-feldspar schists, some of which are mixed with argillaceous and calcareous material, are interpreted to be mainly arkose sandstones; but some of these show chemical as well as textural characteristics of silicic lavas and pyroclastics.

The metavolcanics, which are mainly basaltic or andesitic in chemical composition, having been crystallized from the lava flows, are usually seen to exhibit as a relic a blastoporphyritic texture; but other relic fabrics, such as fluidal, amygdaloidal, perlite, and pillow lava texture and structure, likewise indicate a volcanic origin. The pyroclastic material shows relics of banding of different layers and beds of agglomerates, and volcanic conglomerates afford the best evidence of a volcanic origin.

The Svecofennidic schists had been usually metamorphosed under conditions of low-pressure amphibolite facies, but in some places under conditions of the granulite facies. In certain narrow zones, retrograde metamorphism took place producing mineral assemblages of the greenschist facies.

The graywacke slates with well-preserved sedimentary structures represent the lowest grade of metamorphism of the Svecofennidic micaceous schists. They do not contain porphyroblasts of Al-minerals and they occur in the schist zones where penetrating plutonic bodies are rare. The graywacke slates pass gradually into mica schists, usually seen to

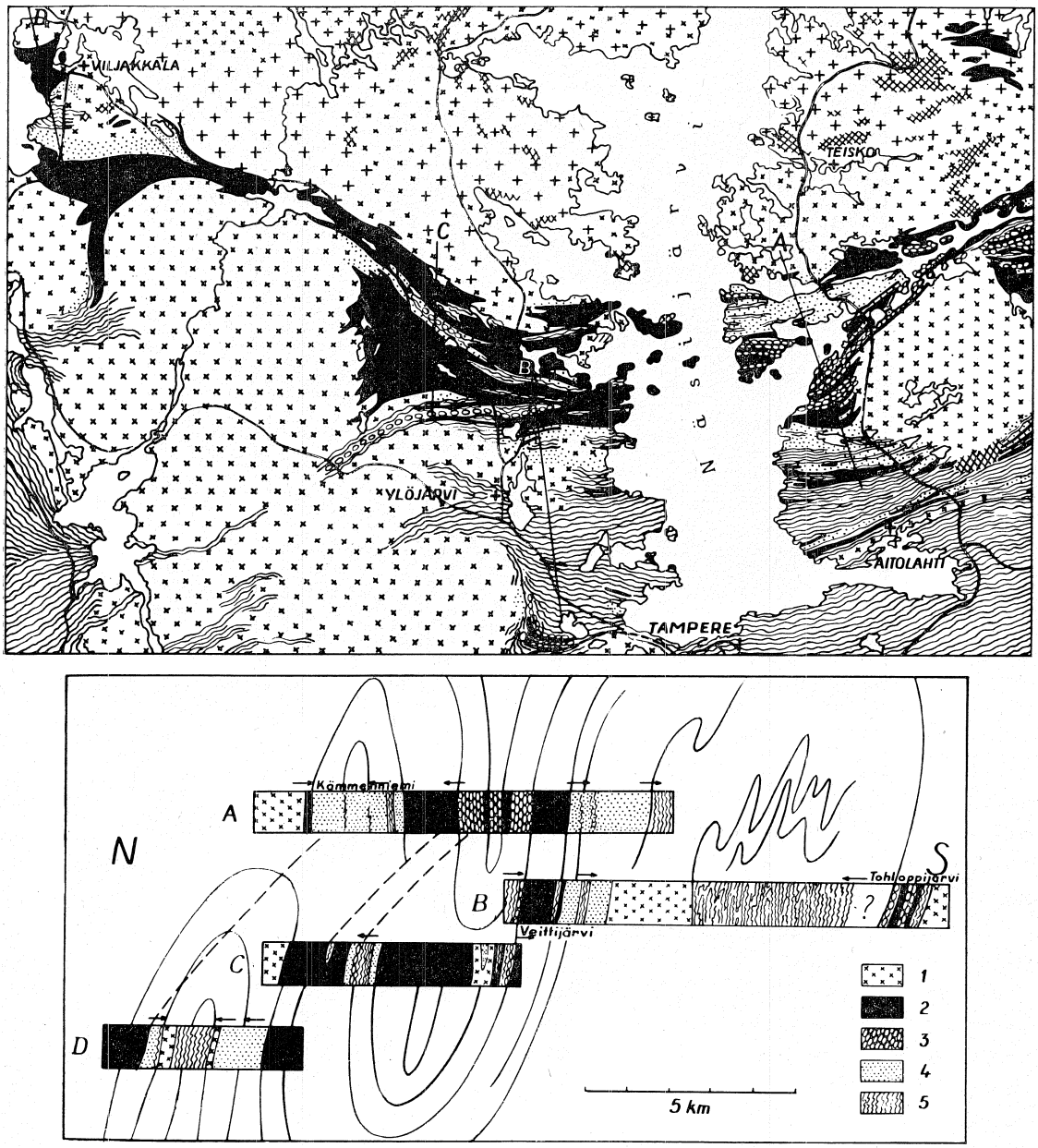

Fig. 17. The Tampere schist belt with vertical sections. 1, plutonic rocks; 2, mafic metavolcanics; 3, conglomerates; 4, quartz-feldspar rocks; 5, graywacke-slates. Arrows show the direction of the base determined by graded bedding. After A. Simonen.

contain porphyroblasts of cordierite and andalusite and in some cases staurolite. The highest grade of metamorphism is represented by coarse-grained mica gneisses containing almandine, cordierite and sillimanite.

The mafic metavolcanics usually show the mineral association hornblende-plagioclase, which indicates the conditions of the amphibolite facies. In certain narrow zones, owing to retrogressive metamorphism, the mineral associations

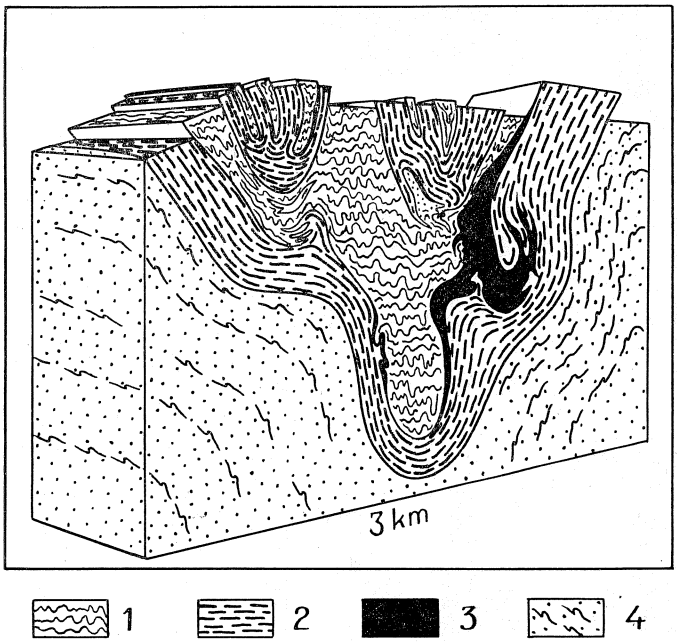

Fig. 18. Cross section of the Parainen (Pargas) basin, southwestern Finland. 1, garnet-bearing mica gneiss; 2, amphibolite; 3, limestone; 4, migmatite granite with remnants of garnet-bearing mica gneiss. After A. Metzger.

of the amphibolite facies were altered into those of the epidote-amphibolite and greenschist facies. The associations produced have not attained complete equilibrium, but many unstable relics of higher-grade regional metamorphism are common.

The charnockitic rocks of the granulite facies occur in the West Uusimaa complex, southern Finland, where the association hypersthene-diopside is typical. In the mica gneisses of this area, garnet and potassium feldspar occur together with cordierite.

The general strike of the Svecofennidic belt is quite variable. Rectilinear schistosity is typical in the zones of abundant metavolcanics, but broad areas of the migmatitic mica gneisses show great local variations in the strike of the foliation. The dips of the schistosity and the foliation are usually vertical or steep. Gently dipping foliation occurs in the areas of migmatitic gneisses, where the trends of the schist zones are markedly curved. The attitude of the schistosity and foliation is usually parallel to that of the bedding. A schistosity transverse to the bedding schistosity occurs only sproradically as a fracture cleavage and as axial plane schistosity. Furthermore, foliation caused by faulting occurs along the numerous fault zones of different ages.

The Svecofennidic schists are conspicuously folded. The fold axes of the main folding are gentle or subhorizontal. The axial planes are steep or vertical. The synclines and anticlines have often been tilted into steep isoclines. The type of folding varies with the plasticity of the folded material. The micaceous schists have been deformed into small folds, whereas the more competent beds of the metavolcanics may form wide synclines. Sections through the Svecofennides, showing some examples of the folding, are presented in Figs. 17—18.

The direction of the lineation, appearing as an elongation of the minerals and the mineral aggregates, or as crenulation and small folds, varies greatly in relation to the subhorizontal tectonic b-axis of the major folds. In the areas of abundant competent beds of metavolcanics, the linear structures observed on the nearly vertical bedding planes are generally quite steep and run in the direction of the tectonic transport, perpendicular to the subhorizontal b-axis of the main folding. Moderate and gently dipping lineations are typical features in the areas of silicic schists and mica gneisses and they often show parallelism with the fold axis. The updoming of the migmatite granite bodies of the migmatite terrains has caused many complications in the directions of the lineations, and faults of different ages have caused lineations showing varying directions.

An interpretation of the stratigraphical sequence of the intensely folded and migmatitic Svecofennidic schist belt has been possible only in certain key areas, where the structures are simple or the relics of the sedimentary or volcanic structures are so well preserved as to allow the sequence of layered rocks to be determined, although the beds have been folded to a vertical position.

In many Svecofennidic schist zones, thick accumulations of immature metasediments underlie the mafic metavolcanics, which in some areas are overlain by micaceous schists. The Svecofennian strata have been tentatively divided into Lower, Middle and Upper Svecofennian subgroups as follows:

Upper Svecofennian:	argillaceous sediments
Middle Svecofennian:	mafic volcanics (lavas and pyroclastics) with intercalated sediments (arkoses, graywackes and conglomerates)
Lower Svecofennian:	immature sediments (arkoses and graywackes) with thin interbeds of calcareous material and mature sandstones in the arkoses of some areas.

The sequence of the Tampere schist zone, which has been a key area in working out the stratigraphy, is from the highest stratigraphical unit to the lowest as follows:

	Thickness in meters
mafic volcanics	> 1 000
conglomerates and associated beds of graywacke slates and arkoses	700— 800
mafic and intermediate volcanics	800—1 500
quartz-feldspar rocks (arkoses, graywackes and pyroclastics)	1 500—2 200
graywacke slates	> 3 000

This sequence includes the Lower and Middle Svecofennian subgroups. The total thickness of the strata, which are related to the graywacke-basalt association of eugeosynclinal deposits, is at least 8 kilometers.

Taken as a whole, the Svecofennidic schists were originally products of a geosynclinal sedimentation. The micaceous schists show compositional and structural characteristics similar to the graywackes of the orogenic belts. The quartz-feldspar schists have been interpreted mainly to be impure arkoses. The mafic metavolcanics represent geosynclinal volcanism and their intimate association with immature sediments shows the eugeosynclinal character of the Svecofennidic schist belt.

The data illustrating the age of the Svecofennian sedimentation are very scanty. The age of detrital zircon from the metagraywacke in the Tampere field is ∽ 2 400 Ma, indicating the minimum age of the pre-existing source area. On the other hand, the intraformational conglomerates of the Tampere field contain some pebbles of plutonic rocks, whose zircon is only ∽ 1 900 Ma or highly similar to that of the granitoids (∽ 1 880 Ma) penetrating the schists.

It is only possible to state tentatively that the Svecofennian sedimentation took place about 2 400—1 900 Ma ago. Presumably, however, the geosynclinal deposition happened for the most part immediately before the climax of the orogenic movements, which were marked by intrusions of synorogenic granitoids with an age of ∽ 1 900 Ma. The Svecofennian geosynclinal volcanism has been dated using the zircon fractions of intermediate and silicic metavolcanics. The ages range between the limits 1 920—1 880 Ma. It is particularly noteworthy that the Svecofennian geosynclinal volcanism is younger than the Jatulian volcanism (2 200—2 000 Ma) and only slightly older than the synorogenic plutonism of the Svecokarelides (1 880 Ma).

Plutonic rocks of the Svecokarelides

Abundant plutonism, characterized especially by the emplacement of the granitoid rocks, is a typical feature of the Svecokarelidic orogeny. The plutonic rocks occupy about 40 % of the Karelidic folded area and about 80 % of the Svecofennidic area. The abundance of the different plutonic rock types in the Karelidic (1) and Svecofennidic (2) folded areas is as follows:

	1	2
ultramafic and gabbro	3.3 %	5.9 %
quartz diorite and granodiorite	23.6 %	56.5 %
granite	73.1 %	37.6 %

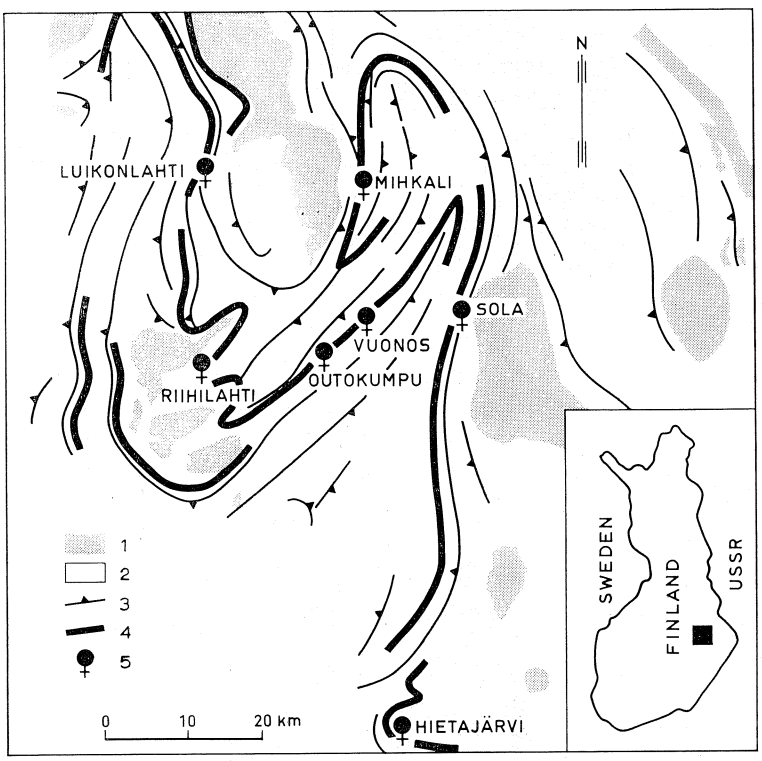

Fig. 19. The zones of the ultramafics in the Outokumpu field, North Karelia. 1, Presvecokarelidic rocks; 2, Karelidic rocks; 3, bedding; 4, zone of ultramafics (Outokumpu zone); 5, sulphide ores. After A. Huhma and E. Peltola.

The occurrence of ultramafic small bodies, metamorphosed and metasomatically altered into serpentinites, talc-magnesite rocks and chlorite-, anthophyllite- or asbest-bearing rocks, is a characteristic feature of the Kalevian group of the Karelidic schist belt. These ultramafics occur as lenticular bodies forming discontinuous zones as interbeds in the Karelidic micaceous schists (Fig. 19). They are mainly antigorite- and chrysotile-bearing serpentinites. Relics of olivine indicate that the original rock was a dunite. A characteristic feature of these ultramafics is the complete absence of more silicic differentiates.

Ultramafics of the Svecokarelides, associated with silicic differentiates, are represented by small bodies of peridotites or hornblendites. Peridotites usually contain serpentinized olivine, diopsidic pyroxene and hornblende. These ultramafics occur commonly in connection with gabbro bodies and pass gradually into the more silicic rock types. Most of the gabbros contain hornblende and relics of diopsidic pyroxene surrounded by hornblende have only occasionally been found. Noritic gabbros, containing both rhombic and monoclinic pyroxene, occur in association with pyroxene-bearing silicic differentiates. The main salic mineral of the gabbros is a plagioclase that shows zoning with a more anorthitic core. Anorthosites and anorthositic gabbros are rare. A striking feature of the gabbros, with a color-index of 30—50, is that they contain small amounts, 10—15 %, of free quartz. These quartz gabbros are quite common among the Svecokarelidic gabbroidic rocks.

The majority of the Svecofennidic plutonic rocks are represented by different kinds of granitoid rocks whose color-index is < 30. These rocks are commonly quartz dioritic, granodioritic or granitic in chemical composition. The plutonic rocks are calcic or calc-alkalic, and detailed petrographic study has shown that they form different plutonic provinces with their own mineralogical and chemical characteristics. In the Svecofennidic area, the plutonic rocks of which are studied in more detail, the petrographic provinces have been named according to the most acid end members as follows:

granodiorite province,
trondhjemite province,
charnockite province,
granite province, and
microcline granites.

Granites are abundant among the plutonic rocks of the Karelidic belt. Some of these are the most silicic members of continuous rock series containing mafic and intermediate rock types. These rocks show similarities to the plutonic rocks of the granite province. Some of the granites are migmatite-forming and related to the microcline granites.

Variations in the mineralogical composition of different plutonic rock provinces are given in Fig. 20. To the separate provinces, excepting the microcline granites, belong mafic, intermediate, and silicic plutonic rocks, which form continuous rock series suggesting magmatic differentiation. Furthermore, reaction series of the mafic and salic minerals of the provinces indicate magmatic evolution. The most silicic end members of the granodiorite, trondhjemite and charnockite provinces are characterized by a preponderance of plagioclase over potassium feldspar, whereas real granites ($Or > Ab + An$) are present only in the granite province and among the migmatite-forming microcline granites.

The provinces characterized by plagioclase-rich silicic end members differ from each other mainly in respect to the different reaction types of mafic minerals. A meta-aluminous association (hornblende and biotite) is characteristic of most of the silicic members of the granodiorite province, a peraluminous reaction type (biotite) of the trondhjemite province, and a subaluminous reaction type (pyroxene) of the charnockite province. Differences in the mineralogical com-

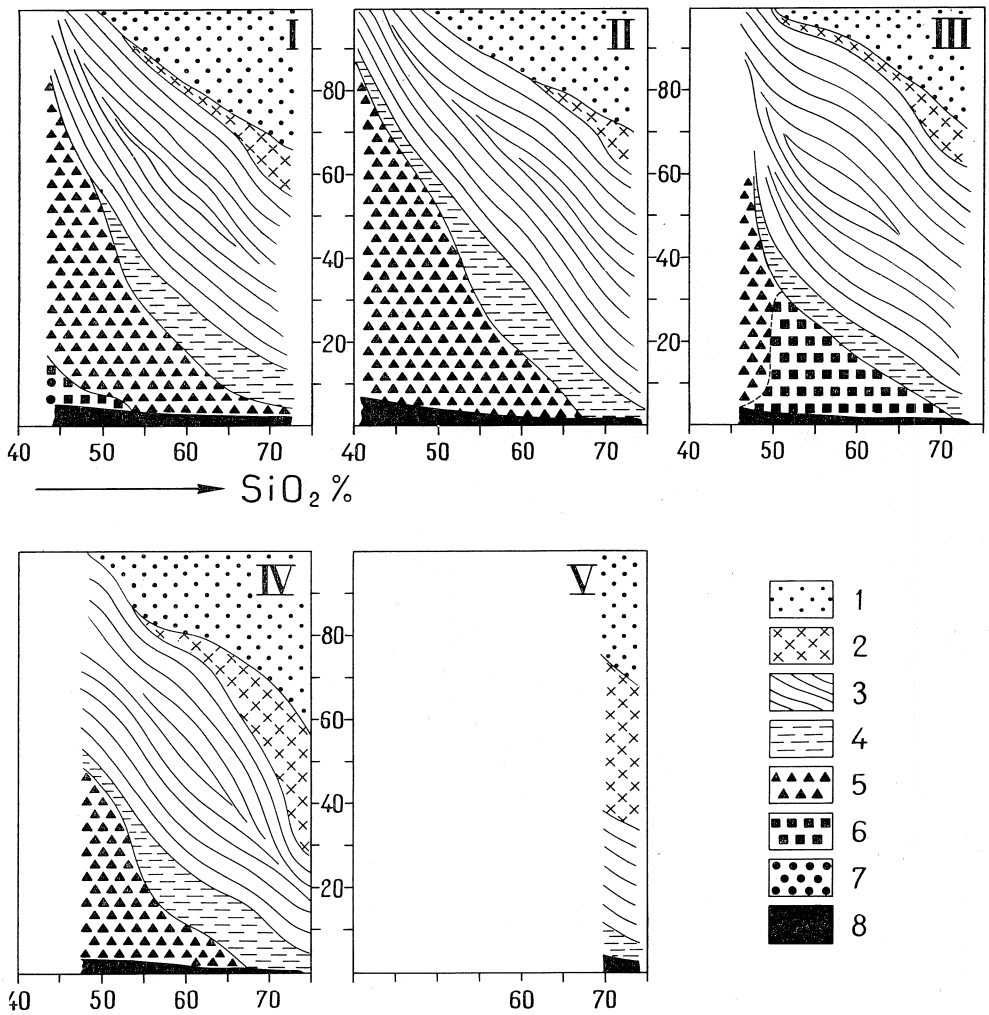

Fig. 20. Mineralogical composition of the plutonic rock provinces. I, granodiorite province; II, trondhjemite province; III, charnockite province; IV, granite province; V, microcline granites. 1, quartz; 2, microcline; 3, plagioclase; 4, biotite; 5, hornblende; 6, pyroxene; 7, olivine; 8, accessories. After A. Simonen.

position of the provinces mentioned are most apparent in silicic end members, whereas the mafic rocks of different provinces are mineralogically closely related.

In addition to the mineralogical differences between the plutonic provinces there are also chemical differences, which appear especially in the content of CaO, Na_2O and K_2O. The rocks of the granodiorite province contain more lime than the corresponding rocks of the other provinces, the trondhjemites are characterized by a high content of soda; and a high content of potassium is typical both of the granite province and of the microcline granites.

The chemical characteristics of the plutonic provinces are given by normative proportions Or : Ab : An (Fig. 21) and Q : Ab : Or (Fig. 22). The fields of the trondhjemite and charnockite provinces have the same position, and

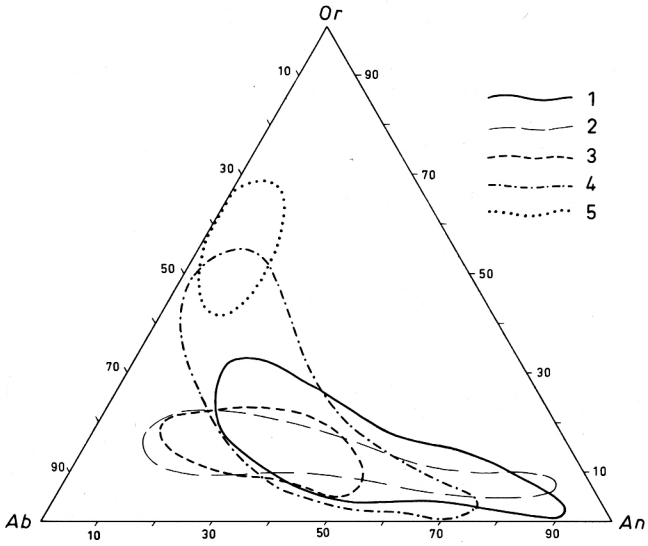

Fig. 21. Normative proportions Or : Ab : An of the plutonic provinces. 1, granodiorite province; 2, trondhjemite province; 3, charnockite province; 4, granite province; 5, microcline granite. After A. Simonen.

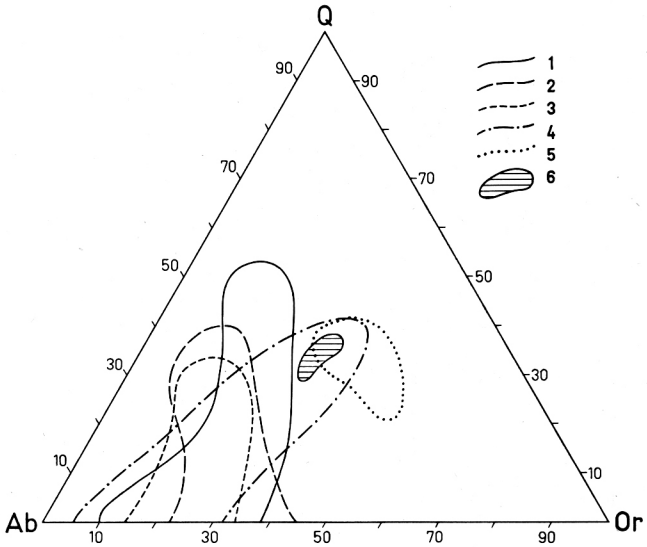

Fig. 22. Normative proportions Q : Ab : Or of the plutonic provinces. 1, granodiorite province; 2, trondhjemite province; 3, charnockite province; 4, granite province; 5, microcline granite; 6, »eutectoid» granite field. After A. Simonen.

they deviate distinctly, especially by having a high content of Ab, from the other provinces. The granodiorite, trondhjemite and charnockite provinces do not continue into the »granite field». The most silicic members of the granite province show a eutectoid granite composition, whereas the microcline granites are characterized by a higher content of Or than the granites of the granite province.

Chemical differences between the plutonic provinces are shown also by the alkali-lime index (Fig. 23). The granodiorite province is the most calcic with an index of 62, the trondhjemite and charnockite provinces have an index of 60—61, whereas the granite province is calc-alkalic, with an index of 59.

The magmatic origin of plutonic rocks belonging to provinces with a gradual transition

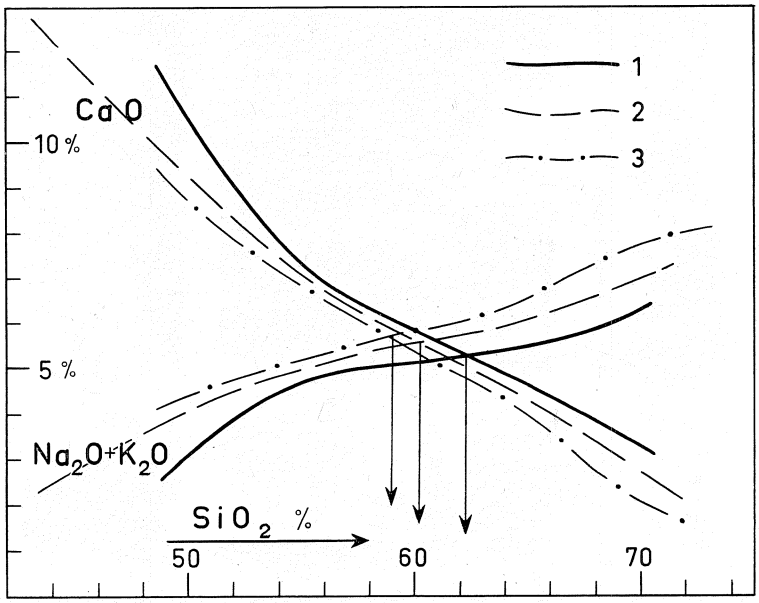

Fig. 23. Alkali-lime index of the plutonic provinces. 1, granodiorite province; 2, trondhjemite province; 3, granite province. After A. Simonen.

from mafic into silicic members has been pointed out by various authors. The chemical characteristics of the plutonic provinces indicate slight regional differences in the composition of the parent magma. The primary compositional differences, appearing especially in the content of CaO, Na_2O and K_2O, have been the principal factors producing different petrographic provinces. The main factor controlling the different paths of evolution of the trondhjemite and charnockite provinces, which are chemically closely related, has been the different contents of volatile substances in the parent magma. The trondhjemites have been differentiated from a parent magma rich in water, whereas the charnockites have been crystallized from a dry magma. The preponderance of silicic plutonic rocks over gabbros suggests that the parent magma had not been basaltic, but more acid, probably quartz dioritic or granodioritic in composition. Great quantities of acid, anatectic magma may have originated in the root zone of the ancient mountain chain.

The migmatite-forming microcline granites have a unique position among the Svecokarelidic plutonic rocks. These granites do not belong to any of the other plutonic provinces as a silicic end member, because a marked break occurs between them and the other provinces. These granites are not genetically associated with mafic and intermediate rock types, but on the contrary they show much evidence of metasomatic granitization. The granitization of all kinds of primary material (schists and plutonic rocks) tends toward a granitic composition of the microcline granite, which does not correspond to a »eutectoid» granite composition of magmatic evolution. The granite formed by granitization usually contains ghost-like, nebulitic remnants of the pre-existing rocks. The relic stratigraphy and structures of many microcline granite bodies indicate that in the place of the present granite there had been older solid rocks, and the granite body has been emplaced by metasomatic processes.

A characteristic feature of many Svecokarelidic areas, especially in southern Finland and around the wide granite massif of Central Lapland, is an abundance of mixed rocks or

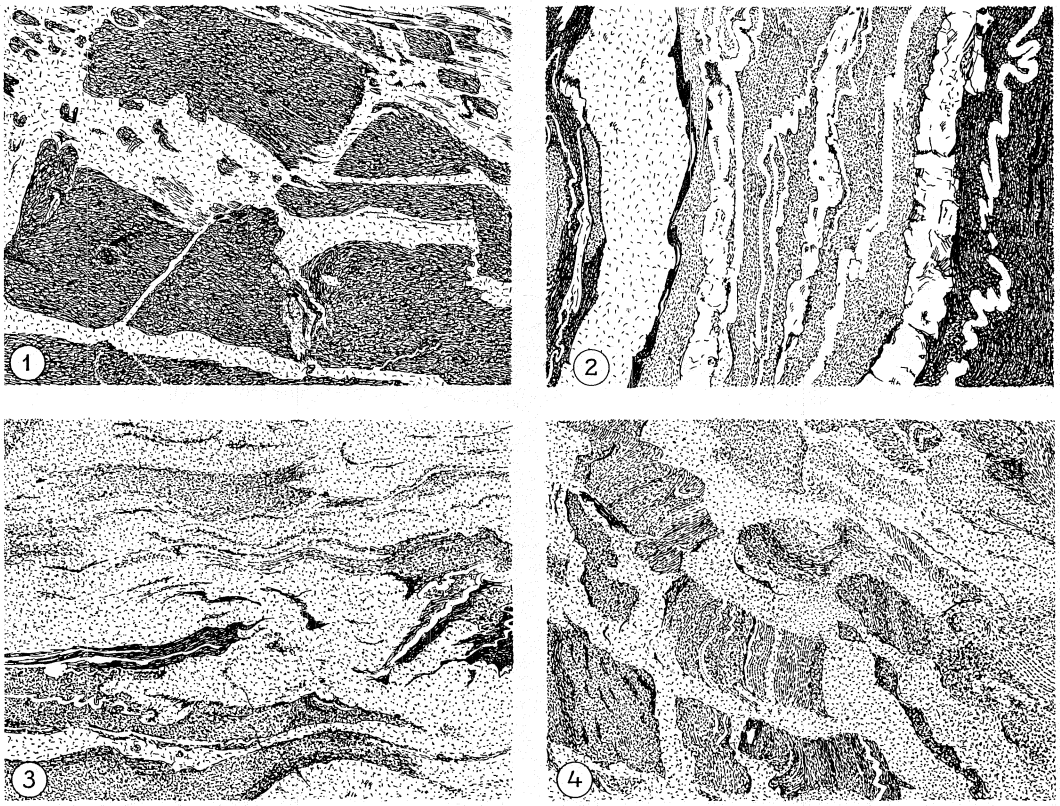

Fig. 24. Some structures of the Svecokarelidic migmatites. 1, agmatite; 2, veined gneiss; 3, nebulite; 4, polymigmatite. Drawn by Toini Mikkola.

migmatites with two components of different character. The older component is a metamorphic schist or a plutonic rock and the younger component is an igneous-looking granitoid rock, usually microcline-rich granite. The migmatite-forming microcline granites with associated pegmatites and aplites penetrate all the older rocks, forming a great variety of migmatites, some typical of which structures are given in Fig. 24.

Migmatization caused by the emplacement of microcline granite is closely connected with the metasomatic granitization of the host rocks, and gradual transitions between the different components of the migmatite are therefore common. Because of intense metasomatic granitization, the migmatites pass into nebulites, which are granites showing only a relic stratigraphy and structure of the primary host rocks of the migmatite granite. The large bodies of migmatite granites are the final products of migmatization and granitization. The origin of the large nebulitic granite masses signifies that great quantities of granite material had moved into a zone of regional migmatization and granitization. This material had probably been a granite melt, which caused the metasomatic granitization of the host rocks.

The emplacement of the Svecokarelidic plutonic rocks is closely connected with the orogenic, mountain building movements. The commonly used tectonic classification of the granitoid rocks has been developed on the basis of the relationship between the emplace-

ment of the plutons and the orogenic folding movements. The orogenic plutons, which are contemporaneous with the folding, are divided into two subgroups, synorogenic and late orogenic. Both synorogenic and late orogenic bodies were emplaced while the folding was still in progress, and in structure they are in harmony with the adjoining country rocks. In addition, there are some very few small massive postorogenic granitoid plutons, which belong, in space and time, to a period of the Svecokarelidic mountain folding.

The synorogenic plutonic rocks are mainly gneissose quartz diorites and granodiorites associated with minor bodies of mafic differentiates consisting of peridotites, gabbros and quartz gabbros. The plutonic rocks of the granodiorite, trondhjemite and charnockite provinces are typical representatives of the synorogenic group. Synorogenic plutons were emplaced during the main period of folding. The orogenic deformation and folding continued after the emplacement, causing the remarkable gneissose texture of the synorogenic plutonic rocks. Gneissose

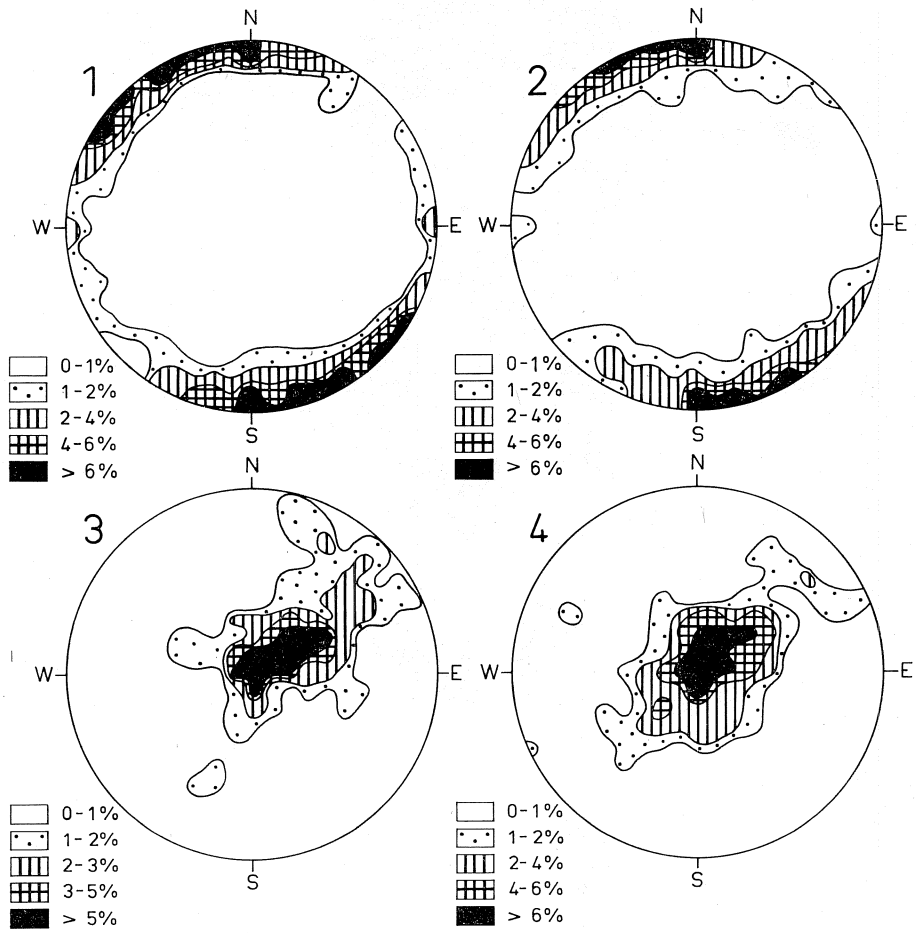

Fig. 25. Structural diagrams of synorogenic plutonic rocks and schists in the Svecofennidic schist belt of the Tammela-Kalvola area, southern Finland. Foliation, schistosity, and lineation plotted on the Schmidt net, lower hemisphere: 1, foliation of plutonic rocks (430 samples); 2, schistosity of schists (625 samples); 3, lineation of plutonic rocks (173 samples); 4, lineation of schists (221 samples). After A. Simonen.

varieties are especially abundant at the margins of the plutons. The synorogenic rocks form elongated and ovoidal masses, concordant with the adjoining country rocks. They have steep side walls, and their structures (foliation and lineation) coincide quite closely with those of the surrounding schists, as is shown in the structural diagrams of a Svecokarelidic folded area presented in Fig. 25. The emplacement of the synorogenic plutonic rocks indicates the climax of the Svecokarelidic orogeny, for the regional metamorphism and deformation took place in close connection with their emplacement. The synorogenic plutonic bodies were emplaced as lenticular masses, in particular along the bedding and foliation planes in the anticlines of the folded belt, and their emplacement tilted the gentle synclines and anticlines into steep isoclinales.

The late orogenic plutonic rocks are granites, which are more massive than the synorogenic gneissose rock types. The migmatite-forming

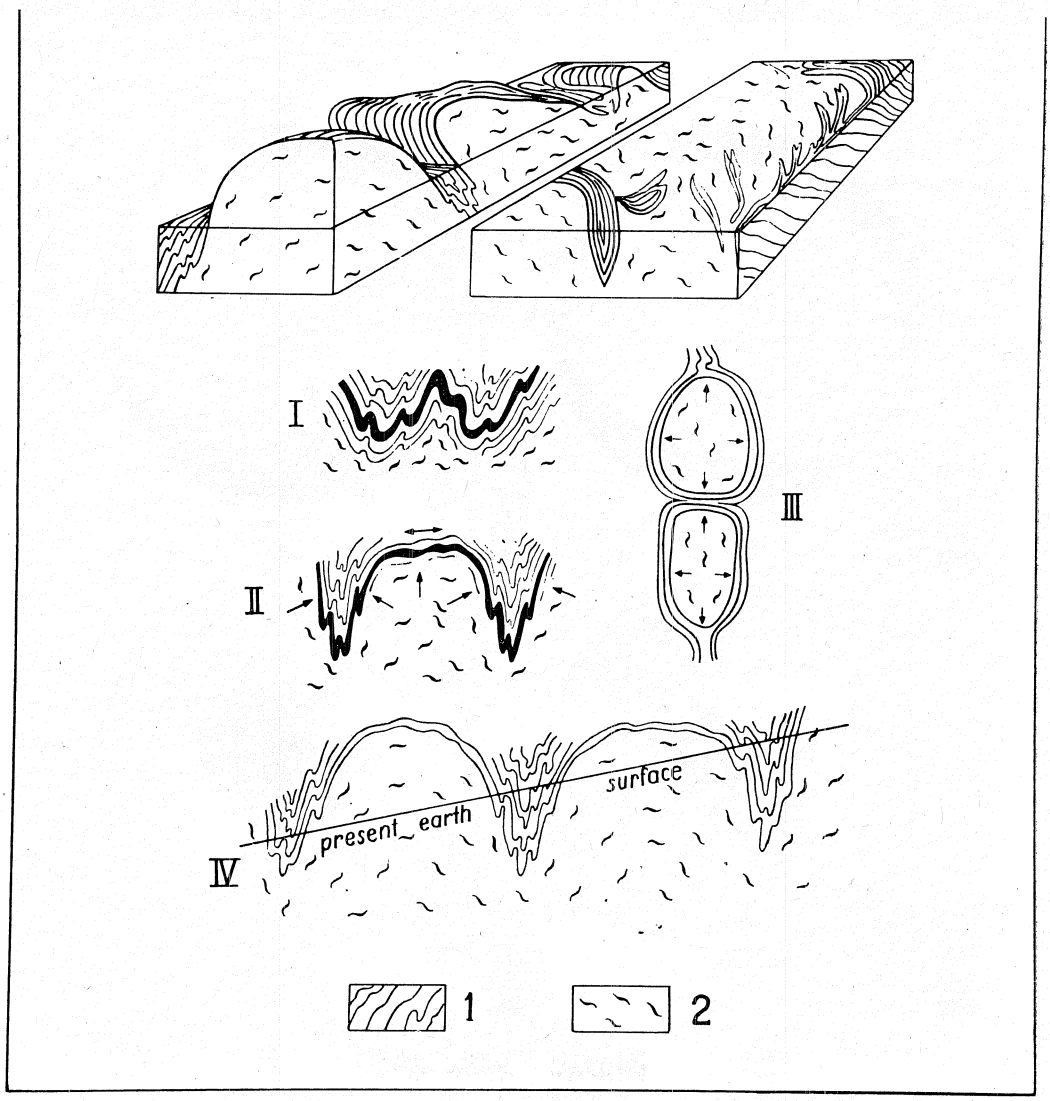

Fig. 26. Stereogram of a dome and sketches showing evolution of migmatite granite domes. 1, gneisses; 2, migmatite granites. After N. Edelman.

microcline granites are typical representatives of the late orogenic group. In addition, the most silicic members of the granite province are massive rocks of a late orogenic type. The emplacement of the late orogenic bodies affected the adjoining country rocks structurally in many ways, and the resultant structures are prominently superimposed on the older tectonics of the folded belt produced during the main period of folding. The structural elements of the late orogenic plutons and their schist aureoles deviate from those of the principal fold belt.

The late orogenic plutonic rocks occur as dome-like bodies or form migmatites with the schists and synorogenic plutonic rocks. The emplacement of the late orogenic granite domes is characterized by diapiric updoming, cross folding, highly plastic migmatite structures, and metasomatic granitization. The main phases of the structural evolution of the late orogenic migmatite granite domes in the Svecokarelidic fold belt in southwestern Finland are depicted in Fig. 26. Granitization, producing the migmatite granite, took place in the lowest levels of the gently folded belt (Fig. 26, I). Granite diapirs rose upward in anticlines. Gneiss synclines sank between the granite domes and were compressed into steep isoclinals. The gneisses situated on the tops of the rising domes were stretched and flattened (Fig. 26, II). Compression between the rising domes, which were situated one after the other in the principal direction of the fold belt, caused cross folding (Fig. 26, III). The varying tectonic forms may have been caused by an oblique cut through the fold belt (Fig. 26, IV). A deeper level is marked by gneiss basins in the granite area, whereas an upper level is represented by granite domes surrounded by continuous gneiss belts. A tectonogram, showing old tectonics of the schist belt deformed by rising domes of migmatitic granite, is given in Fig. 27.

Small stocks of massive granitoids, which show no sign of orogenic movements in their structures, mark the youngest postorogenic intrusions of the Svecokarelides. The emplacement of the postorogenic bodies caused the gradual bending of the adjoining schists to follow the contacts of the rounded stocks. The

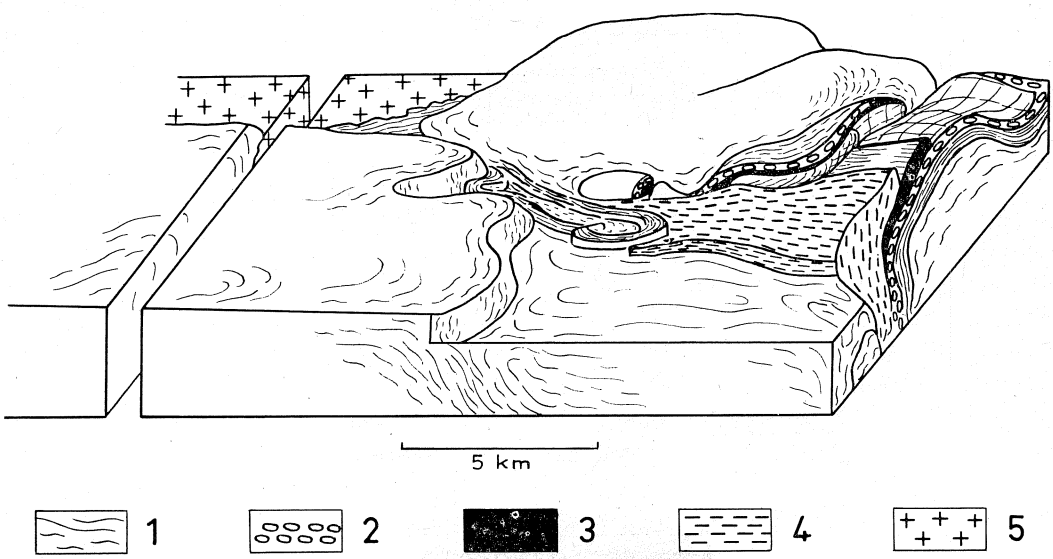

Fig. 27. Tectonogram of the surroundings of Helsinki. Old supracrustal tectonics deformed by rising domes of mobilized migmatitic material. 1, metasediments and their relics in migmatite granite; 2, metavolcanics; 3, gneissose granite; 4, migmatite; 5, rapakivi-type granite. After E. H. Kranck.

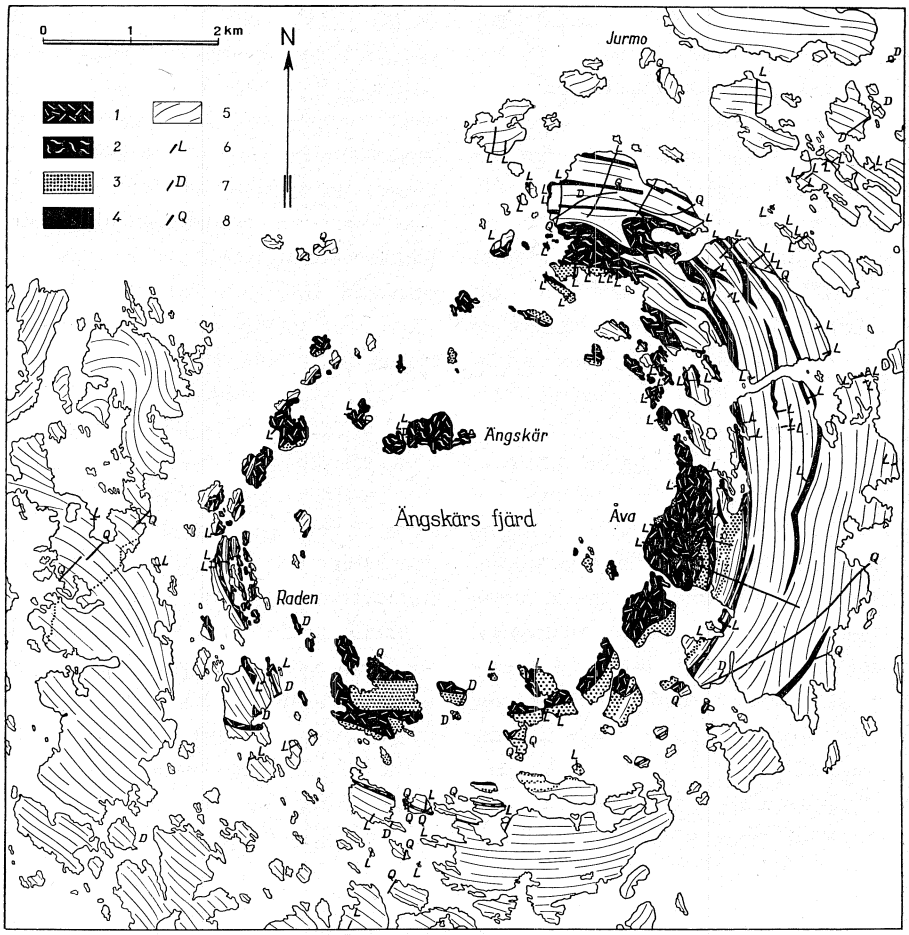

Fig. 28. Geological map of the Åva ring intrusion, Åland Islands, SW Finland. 1, porphyritic granite; 2, irregular dikes of porphyritic granite cutting the migmatite; 3, monzonite; 4, fine-grained granite; 5, migmatite; 6, lamprophyre dike; 7, diabase dike; 8, quartz porphyry dike. After S. Kaitaro.

geological map of the Åva granite in south-western Finland, which is associated with ring dikes, is reproduced as an example of the manner of occurrence of the postorogenic intrusions (Fig. 28).

The zircon ages of the Svecokarelidic synorogenic plutonic rocks are usually 1 880 ± 20 Ma. An age of slightly over 1 900 Ma has been determined for the trondhjemite. Some granitoids with a zircon age of ~ 1 900 Ma yield younger ages (~ 1 800 Ma) for sphene and monazite, indicating a late or postorogenic phase of metamorphic recrystallization of the Svecokarelides. The zircon ages of the post-orogenic stocks of the Svecokarelides found in different parts of the folded area are ~ 1 800 Ma.

Postsvecokarelian igneous and sedimentary rocks

The Svecokarelidic orogeny was followed by a long period of cratonization and erosion. The great geological events recorded from the time after the Svecokarelidic diastrophism were

platform-type intrusions of the rapakivi granites, gabbro-anorthosites and diabases of varying ages and the deposition of Jotnian sediments.

Rapakivi granites

The rapakivi plutons in southern Finland cut sharply all the structures of the metamorphic and migmatitic rock crust and they were not influenced by orogenic movements. The plutons are commonly seen to have sharp, outward-sloping contacts. Intrusive contacts with sharp-edged, mostly rotated fragments and many roof pendants of considerable size commonly occur in the rapakivi massifs.

The rapakivi granites (Fig. 29) are predominantly coarse-grained, porphyritic granites with large ovoids of orthoclase, many of which are surrounded by plagioclase mantles (wiborgite type). In some varieties, there is an almost total lack of plagioclase mantles around the potassium feldspar ovoids (pyterlite type). The ratio between the mantled and non-mantled ovoids varies greatly, and texturally there is a gradual transition from the wiborgite to the pyterlite. The porphyritic rapakivi granites with porphyritic, angular potash feldspar grains are likewise sporadically present and a gradual transition from this rock to the pyterlite is observed. The proportions of mantled and non-

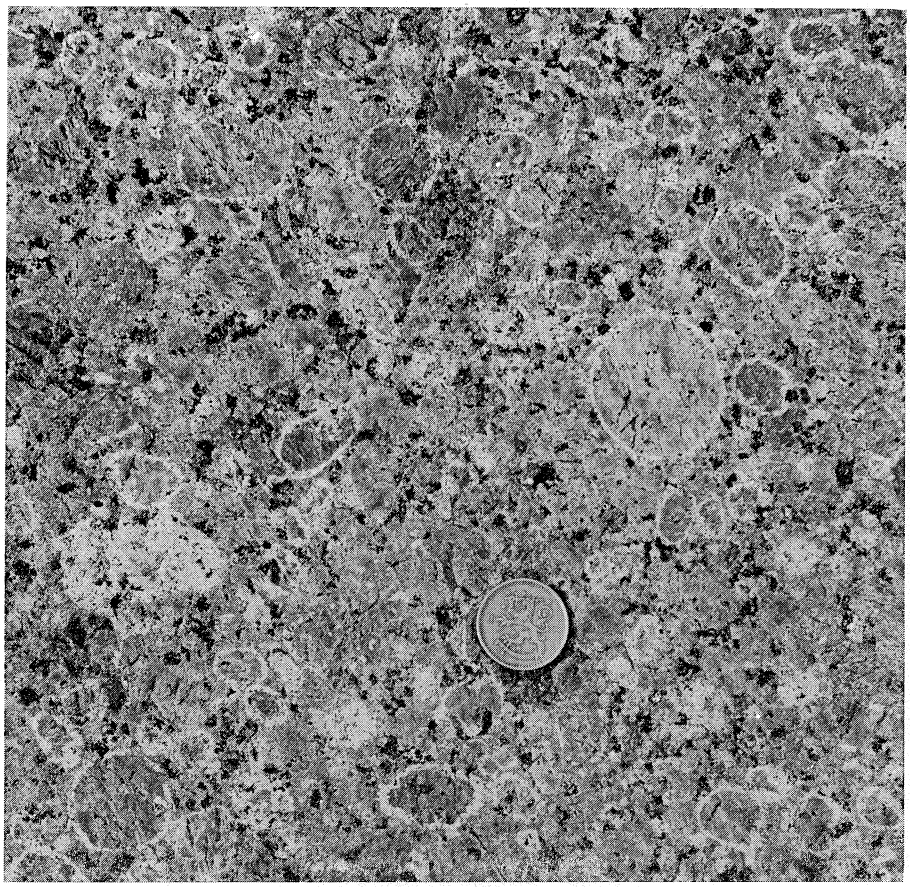

Fig. 29. Rapakivi, wiborgite, orthoclase ovoids surrounded by plagioclase mantles. Vehkalahti. 1/3 nat. size. Photo J. Sederholm.

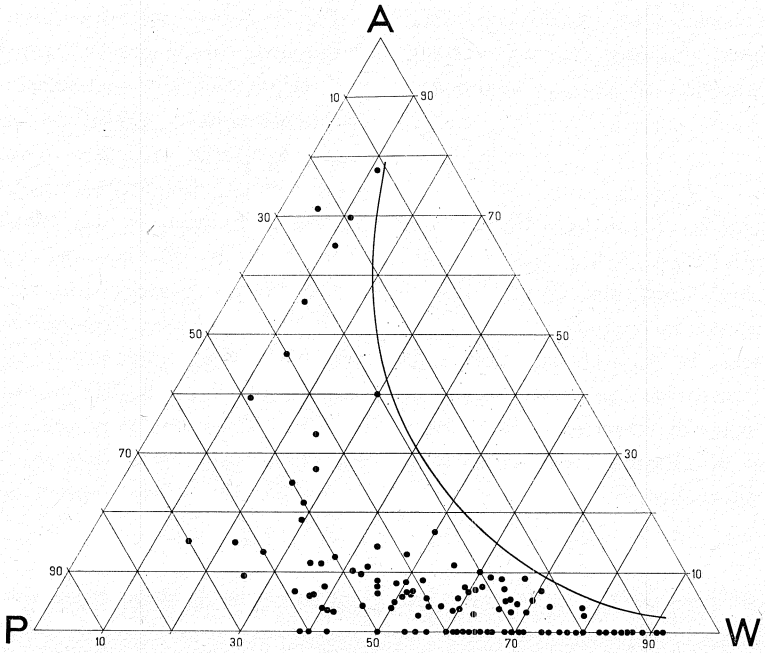

Fig. 30. Ratios between mantled, nonmantled and angular porphyritic potash feldspar grains in the rapakivi rock series, wiborgite-pyterlite-porphyritic rapakivi granite, in the Wiborg rapakivi massif. W, orthoclase ovoids mantled by plagioclase (wiborgite type); P, orthoclase ovoids without plagioclase mantle (pyterlite type); A, angular, porphyritic potassium feldspar grains (porphyritic rapakivi granite type). After A. Simonen and A. Vorma.

mantled and angular porphyritic potassium feldspar grains in the coarse-grained, porphyritic varieties (wiborgite-pyterlite-porphyritic rapakivi granites) of the rapakivi in the Wiborg massif are given in the triangular diagram (Fig. 30).

In addition to the foregoing porphyritic varieties, there are even-grained, granite porphyritic, quartz porphyritic, porphyry aplitic, aplitic and pegmatitic types of rapakivi. Furthermore, miarolitic cavities are typical. The areal distribution of the different varieties in the Finnish part of the Wiborg rapakivi massif is as follows:

wiborgite	76.2 %
dark-colored wiborgite	4.9 %
pyterlite	6.1 %
porphyritic rapakivi granite	1.2 %
dark-colored rapakivi granite	3.1 %
even-grained rapakivi granite	7.8 %
porphyry aplite	0.7 %
quartz porphyry and granite porphyry	< 0.1 %
aplite and pegmatite	< 0.1 %

The main salic minerals in all the rapakivi varieties are potassium feldspar (orthoclase), plagioclase (oligoclase) and quartz. Only slight deviations occur in their relative contents. The most remarkable deviations between the different rapakivi varieties appear in the mineral associations of the Fe-Mg-silicates. Hornblende and biotite are the most common mafic minerals contained in the rapakivi rocks. Some dark-colored, hornblende-bearing varieties contain fayalite and, as alteration products, iddingsite and grünerite. Fluorite, zircon and apatite are characteristic accessory minerals. In some gran-

itic varieties, topaz and anatase are sporadically present.

All the rapakivi varieties are chemically characterized by high contents of silica and potassium, whereas the contents of lime and magnesia are low. The different rapakivi varieties show only slight variation in their chemical composition. In the Wiborg massif, the dark-colored wiborgite and dark-colored even-grained granite contain less silica and more FeO, MgO and CaO than the other rapakivi varieties. Furthermore, the contents of FeO, MgO and CaO in wiborgite are higher than those in pyterlite. Pyterlite, porphyritic rapakivi granite, even-grained rapakivi granite, porphyry aplite and quartz porphyry are chemically closely related. Small differences in chemical composition between rapakivi rocks of different massifs have also been observed.

The best evidence of the magmatic origin of the rapakivi is proved by the sharp intrusive contacts and effusive types (quartz porphyries and granite porphyries) associated with the rapakivi granites. The emplacement of the rapakivi magma produced thermometamorphic aureoles around the massifs. Mineral assemblages of the pyroxene-hornfels facies have been found in the xenoliths and country rocks along the innermost contact zones of the rapakivi massifs. Furthermore, the original microcline of the country rocks (primarily metamorphosed under the low-pressure conditions of amphibolite facies) was transformed around the rapakivi massifs into orthoclase owing to heat generated by rapakivi. The orthoclase aureole around the big massif may be up to 5 kilometers broad, but around small massifs it is much narrower. The emplacement temperature of the rapakivi magma has been estimated to exceed 800 °C.

The rapakivi magmas may have originated by ultrametamorphism during the culmination of the Svecokarelidic orogeny in the lower crust and remained in a liquid state for long periods of time, capsuled in their deep-seated reservoirs. The diapiric rise of the anatectic magma into the upper crust took place after orogenic folding in connection with epeirogenic movements characterized by fracturing and vertical block movements. The emplacement of the rapakivi magma took place into the deeply denuded roots of the cratonized, Svecokarelidic folded belt. The rapakivi massifs, connected with effusive counterparts, represent typical disharmonious or epizonal granites.

The many rapakivi intrusions are closely associated with mafic magmatites (basaltic lava flows, diabases, anorthosites), which indicate the deep-seated origin of the magmas. It is probable, that both juvenile melts and anatectic magmas took part in the lively Postsvecokarelian magmatism in southern Finland.

The age determinations by the U-Pb method on zircons show that the crystallization of the rapakivi granites occurred 1 700—1 540 Ma ago. The ages of the different massifs vary and, furthermore, in some massifs there are many magmatic phases of different ages. The oldest phases of the rapakivi granites have been recorded from the Wiborg and Åland massifs, the ages of which are 1 700—1 640 Ma and 1 670 $\pm$ 20 Ma, respectively. Three major magmatic phases, 1 700—1 660 Ma, 1 660—1 640 Ma and 1 640 $\pm$ 15 Ma, have been tentatively reported from the Wiborg massif. The most probable ages of the Vehmaa and Laitila massifs are 1 590 Ma and 1 570 Ma, but the youngest intrusive phase in these massifs occurred only 1 530—1 540 Ma ago.

Mafic igneous rocks

A common occurrence was the intrusion of mafic igneous rocks, mainly diabases and gabbro-anorthosites, into the craton stabilized after the Svecokarelidic orogeny. These mafic rocks are closely associated with either rapakivi intrusions or grabens of the Jotnian sediments. Some of the mafites are only slightly older than the rapakivi rocks, whereas some of them

are younger than the Jotnian sediments. Small masses of anorthositic gabbros and anorthosites occur in connection within many rapakivi plutons. The largest is the horseshoe-shaped gabbro-anorthosite complex around the Ahvenisto rapakivi massif. The gabbro-anorthosites are coarse-grained and their main minerals are plagioclase (An_{48-58}), orthopyroxene, amphiboles and biotite. Small bodies of anorthosites are present, composed of plagioclase (An_{53-58}) with a mafic mineral content of less than 10 per cent. Furthermore, in the middle of the gabbro-anorthosite intrusions there occur pegmatoidic bodies consisting mainly of plagioclase and hypersthene crystals up to one meter in length. The age of the gabbro-anorthosite around the Ahvenisto rapakivi massif is ~ 1 680 Ma, or only slightly older than the rapakivi, which penetrates the mafic rocks.

In southern Finland there occurs a diabase dike set about 150 km long, the main trend of the vertical or steeply dipping dikes is N 60 °W. The easternmost continuation of the dike set is situated in southeastern Finland on the northern border of the rapakivi massifs, and the diabases are penetrated by rapakivi. The deep faults and the opening of the fractures controlling the diabase intrusions were probably caused by the upward movement of the rapakivi magma. The diabases cut the metamorphic and migmatitic rocks, and they show chilled contacts against the wall rocks. Their main minerals are plagioclase, clinopyroxene and olivine. Many of the diabase occurrences contain autoliths and plagioclase megacrysts. Moreover, quartzite xenoliths are characteristics of many of the diabase dikes. Rheomorphic dikes, produced by the heat of intruded diabase magma from different rocks of the metamorphic complex, are common. The diabase dikes are only slightly older than the oldest intrusions of the rapakivi magmas.

It is noteworthy that the intrusions of the magma, which formed the foregoing gabbro-anorthosites and diabases, also reached the ancient surface and produced subvolcanic and volcanic rocks. At the southern margin of the Wiborg rapakivi massif, on the island of Hogland in the Gulf of Finland, composite lava flows, consisting of porphyrites and quartz porphyries comagmatic with the rapakivi, overlie the Svecokarelidic rocks. Further, the study of roof pendants in the Wiborg rapakivi massif has shown that the roof consisted partly of Svecokarelidic rocks and partly of Postsvecokarelian mafic and silicic volcanic rocks. The mafic volcanics are diabases and lava flows of plagioclase porphyrites and they are older than silicic porphyries interpreted partly as ignimbrite eruptions. The porphyries caused hybridization of the diabase, and the rocks of the roof pendants were metamorphosed thermally by the rapakivi granite. The zircon age of the diabase in the roof pendant, is ~ 1 690 Ma and that of the porphyry ~ 1 685 Ma.

The foregoing mafic igneous rocks (gabbro-anorthosites, diabases and lava flows) mark the emplacement of the basaltic magma into different levels of the crust. The field relationships and age data indicate that these mafic igneous rocks are only slightly older than the oldest intrusions and extrusions of the rapakivi magma. The close association of the mafic igneous rocks and rapakivi granites has been pointed out by many Nordic geologists, and these rocks have been usually named »Subjotnian» in the age classification of the Precambrian in Fennoscandia.

Diabase dikes and sills younger than the Jotnian sediments occur abundantly in association with the Jotnian sandstone area of Satakunta and in the archipelago of southwestern and western Finland. They show both vertical and horizontal chilled contacts against country rocks consisting of the Svecofennidic rocks, rapakivi granites and Jotnian sandstones. Diabases represent hypabyssal eruption channels of basaltic magma intrusions into a stable platform characterized by faulting tectonics.

The main minerals of these Postjotnian diabases are plagioclase, augite and olivine. The chemical composition is basaltic, similar to that of plateau basalts.

Contact phenomena of the diabase, resulting in partial or almost complete melting of country rocks, are common. Partial melting of various silicic country rocks, located in the immediate vicinity of the diabase contact, produced an intergranular melt of eutectoid granite composition. This melt intruded from the host rock into the chilled contact zones of the diabase and resulted in the formation of »palingenic dikes», consisting mainly of quartz and alkali feldspar. The reactions between the anatectic granite melt and the solidified diabase caused hybridization of the original contact zones.

So far is known, the Postjotnian diabases in southwestern Finland represent the youngest Precambrian rocks in the country. These diabases give zircon and Rb-Sr ages ranging between the limits 1 250—1 275 Ma.

Jotnian sediments

A long period of denudation followed the intrusions of the rapakivi rocks, and the Jotnian sediments were deposited on the deeply eroded craton, especially in the grabens and depressions caused by vertical block movements. So far as is known, the Jotnian sediments represent the oldest unmetamorphic sedimentary cover of the Baltic Shield.

The Jotnian deposits of Finland occur in downfaulted blocks of the folded Precambrian complex in Satakunta and Muhos. The drillings show that the Muhos graben has been downfaulted about one kilometer and the Satakunta graben at least 650 meters. It is further noteworthy that Jotnian sediments occur abundantly at the bottom of the Gulf of Bothnia.

The Jotnian sediments of Satakunta consist of red-colored, stratified arkosic sandstones with thin intercalated beds of red or black shales. The mineralogical as well as chemical characteristics of the sandstone are typical of the red, immature sandstones of the arkose suite. The feldspar is predominantly potassium feldspar and it occupies 20—40 per cent of the total amount of sand particles, whose roundness and sorting are poor. The stratification of the sandstone is generally horizontal and many sedimentary structures indicating terrestrial conditions of deposition can be observed. Current bedding is common and ripple marks, made by water, are symmetric or asymmetric. Furthermore, mud cracks, clay galls, and rain drop impressions have been found.

The Jotnian sediments in the Muhos area begin with basal conglomerates and arkoses lying unconformably upon the metamorphic basement complex. The conglomerates contain rounded and angular pebbles of granite and schist and the matrix is brown-colored arkose rich in silty material. The red arkosic sandstone of Muhos is similar to the Satakunta arkose. The main part of the Muhos sediments, many hundred meters thick, consists of red, brown or greyish green siltstones and shales with thin interbeds of arkosic sandstone. The red and brown siltsones and shales are predominant, forming 80—90 per cent of the total thickness of the sequence.

The general characteristics and the red color of the afore-mentioned Jotnian sediments indicate an oxidizing condition of terrestrial sedimentation. The Jotnian deposits in the Satakunta and Muhos areas are related to floodplain deposits in the piedmont facies of postgeosynclinal basins.

The Jotnian shales were dated by K-Ar and Rb-Sr methods. The tentative age of the rocks is 1 300—1 400 Ma. Mention must be made of the fact that the Jotnian arkoses of Satakunta are penetrated by the diabases, whose age is ~ 1 270 Ma.

End of the Precambrian

Erosion after the deposition of the Jotnian sediments produced a peneplain upon which

the Cambrian transgression took place. Sporadic occurrences of Cambrian quartz sandstone and other Cambro-Silurian sediments have been found in southwestern Finland and along the rand zone of the Caledonidic mountain chain in the northwesternmost part of Finnish Lapland. However, most of these sediments were later removed by denudation. The Cambrian sandstone in southwestern Finland occurs commonly as sandstone dikes in Precambrian rocks or as fillings of solution cavities in Precambrian crystalline limestone. These remains of the Cambrian sandstone, spilled as sand from the surface to the fissure cracks and solution cavities, indicate that the ancient sub-Cambrian peneplain, on which these sandstones were deposited, has been situated slightly above the present surface. Therefore, the erosion of the Precambrian crust after Cambrian time was very slight. The sub-Cambrian peneplain is still seen as a tangential upper surface of the hills and this peneplained Precambrian surface dips gently under the sedimentary cover of the Russian platform.

CONCLUDING REMARKS ON THE EVOLUTION

The most important phases of the evolution of the Finnish Precambrian are summarized in the geological timetable presented in Fig. 31. Many geological events of different ages have been documented in the timetable, which also shows long periods lacking documents on the ancient history of the Earth.

The most important events in the geological evolution of Finland have been the revolutions producing the Presvecokarelidic and Svecokarelidic folded areas. These revolutions took place 2 800—2 600 Ma and 1 900—1 800 Ma ago, respectively, and most of the Finnish Precambrian rocks received their present appearance during these ancient events. The great revolutions connected with folding, plutonism and metamorphism lasted a relatively short time in the long Precambrian history. The time during which the endogenic processes had been in progress was suprisingly short and the rocks produced have slept a long time, like Sleeping Beauty.

The oldest Presvecokarelidic folded area (2 800—2 600 Ma) of the Finnish Precambrian is characterized by broad areas of granodioritic basement gneisses in eastern and northern Finland. True potassium-rich granites, which are usually common in the younger folded areas, do not occur abundantly. The Presvecokarelidic schist zones occur only as narrow, steep isoclinales between the blocks of basement gneisses and they contain a profusion of mafic and ultramafic metavolcanics. Abundant igneous activity in the earliest geological times may indicate that magma masses had existed at rather shallow depths beneath the crust. The metasediments are mainly micaceous schists, and graphite-bearing black schists occur as interbeds. Sedimentary limestones are lacking. Quartz-banded iron formations are characteristic and suggest an anoxygenous environment of ancient atmosphere. No valid evidence of the existence of relics of ancient organisms has been known. The characteristics of the Presvecokarelidic schists indicate conspicuous similarities to so-called Archean greenstone belts of the other continents.

The folded basement area stabilized about 2 600 Ma ago and the denudation started. An igneous activity in this stabilized craton took place about 2 400 Ma ago, and it is represented mainly by Presvecokarelian mafic intrusions, which form layered sheet- or lopolith-like bodies. The emplacement of the carbonatite complex of Siilinjärvi, which is one of the oldest carbonatite occurrence in the world, also took place into the stabilized basement 2 400—2 500 Ma ago.

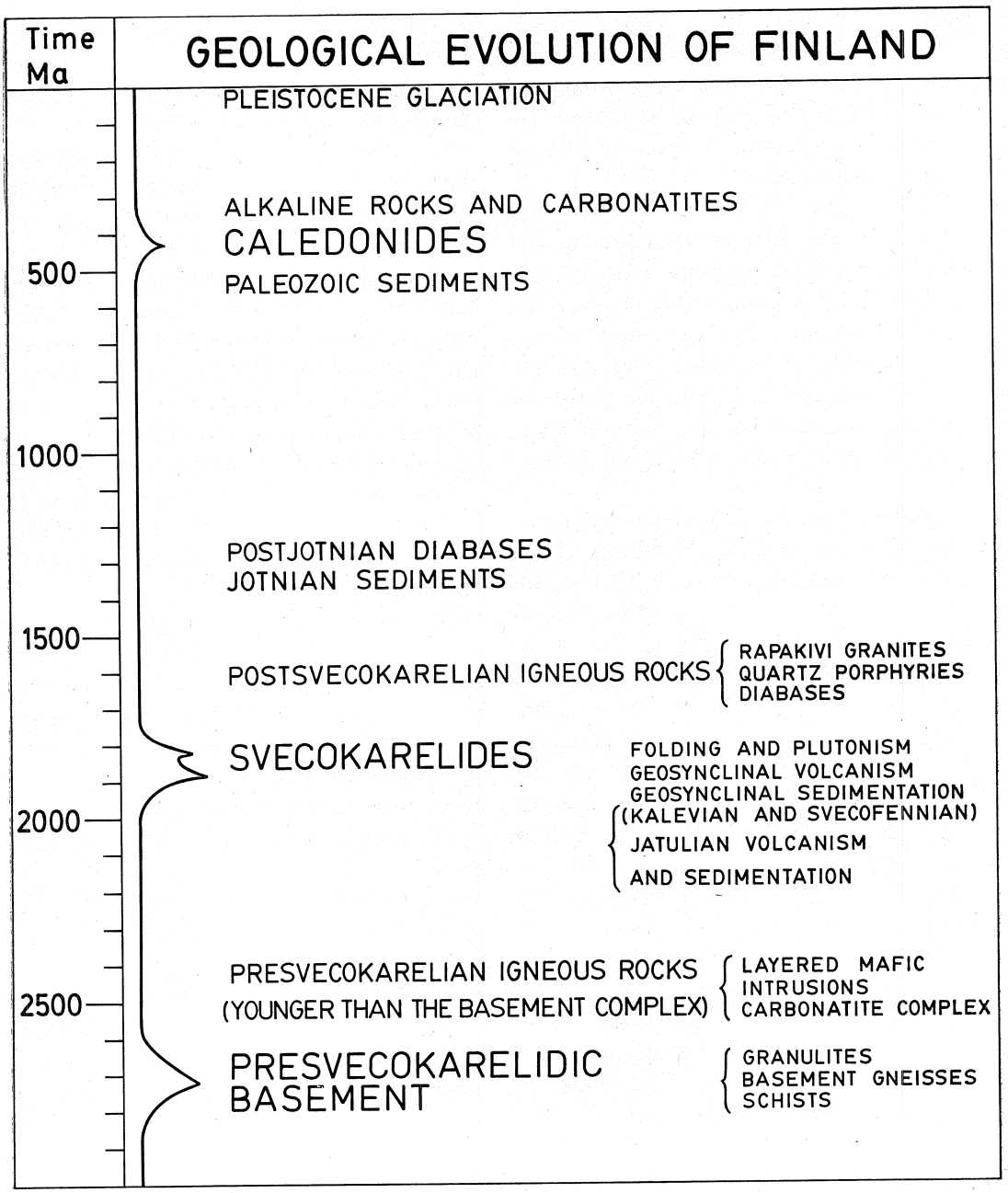

Fig. 31. Geological timetable of the Precambrian in Finland. Compiled by A. Simonen.

The Presvecokarelidic basement was deeply eroded and peneplained about 2 300 Ma ago, and forming the so-called Jatulian continent. Upon this continent and along its borders, the deposition of the Jatulian group (basal beds, quartzites, dolomites and sapropelic pelites) started some 2 300—2 200 Ma ago. The epicontinental, transgressive group of Jatulian

sediments is separated by a marked unconformity from the Presvecokarelidic basement and it is overlain by thick accumulations of Kalevian phyllites and mica schists, which are products of incomplete chemical weathering and show characteristics of geosynclinal sediments.

The time of the Jatulian sedimentation was associated with lively igneous activity, represented by mafic volcanics and diabases occurring as interbeds, sills and dikes in the Jatulian sequence. It is noteworthy that the Jatulian diabases penetrate both the Presvecokarelidic basement and the Jatulian sediments, but not the Kalevian rocks overlying the Jatulian group.

The pulses of the Jatulian magmatism range between the limits of 2 200—2 000 Ma, dated by the U-Pb method on zircons. The Pb-Pb age of the dolomite and the age (total lead of the whole rock, isochron) of the iron formation, both rocks belonging to the upper part of the Jatulian group, are ~ 2 050 Ma and ~ 2 080 Ma, respectively. On the basis of the ages mentioned, it is possible to conclude that the time of the Jatulian sedimentation continued over 200 Ma (~ 2 200—2 000 Ma ago). The Kalevian sediments, overlying the Jatulian, are younger than ~ 2 050 Ma, but older than the synorogenic Svecokarelidic plutonic rocks (~ 1 900 Ma) which penetrate them.

The geosynclinal basins developed to the west of the ancient Presvecokarelidic craton and thick accumulations of Svecofennian geosynclinal deposits took place. The immature sediments are mainly graywackes and arkoses. This sedimentation is closely associated with geosynclinal volcanism, showing a eugeosynclinal type of deposition. The Svecofennian geosynclinal sedimentation and volcanism took place immediately before and during the climax of the Svecokarelidic orogenic movements about 1 900 Ma ago. The age of the Svecofennian volcanism is 1 920—1 880 Ma and only slightly older than the synorogenic plutonism of the Svecokarelides marking the main revolutionary phase of the orogenic movements. The main phases of the evolution of the Svecofennides are summarized in Table 2.

The Karelian and Svecofennian rocks, which accumalated upon the Presvecokarelidic basement and in the geosynclinal basins, metamorphosed into crystalline schists during the Svecokarelidic folding, which took place about 1 900 Ma ago. In close connection with the orogenic movements, enormous masses of granitoids (1 900—1 800 Ma) emplaced into the schists. The duration of the whole Svecokarelidic orogenic cycle (from evolutionary sedimentation until the intrusion of the postorogenic granites) is about 500 million years in the interval ranging from 2 300 Ma to 1 800 Ma; but the duration of the revolutionary phase, connected with folding, metamorphism and intrusions of orogenic plutonic rocks, is only about 100 million years (1 900—1 800 Ma). Mention must be made of the fact that certain parts of the Presvecokarelidic basement (for example: the cores of the mantled gneiss domes and the granulite belt) participated in the Svecokarelidic movements, becoming rejuvenated and remobilized. It can be stated that the Finnish Precambrian gained its present appearance for the greatest part within the Svecokarelidic orogeny.

The metasediments and metavolcanics of the Svecokarelides are in many areas quite well-preserved and show, along with relics of primary structures and textures, many actualistic features. The fact should be noted that the research done on these rocks at the end of the 19th century proved, for the first time, the actualistic method to be the correct approach in the study of metamorphic Precambrian formations. Furthermore, the deposited rock sequences and their folded structures are commonly related to those of the younger orogenic belts. Owing to the deep erosion of a section of the Svecokarelides, the abundance of orogenic plutonic rocks is a special feature, indicating that the

Table 2. Precambrian evolution of the Svecofennidic terrain in Finland. After A. Simonen.

Phases	Processes	Rocks
Time of cratonization:		
Postjotnian	intrusion	diabase dikes
Jotnian	sedimentation	sandstones and siltstones
Subjotnian	intrusion	rapakivi granites and diabase
SVECOFENNIDES:		
Orogenic phases:		
Postorogenic phase	intrusion	postorogenic granitoids
Late-orogenic phase	emplacement of late-orogenic granites, migmatization, granitization, diapiric updoming and cross folding	migmatites and migmatite-forming granites
Intraorogenic phase	jointing and intrusion	amphibolite dikes
Synorogenic phase	emplacement of synorogenic plutonic rocks, regional metamorphism, deformation and folding	synorogenic plutonic rocks (mainly quartz diorites and granodiorites), metamorphic schists (mainly micaceous schists and gneisses, quartz-feldspar schists and amphibolites)
Geosynclinal phases of deposition:		
Upper Svecofennian	sedimentation	argillaceous sediments
Middle Svecofennian	volcanism and sedimentation	mafic volcanics and intercalated sediments
Lower Svecofennian	sedimentation	mainly graywackes and impure arkoses
Presvecofennidic	basement unknown	

root zone of the folded belt was invaded by ernormous masses of granitoid rocks.

The most valid signs of ancient life (Figs. 32—33) during the sedimentation of Svecokarelian strata are stromatolite structures in the Jatulian dolomites and carbonaceous sacs *(Corycium)* in the Svecofennian graywacke-slates of the Tampere field. Furthermore the black schists occurring as interbeds have been interpreted to be bituminous, sapropelic sediments.

The evidence relating to the geological evolution of the Finnish Precambrian after the Svecokarelidic orogeny is highly sporadic and full of gaps. The Svecokarelidic orogeny was followed by a long period of erosion and cratonization. The many pulses of rapakivi intrusions and the emplacement of gabbro-anorthosites, diabases and volcanic rocks (porphyrites and quartz porphyries), connected closely with extremely lively igneous activity of the rapakivi, took place in the stable platform 1 700—1 550 Ma ago. The intrusions of rapakivi and related granites seem to be a special feature of the crustal evolution in the Middle Precambrian of many continents.

The Jotnian red beds, representing oxidized terrestrial sediments, were deposited about 1 400—1 300 Ma ago upon the deeply eroded Precambrian surface. They form the oldest sedimentary cover of the metamorphic Precambrian crust. The Postjotnian diabases (~ 1 275 Ma) are the youngest Precambrian igneous rocks in Finland. No Precambrian sedimentary

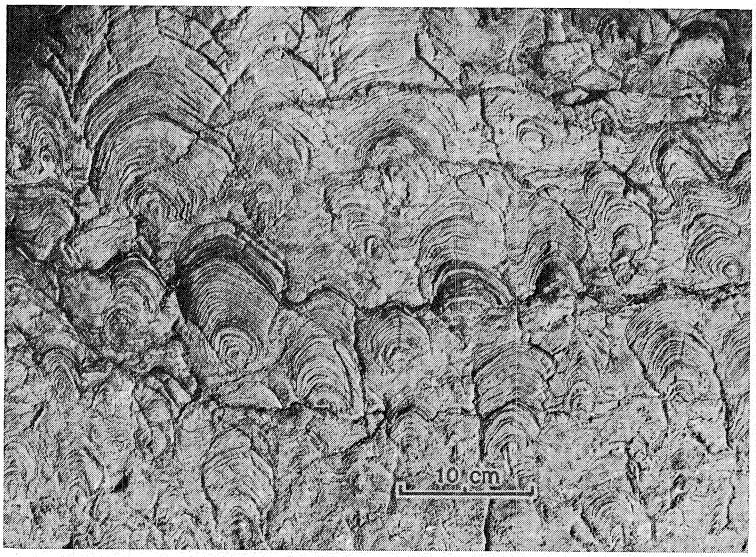

Fig. 32. Stromatolite structure in dolomite. Ollitervo, Tervola. After M. Härme and V. Perttunen.

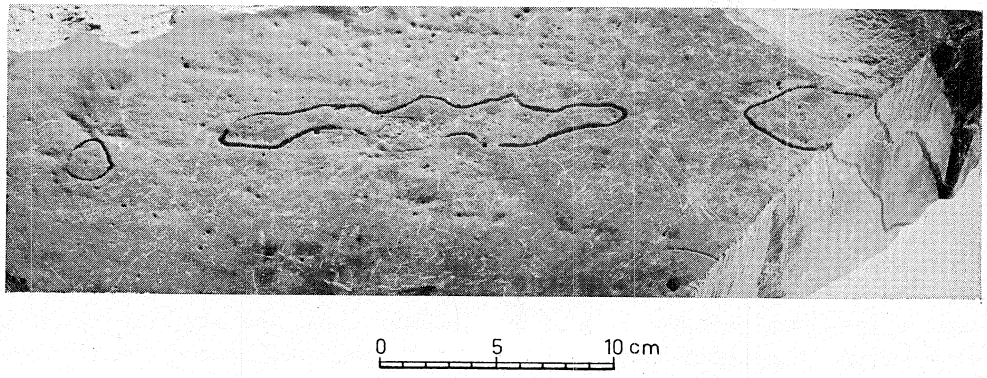

Fig. 33. Carbonaceous sacs (Corycium) in graywacke-slate. Tähtinen, Aitolahti, Tampere. Photo E. Halme.

rocks younger than the Jotnian have been found, but the erosion continued and at the dawn of Cambrian time the Precambrian crust of Finland was denuded almost to its present level.

ECONOMIC GEOLOGY

The Precambrian rock crust of Finland contains many different types of ore deposits, industrial minerals and rocks, which have given rise to mining operations. The most important mines and quarries operated at present are shown in Fig. 34.

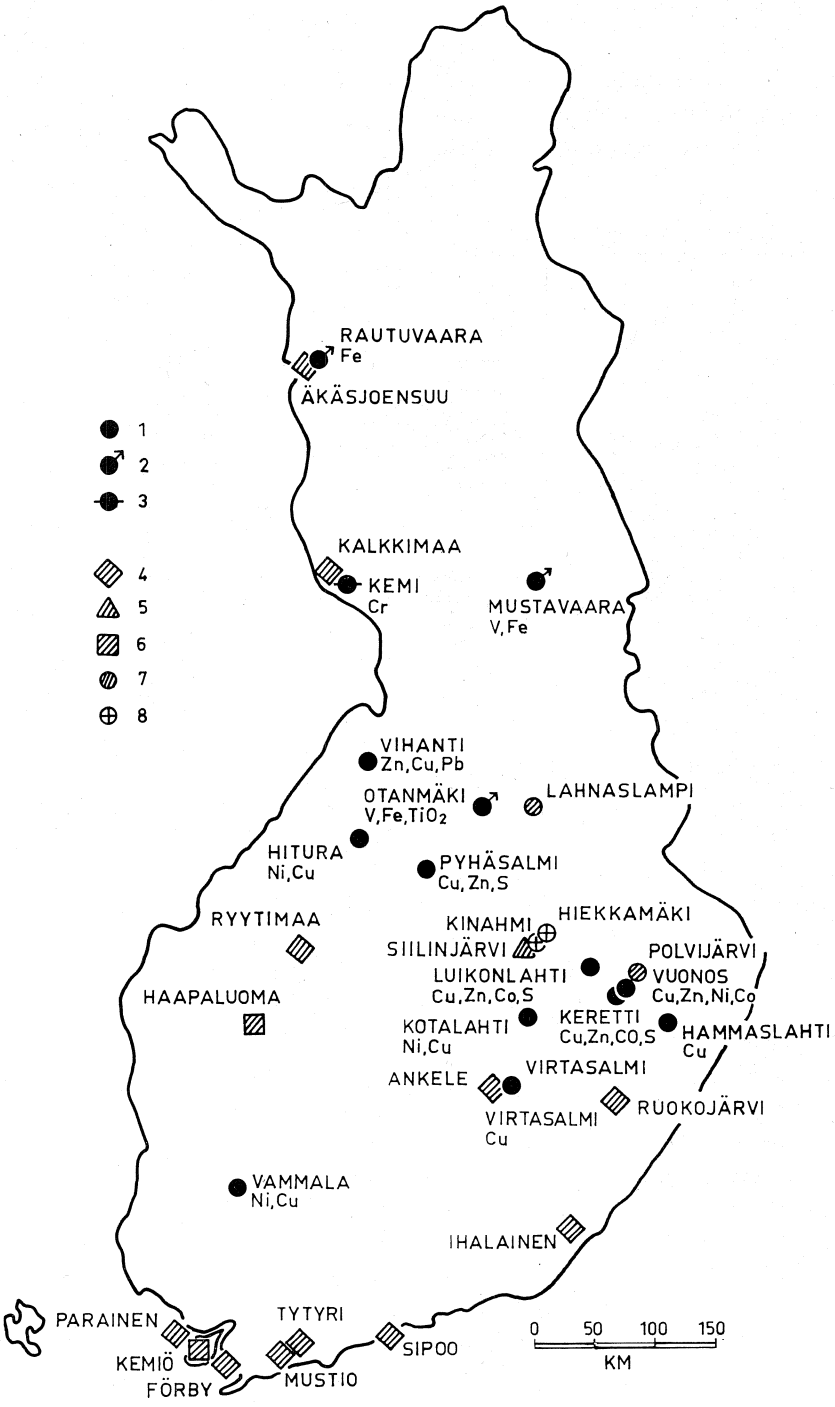

Fig. 34. Mines and quarries in Finland. 1, sulphide ore; 2, iron ore; 3, chromium ore; 4, limestone; 5, apatite; 6, feldspar; 7, talc; 8, quartz.

Ore deposits

The ore deposits now mined in Finland are listed in Table 3, which shows the main products and the planned average output of the mines.

Table 3. Mines in Finland.

Mine	Main products	Planned annual output in tons
1 Kemi	Cr	800 000
2 Mustavaara	V	1 750 000
3 Otanmäki	V, Fe, TiO_2	1 250 000
4 Rautuvaara	Fe	1 500 000
5 Vihanti	Zn, Cu, Pb	800 000
6 Pyhäsalmi	Cu, Zn	1 000 000
7 Hitura	Ni, Cu	400 000
8 Vuonos } Outo-	Cu, Zn, Co, S	400 000
9 Keretti } kumpu	Cu, Zn, Co, S	400 000
10 Kotalahti	Ni, Cu	500 000
11 Luikonlahti	Cu, Zn, Co, S	350 000
12 Hammaslahti	Cu	400 000
13 Virtasalmi	Cu	300 000
14 Vammala	Ni, Cu	300 000

Most of the deposits are sulphide ores. Some of them are nickel-copper deposits associated with mafic and ultramafic plutonic rocks of the Svecokarelides and some sulphide ores containing copper, zinc, cobolt, nickel and lead and situated in the Svecokarelidic schist belt. Among the oxide ores are the chromite deposit of Kemi and iron ore occurrences containing in some cases vanadium and titanium.

The most important sulphide occurrences (over 90 per cent of the known reserves) are situated in the »Main Sulphide Ore Belt», which runs diagonally across the country from Lake Ladoga to the northern coast of the Gulf of Bothnia (Fig. 35). This Belt runs roughly in the direction of the boundary between two main structural units of the Finnish Precambrian, the Presvecokarelidic craton and the Svecokarelidic folded area. The southwestern side of the Belt is characterized by a deep negative gravimetric anomaly, and many fault lines, which have been active in different times, are located in the direction of the Belt. The sulphide ores of the Belt are divided into the Outokumpu ore district and the ore zones of Vihanti and Kotalahti (Fig. 35).

The ores of the Outokumpu district (Vuonos, Keretti and Luikonlahti in Table 3) are sulphidic copper deposits containing zinc and cobalt. They occur as stratiform lenses in a unique, narrow zone (Outokumpu zone) characterized by the rock association: black schist, serpentinite, dolomite, skarn and quartzite. This folded zone occurs as an intercalation in the Svecokarelidic (Kalevian) micaceous schists. The serpentinite lenses of the Outokumpu zone are in many places rimmed by dolomite, skarn and quartzite. The dolomite may be a product of metasomatism of the serpentinite, and the quartzite may have originally been a sinter-like, chemical silica precipitate. The skarn with green chrome-bearing minerals (diopside, tremolite, uvarovite, etc.) is a reaction product between carbonate and silicate rocks. The ores are situated in quartzitic rocks, near the contact of serpentinite. The ores were probably produced by the early geosynclinal magmatism represented by the ultramafics of the Outokumpu zone. The lead model age of the galena in the Outokumpu is $\sim$ 2 100 Ma.

The ores of the Vihanti zone (Vihanti and Pyhäsalmi in Table 3) are polymetallic sulphide deposits containing zinc, copper and lead as well as a little gold and silver. These deposits are situated in Svecokarelidic schists composed of metasediments and metavolcanics of varying composition. An abundance of skarns and cordierite-anthophyllite rocks in the surroundings of the ore deposits is characteristic. The ores seem to be associated with the acid volcanism of the region. The lead model ages of the galenas from the Vihanti zone are 1 925—1 975 Ma.

The ores of the Kotalahti zone (Hitura and Kotalahti in Table 3) are sulphide deposits containing nickel and copper. The host rock of the ores is serpentinite, pyroxenite or norite. The ore deposits are early magmatic and as-

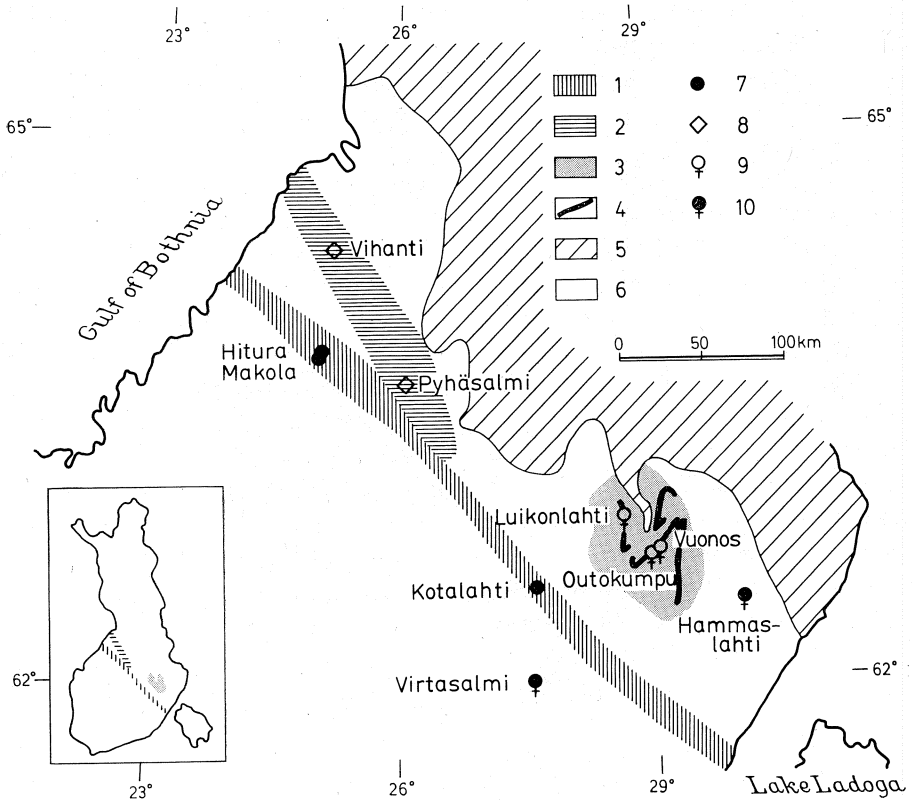

Fig. 35. Main Sulphide Ore Belt. 1, Kotalahti zone (Ni, Cu); 2, Vihanti zone (Zn, Cu, Pb); 3, Outokumpu district (Cu, Co, Zn, Ni); 4, serpentinites of the Outokumpu zone; 5, Presvecokarelidic basement; 6, Svecokarelides; 7, Ni-mine; 8, Zn-Cu-Pb mine; 9, Cu-Co mine; 10, Cu-mine. After A. Kahma.

sociated with the Svecokarelidic plutonism (~ 1 900 Ma).

Other sulphide deposits, deviating from the afore-mentioned ore types or occurring outside the Main Sulphide Belt, are being mined at Hammaslahti, Virtasalmi and Vammala. The ores of Hammaslahti and Virtasalmi are situated in the Svecokarelidic schists and they are copper deposits with no economically significant amounts of other metals. The epigenetic origin of the Hammaslahti ore has been pointed out: material was remobilized from the host rocks. The copper ore of Virtasalmi has been explained as a contact-pneumatolytic deposit. The nickel-copper deposit of Vammala is associated with the Svecokarelidic mafic and ultramafic plutonic rocks, but this ore body is situated far from the Main Sulphide Belt.

The oxide ore mines (Kemi, Mustavaara, Otanmäki and Rautuvaara in Table 3) are located in northern Finland. The oxide ores, with the exception of the Rautuvaara deposit, are genetically associated with mafic and ultramafic plutonic rocks. The chromite ore of Kemi and the iron-vanadium ore of Mustavaara are associated with the differentiated, layered mafic intrusions of the age group ~ 2 400 Ma, whereas the titaniferous iron ore of Otanmäki seems to have been associated with the initial Jatulian magmatism of the Svecokarelides. The magnetite iron ore of Rautuvaara is situated in the Svecokarelidic

schist zone, and its surroundings are characterized by skarns. A metasomatic origin of the Rautuvaara ore has been pointed out.

Industrial minerals and rocks

In addition to the afore-mentioned ore deposits some occurrences of industrial minerals and rocks are mined and quarried. The most important are the limestone mines and quarries (both calcitic and dolomitic) in the different parts of the Svecokarelidic area (see Fig. 34). The carbonatite of the Siilinjärvi complex (cf., p. 23) is quarried for apatite, and the apatite-bearing Paleozoic carbonatite stock of Sokli in northern Finland is under investigation. The serpentinites of the Karelidic belt have been altered by metasomatism into talc-bearing rocks, which are quarried for talc in Lahnaslampi and Polvijärvi. A nickel concentrate (pentlandite) is separated as a by-product of the talc industry.

Many bodies of complex granite pegmatites with rare minerals occur in different parts of the country. Only two of these, Kemiö and Haapaluoma, are quarried at present for feldspar and quartz. Sericite quartzite is quarried in Kinahmi and Hiekkamäki, also for quartz.

Granite and slate as well as rocks used in the production of cement and mineral wool are quarried in many places throughout the country, mostly on a small scale. The even-grained, homogeneous red granite of Vehmaa, in southwestern Finland, is one of the most frequently used granites in Finland. The Vehmaa granite, commercially known as »Balmoral red», belongs to the group of rapakivi granites. Grey granite has been quarried in, for example, the archipelago of Uusikaupunki (trondhjemite) and in the district of Kuru (north of the town Tampere). Black granite (diorite, gabbro) has been quarried in the districts of Hyvinkää, Kuru and Jyväskylä, for example. The granites of different colors are quarried mostly to produce monuments, tombstones and stone for building facades. Some rocks, usually with exceptional color, are quarried for ornamental purposes and some minerals (chrome diopside, smoke quartz, jasper, garnet, labradorite with labradorescense, etc.) are used as gemstones. As a curiosity, it might be mentioned that alluvial gold occurs in Lapland along the southern part of the granulite arch and some private gold-diggers as well as some amateurs and tourists dig and pan for the precious metal during the short summer.

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