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Petrogenetic and geochronological studies of metavolcanic rocks and associated granitoids in the Pihtipudas area, Central Finland

by Lea Aho

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PETROGENETIC AND GEOCHRONOLOGICAL STUDIES OF METAVOLCANIC ROCKS AND ASSOCIATED GRANITOIDS IN THE PIHTIPUDAS AREA, CENTRAL FINLAND

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LEA AHO

with 15 figures, 5 tables, and one appendix

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A petrographic description is given for a metavolcanic rock sequence and associated granitoids in the Pihtipudas area in the Svecofennian formation of the Finnish Precambrian.

U-Pb isotopic ages were measured on zircons from five synorogenic granitoids, a metadasitic dyke and three metavolcanic rocks. They yielded an age of 1883 Ma. Three titanites from granitoids and a monazite from an orbicular quartz-dioritic rock gave a fairly concordant age of 1800 Ma. A Pb-Pb isochron age was obtained for the metavolcanic rock sequence. The isotopic ratios of lead defined a line with a slope of 0.11615 ± 0.00168, which indicates an age of 1898 ± 26 Ma.

The isotopic compositions of lead in three ore deposits, Outokumpu, Pyhäsalmi and Pihtipudas, are given and their genetic relationship with a plumbotectonic model is discussed.

Key words: metavolcanic rocks, granitoid, dating, Precambrian, Finland.

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INTRODUCTION

The area described is situated in Pihtipudas, Central Finland, between latitudes 63°17′ and 63°27′30″ N, and longitudes 25°30′ and 26°00′ E. The area is outlined in Fig. 1, which shows the relation to the main geological elements of Central Finland.

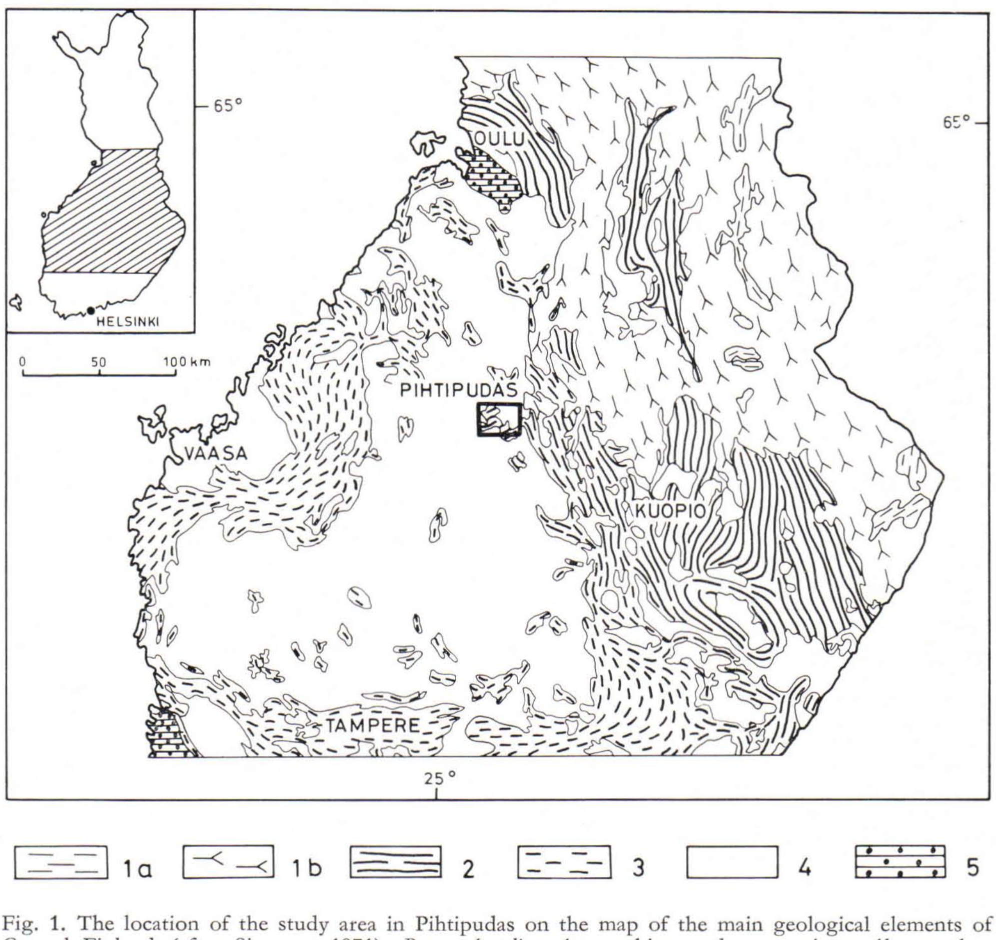

Fig. 1. The location of the study area in Pihtipudas on the map of the main geological elements of Central Finland (after Simonen 1971). *Presvecokarelian:* 1a = schists and paragneisses; 1b = orthogneisses. *Svecokarelian:* 2 = Karelian schist belt; 3 = Svecofennian schist belt; 4 = orogenic plutonic rocks. *Late Precambrian rock:* 5 = Jotnian sediments.

Geological maps of the area have been compiled on a scale of 1 : 400 000 by Wilkman (1938) and 1 : 100 000 by Salli (1971). Some parts of the area were mapped in greater detail during the summers of 1965—67 in the course of exploration by the Geological Survey of Finland. The results of the exploration were published by the author in 1975. The present study is a summary of the petrogenetic and geochronological relationships between the metavolcanic rocks and the granitoids in the study area.

Three U-Pb ages were determined on zircons from metavolcanic rocks; four U-Pb ages on zircons and three on titanites from granitoids, and one on zircon from a metadasitic dyke rock. A monazite and a zircon from an orbicular quartz-dioritic rock at Viitasaari were dated and plotted on the concordia diagram of the Pihtipudas rocks.

The uranium and lead isotopic age determinations were made by O. Kouvo and the whole-rock isotopic ones by O. Kouvo and M. Sakko at the geochronological laboratories of the Geological Survey of Finland.

GEOLOGICAL SETTING

The Pihtipudas area is located in that part of the Baltic Shield in Finland where the orogenic cycle is known as Svecokarelian and which includes both Svecofennian and Karelian formations (Simonen 1971).

The Svecofennian formations predominate in southwestern and western Finland. The plutonic and supracrustal rocks in Pihtipudas are situated in the Svecofennian formation near the boundary zone between the Svecofennian and Karelian metamorphic schist belts (Fig. 1). The plutonic rocks in Pihtipudas, synorogenic in character (Simonen 1971), consist mainly of granitoids, granodioritic and granitic rocks, of the northeastern part of the large batholith of Central Finland. One mafic body and a few dyke rocks have been found.

The supracrustal rocks of this area are called Bothnian schists. The deposition of the schists was followed by an episode of regional metamorphism and deformation. Intense thermal metamorphism also accompanied the emplacement of the granitoids.

The schists in Pihtipudas are composed of a metamorphic sequence of sedimentary and volcanic rocks. The sedimentary rocks form a few narrow zones (about 300 m in thickness) in the northern margin of the schist belt. The majority of the metamorphic schists consist of felsic volcanic rocks intercalated with intermediate or mafic volcanic rocks, and of pyroclastic rocks that in places have turned into amphibolites.

The schist belt runs for roughly 15 km from the Pihtipudas church eastwards; it varies in width from 3 to 5 km. The study area, with its metamorphic schist sequence, is clearly distinguished from another metasedimentary rock unit (Fig. 2) that runs from N to S and consists mainly of arkosites; the latter is however beyond the scope of this study.

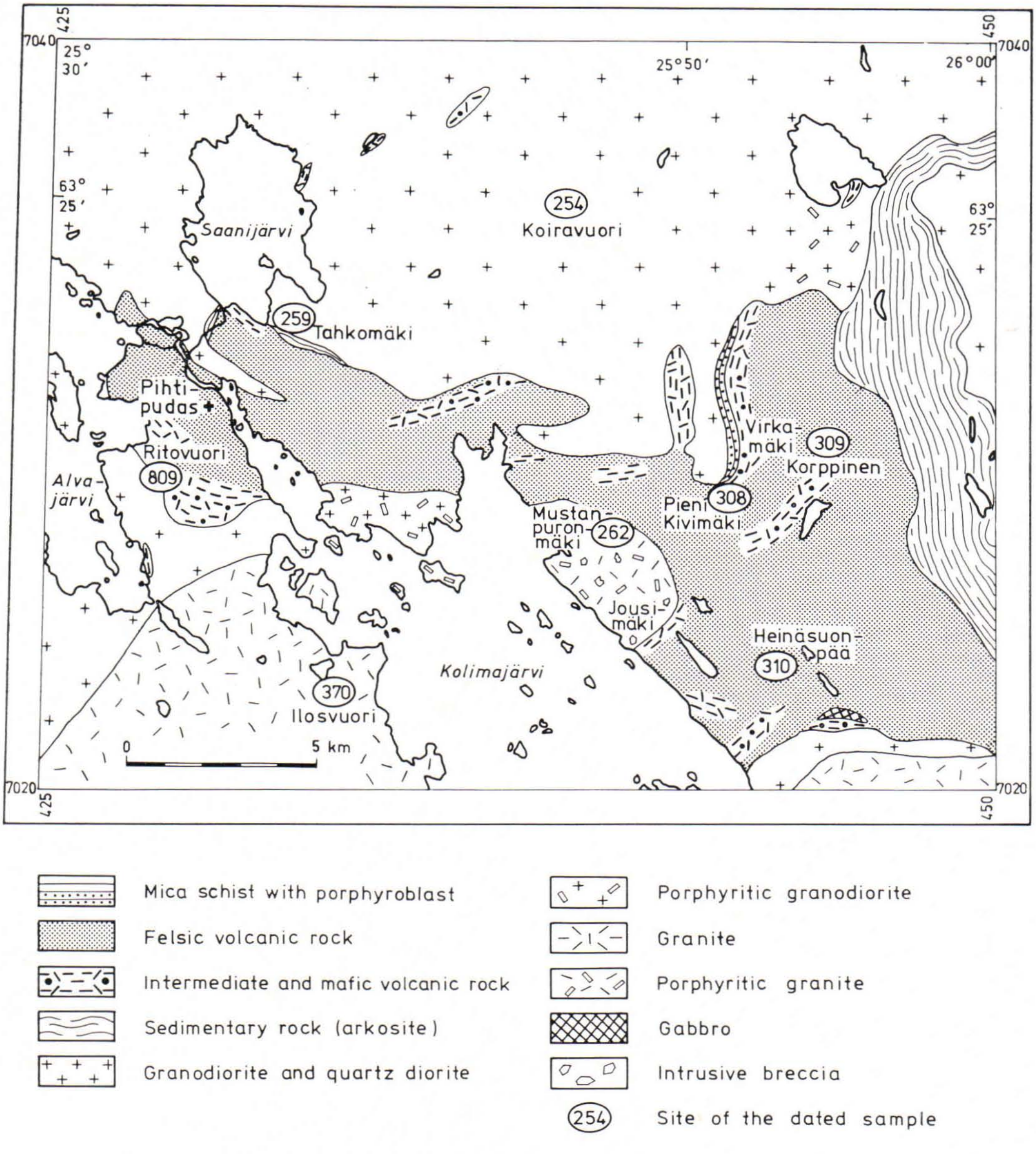

Fig. 2. Generalized geologic map of the Pihtipudas area showing the sampling sites. The numbers refer to the numbers used in Fig. 14. Map co-ordinates from Sheet 3312 (1 : 20 000). Maps by the General Survey Office.

254 Koiravuori	7 036.40/438.60	309 Korppinen	7 029.10/445.25
259 Tahkomäki	7 032.34/431.10	310 Heinäsuonpää	7 023.50/443.90
262 Mustanpuronmäki	7 026.90/439.90	370 Ilosvuori	7 021.50/432.30
308 Pieni Kivimäki	7 027.90/443.40	809 Ritovuori	7 028.50/428.15

PETROGRAPHY

Supracrustal rocks

Metasedimentary rocks

Some narrow zones of metasedimentary rocks lie in the northern margin of the schist belt near Virkamäki and Tahkomäki (Fig. 2). Three zones of metamorphism, whose grade increases eastwards, can be detected in the Virkamäki area. Of rather complicated structure, the three zones are the biotite zone, the andalusite-cordierite zone and the cordierite-sillimanite zone. The cordierite-sillimanite zone, in which the grade of metamorphism is highest, lies at the contact of the metavolcanic rocks. The mica schist at Tahkomäki corresponds to the schists of the biotite zone.

Biotite zone

The main constituents of this schist zone are quartz, biotite and muscovite with some plagioclase (An_{20}) and K-feldspar. The accessories are apatite, tourmaline, zircon and opaque minerals. The grain size varies from 0.05 to 0.1 mm.

Andalusite-cordierite zone

Andalusite and cordierite occur as elongated porphyroblasts with a rounded cross section of 1—2 cm diameter; the schistosity of the rock usually curves around the crystals. The matrix of this schist is comparable with that of the schist in the biotite zone. It contains quartz, biotite, muscovite and plagioclase (An_{32-40}) with the same grain size and accessories as the schists in the biotite zone. The porphyroblasts in this zone all show internal schistosity due to inclusions of quartz, plagioclase, biotite and opaque minerals. Andalusite is locally altered into muscovite, starting from the margin of the crystals. Cordierite is pinitized and sometimes partially replaced by coarse muscovite flakes.

Cordierite-sillimanite zone

This zone is characterized by the absence of andalusite and the occurrence of fibrous sillimanite. Fibrolite, which forms bundles lying parallel to the schistosity, has grown at the expense of biotite. Cordierite has altered into pinite with inclusions of quartz, plagioclase, muscovite and opaque minerals. The matrix has the same mineral composition and grain size as the schists in the andalusite zone.

Metavolcanic rocks

The Pihtipudas schist belt, which largely consists of metamorphic volcanic rocks, can be divided into three different rock units: (a) felsic volcanic rocks (felsite porphyries); (b) intermediate or mafic volcanic rocks (plagioclase and/or uralite porphyrites); and (c) pyroclastic rocks (amphibolites). These metavolcanic rocks are always more or less recrystallized and deformed, and have lost their primary features. It is not possible to establish to what extent the metavolcanic rocks have intermingled with tuffaceous or sedimentary materials. Nonetheless, on the generalized geologic map in Fig. 2, the intermediate and mafic volcanic rocks, including the pyroclastic rocks, are distinguished from the felsic volcanic rocks.

Besides the distinctive mafic volcanic rocks with intercalations of pyroclastic rocks, the schist belt is composed mainly of felsite porphyries whose formation seems to be contemporaneous with the mafic volcanism.

Felsic volcanic rocks (felsite porphyries)

Feldspar-bearing porphyries are the most common variety of felsite porphyries, although some quartz phenocrysts are often conspicuous

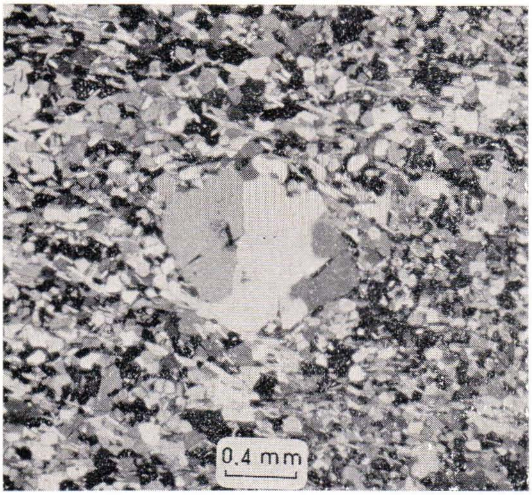

Fig. 3. Quartz grain within a fine-grained muscovite-quartz-feldspar matrix. Crossed nicols. Ritovuori, R7/57.66 m.

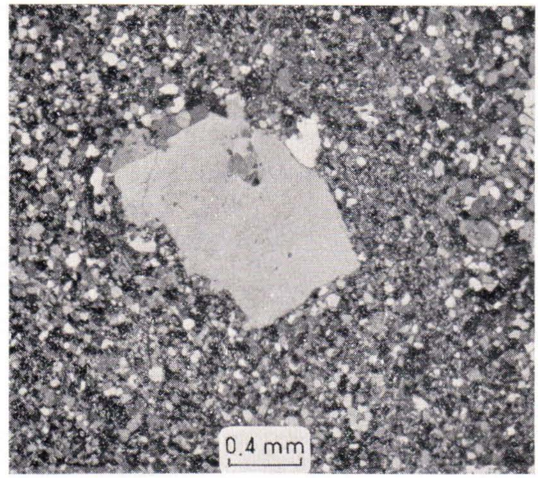

Fig. 4. Example of a quartz grain with matrix inclusions or deep embayments within a felsite porphyry. Crossed nicols. Ritovuori, R7/36.73 m.

as well. The rocks are recognized by their grey or greenish-grey colour or, wherever quartz phenocrysts are prevalent, by their reddish colour. The felsite porphyries are massive or schistose; in the western part of the schist belt they are locally characterized by quartz phenocrysts and in the eastern part by plagioclase and K-feldspar phenocrysts.

The phenocrysts, with an average diameter of 1 to 3 mm, are clearly visible in the matrix, whose grain size is from 0.01 mm to 0.2 mm. The phenocrysts vary in size and abundance. The quartz phenocrysts are rounded to euhedral in shape (Figs. 3 and 4); they may display heavily embayed margins or recrystallized grain aggregates representing the former phenocrysts.

The feldspar phenocrysts are euhedral or subhedral in shape, and usually from oligoclase (An_{10}) to andesine (An_{35}) in composition; sometimes they are zoned and recrystallized. The 'complete' stage of recrystallization (Roddick *et al.* 1976) has generally been reached; thus, the zoning is obliterated and the muscovite inclusions enlarged (Fig. 5). In places, the plagioclase phenocrysts are replaced by K-feldspar, muscovite and quartz. K-feldspar occurs as both subhedral phenocrysts with some sericite grains or plagioclase relics and as grain aggregates. K-feldspar phenocrysts and aggregates do not show microcline twinning; in the matrix K-feldspar, however, has distinct twinning.

The matrix is composed af quartz, plagioclase, K-feldspar and partially recrystallized and chloritized biotite. Other constituents are: muscovite, as poikiloblastic grains of a late generation and replacing plagioclase; apatite, which forms recrystallized aggregates; tourmaline as zonal grains, abundant in the eastern part of the schist belt; and epidote, which is in places abundant and fills the fractures. Accessories are zircon, chlorite, titanite, leucoxene and opaque minerals.

A specific concentric texture, very like that in the ocellar hybrids described by Angus (1962) and Vorma (1975), is visible in these felsic volcanic rocks. The ocelli in the Pihtipudas rocks consist of small rounded bodies, circular or oval in section, which contain a variety of minerals. In these rocks the ocelli usually have a quartz rim (Figs. 6 and 7). The cores of most of them contain one or several oligoclase grains and some opaque minerals. Oligoclase is partially

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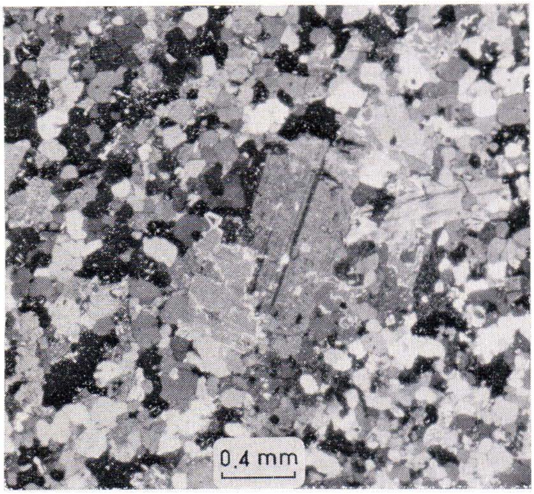

Fig. 5. Internal homogenization of plagioclase ('complete' stage of recrystallization cf. Roddick *et al.* 1976) within a felsite porphyry. Enlarged muscovite inclusions. Muscovite grains have a white rim in the photomicrograph. The matrix consists of quartz, muscovite and feldspars. Crossed nicols. Heinäsuonpää, P 515/MH/65.

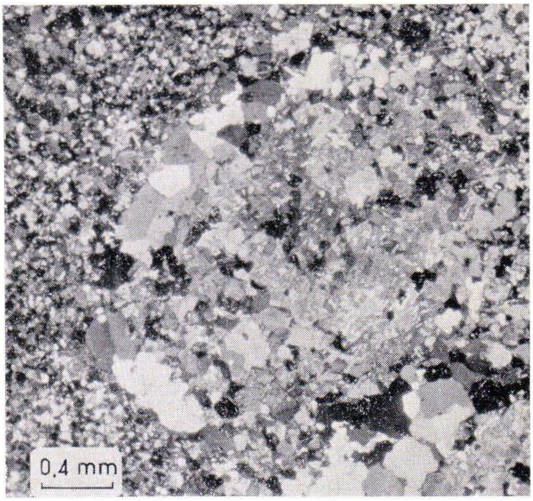

Fig. 6. Ocellar texture within a hybridized felsite porphyry. The centre is composed of plagioclase, poikiloblastic muscovite, K-feldspar and carbonate. The ocellus is surrounded by a quartz rim. Crossed nicols. Ritovuori, P 183/MH/58.

replaced by microcline, carbonate, poikiloblastic muscovite and quartz. Plagioclase is sometimes completely replaced by microcline (Fig. 7).

The formation of the ocelli is attributed to hybridization caused by infiltration of acid fluids from granitic magma. The hybridized rock seems to have been enriched in quartz. As Vorma (1975) pointed out, silicification is an essential factor in hybridization, and the appearance of K-feldspar in the ocelli indicates an increase in the potassium content.

Chemical analyses of these rock types are given in Table 1 in the paper by Salli (1971). Chemical analyses 1, 4—9 and 12 refer to the schist types that in this study are called felsite porphyries. Most of them are from the part of the schist belt that lies near the contact of granitoids in the southeastern corner of the study area. These felsite porphyries were intensely thermometamorphosed, shown by the development of late muscovite. The K/Na ratio varies from 1.26 to 2.49, indicating slightly potassium-extreme varieties.

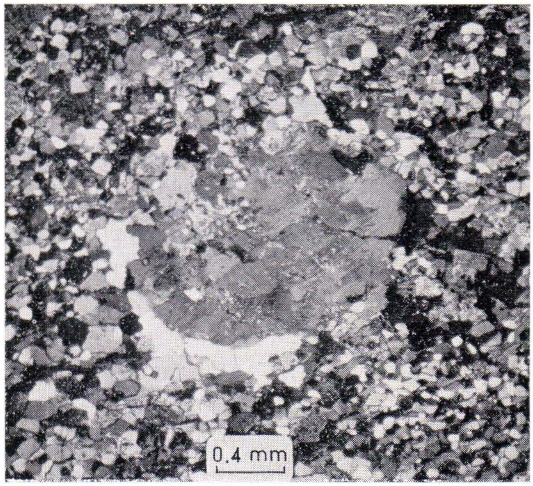

Fig. 7. Ocellar texture similar to that in Fig. 6. Plagioclase is completely replaced by K-feldspar. K-feldspar grains with inclusions of quartz and poikiloblastic muscovite. Crossed nicols. Palovuori, P 21/MH/65.

The modal analyses of three felsite porphyries corresponding to the dated samples are given in Table 1. XRF-analyses of the same samples are given by V. Hoffren in Appendix 1.

Table 1. Modes of metavolcanic rocks in Pihtipudas.

	1.	2.	3.
Quartz	22.3	24.6	28.2
Plagioclase	34.4	35.2	36.1
K-feldspar	27.1	23.2	16.4
Biotite	9.4	13.1	—
Chlorite	1.9	1.4	1.0
Muscovite	1.4	—	12.3
Titanite	0.6	0.2	—
Carbonate	0.5	0.3	1.7
Epidote	0.4	—	2.2
Apatite	0.4	0.7	0.4
Fluorite	0.2	—	0.5
Zircon	—	0.1	—
Opaques	1.4	1.2	1.2
An content of plagioclase	20	15	10

1. Felsite porphyry, Pieni Kivimäki, P 112/MH/65 (308)*
2. Felsite porphyry, Korppinen, P 121/MH/65 (309)*
3. Felsite porphyry, Heinäsuonpää, P 510/MH/65 (310)*

* Number indicates location of dated sample in Fig. 2.

Intermediate and mafic volcanic rocks

The best preserved porphyritic intermediate and mafic volcanic rocks (plagioclase and/or uralite porphyrite) are similar in appearance. Microscopic investigation has revealed a number of different varieties, which generally grade into each other. The rock is dark green or greyish green with some grey plagioclase patches and/or dark green aggregates of hornblende from 1 to 4 mm in diameter. The grain size of the matrix varies from 0.01 to 0.5 mm. The composition of plagioclase ranges from An_{25} to An_{48}, mostly from An_{28} to An_{35}. Plagioclase has a poikiloblastic texture with inclusions of fine-grained quartz, K-feldspar, biotite and hornblende (Fig. 8). The alteration products of plagioclase are sericite, epidote and carbonate. Hornblende occurs as aggregates and recrystallized grains in the matrix. Other constituents are biotite, usually as aggregates, and quartz. Accessory minerals include apatite, sometimes as recrystallized aggregates, epidote, titanite, leucoxene, tourmaline, chlorite, zircon and opaque minerals.

Fig. 8. Poikiloblastic plagioclase with inclusions of biotite and hornblende within a mafic volcanic rock. Crossed nicols. Ritovuori, R 7/15.15 m.

The hybrids of these rocks are characterized by ocellar texture in which quartz grains have a narrow rim of small hornblende crystals (Fig. 9). The ocellar hybrids occur throughout the mafic volcanic rocks at Ritovuori (Fig. 2), although mainly near the contact of granodiorite.

Locally hornblende, quartz and opaque minerals form rounded mineral aggregates that might be vesicles or amygdules (Fig. 10). The mafic volcanic rocks also show somewhat larger amygdules, up to 30 cm in diameter, which consist of epidote, quartz, carbonate and titanite, with plagioclase, K-feldspar, scapolite, hornblende, muscovite and opaque minerals as accessories.

A late metamorphic growth of amphibole (amphibolization) took place in the intermediate and also in the felsic volcanic rocks (Fig. 11). The rock consists of poikiloblastic hornblende grains (1 to 2 cm in diameter) with inclusions of quartz, biotite, feldspar and opaque minerals. The mineral composition of the matrix and the grain size are the same as those in the corresponding volcanic rocks.

A slightly different plagioclase-uralite porphyrite is found in a breccia that contains subangular or rounded fragments of meta-basaltic and meta-andesitic rock (Fig. 12). This

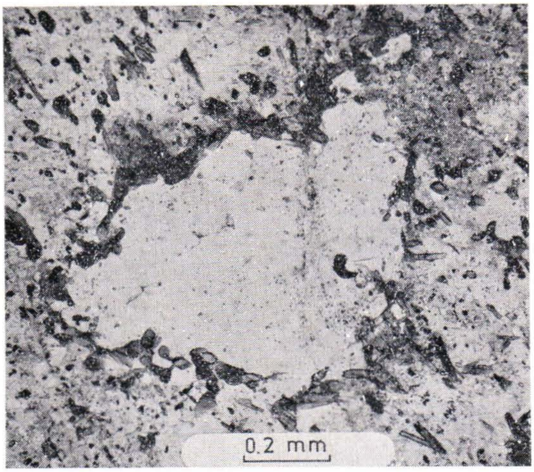

Fig. 9. An ocellus of quartz and ore mineral within an intermediate volcanic rock. Dark hornblende grains form a narrow mantle around the core. One nicol. Ritovuori, R 7/126.24 m.

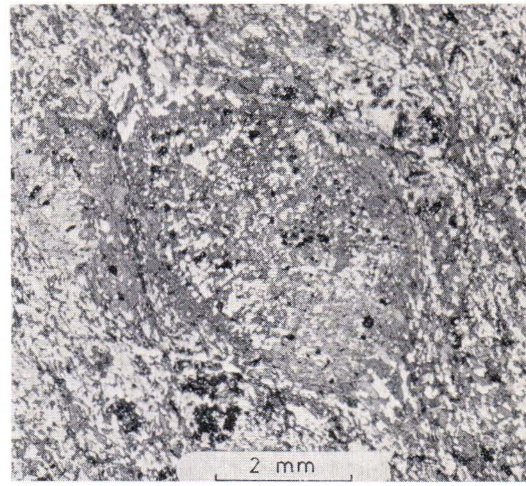

Fig. 10. A vesicle within an intermediate volcanic rock filled with dark hornblende, quartz and opaque minerals. One nicol. Virkamäki, P 109/MH/65.

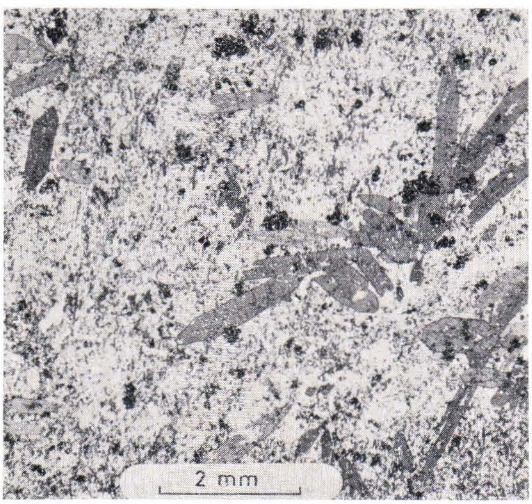

Fig. 11. Late metamorphic amphibolization within an intermediate volcanic rock. One nicol. Hoikanlampi S, P 213/MH/66.

Fig. 12. Intermediate volcanic rock containing fragments of meta-andesitic and metabasaltic rocks (an autobreccia). Tohmonkylä, Somero.

is an autobreccia in which the first consolidated crust of a lava flow was incorporated into the still-fluid portion. The matrix consists of hornblende aggregates, plagioclase (An_{28-32}), biotite and quartz. Accessories include apatite, titanite, epidote and opaque minerals.

Pyroclastic rocks

The occurrence of metamorphic tuffaceous rocks as intercalations within the felsic and intermediate or mafic volcanic rocks suggests rhythmic volcanic activity. Pyroclastic rocks are abundant in the western part of the schist belt; they are dark green, banded and fine-grained (0.02 to 0.5 mm in diameter). The mineral composition is plagioclase (An_{32-60}), green hornblende, sometimes also cummingtonite and biotite. Accessories are apatite, epidote, titanite, carbonate, tourmaline, chlorite, zircon and opaque minerals.

In some places, agglomeratic rocks with slightly rounded or angular fragments occur in a tuffaceous matrix. The fragments vary greatly in shape and size (from 2 to 5 cm in diameter); some of them are rounded and consist of porphyritic felsic or intermediate volcanic rocks. These fragments, which may be as much as 10 cm in diameter, were elongated by deformation.

Plutonic rocks

Granitoids

The predominant plutonic rocks in the Pihtipudas area are synorogenic granitoids. These can be divided into four different rock types, which grade into each other without distinct boundaries: quartz diorite and granodiorite, porphyritic granodiorite, granite, and porphyritic granite. Most abundant are quartz diorite and granodiorite. The porphyritic varieties of the granodiorite and granite are distinguished from the equigranular types on the geologic map in Fig. 2.

The granodiorite north of the schist belt contains numerous mafic autoliths. The autoliths are subangular in shape and vary in diameter from 10 to 20 cm. Eastwards the number of autoliths decreases and the granodiorite grades into porphyritic granodiorite.

South of the schist belt there is a large area of granodiorite that also grades into the porphyritic variety; mafic autoliths are, however, lacking. The porphyritic granodiorite contains K-feldspar phenocrysts (from 2 to 5 cm in diameter) that show relics of plagioclase.

The quartz diorite and granodiorite are often grey or slightly pinkish. The grain size varies from 1 to 5 mm. The major minerals are plagioclase (An_{20-38}), quartz, K-feldspar, hornblende and biotite. Accessories include apatite, titanite, epidote, zircon and opaque minerals.

The granite west of the lake Kolimajärvi is pinkish in colour and almost medium- grained (grain size from 2 to 5 mm). In places, the grain size of K-feldspar attains 2 to 3 cm. Biotite is commonly altered into chlorite. The granite east of Kolimajärvi also shows porphyritic texture with K-feldspar phenocrysts. It exhibits intrusive contacts and large breccia areas. The fragments are angular, up to 20 to 30 m in diameter. They consist mainly of schists of the metavolcanic rock sequence.

Although the granitoids display well-preserved igneous textures and massive fabric, they also reveal some secondary features that are the result of metamorphic recrystallization, deformation and retrograde alteration.

Six modal analyses of granitoids, including the dated samples are given in Table 2. XRF-analyses are given by V. Hoffren in Appendix 1.

Mafic rocks

A mafic rock lens of dark green gabbro was found between the schist belt and quartz diorite in the southeastern corner of the study area (Fig. 2). The outline of the gabbro body indicates that it may be a sill that was injected parallel to a lava flow. The mineral composition is plagioclase (An_{28-65}), hornblende, cumming-

Table 2. Modes of granodiorites and granites in Pihtipudas.

	1.	2.	3.	4.	5.	6.
Quartz	24.1	22.1	30.5	26.4	31.8	44.0
Plagioclase	39.2	42.7	39.7	45.8	47.8	26.3
K-feldspar	19.7	11.4	12.7	14.0	13.1	15.1
Biotite	8.3	18.3	8.8	8.3	—	11.4
Hornblende	4.6	3.0	2.2	3.8	—	—
Apatite	0.9	0.7	1.3	0.8	0.7	1.1
Titanite	0.7	1.1	—	—	0.4	0.6
Zircon	0.7	0.3	0.9	0.3	0.6	0.2
Muscovite	0.6	—	—	—	—	0.1
Chlorite	0.5	0.2	0.4	0.2	5.3	0.7
Epidote	0.4	—	—	—	—	0.2
Monazite	—	—	—	0.2	—	—
Carbonate	—	—	3.5	—	—	—
Opaques	0.3	0.2	—	0.2	0.3	0.3
An content of plagioclase ...	25—38	25	28	26	20	25

1. Granodiorite. Uimalahti, P 213/MH/58
2. Porphyritic granodiorite. Kolima, P 44/MH/65
3. Granodiorite. Tahkomäki, P 36/MH/65 (259)*
4. Granodiorite. Koiravuori, P 353/MH/65 (254)*
5. Granite. Ilosvuori, P 33/LA/67 (370)*
6. Porphyritic granite. Mustanpuronmäki, P 152/MH/65 (262)*

* Number indicates location of dated samples in Fig. 2.

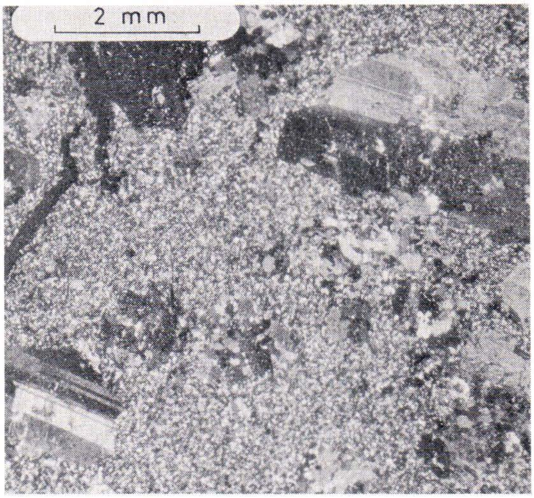

Fig. 13. Metadasitic dyke. The phenocrysts are plagioclase. Crossed nicols. Ritovuori, P 3/LA/65.

tonite and biotite. Accessories are quartz, hypersthene, zircon, apatite, titanite and opaque minerals.

Dyke rocks

Metadasite

The metavolcanic rocks at Ritovuori is intersected by metadasite, a fine-grained, porphyritic equivalent of granodiorite. This subvolcanic rock, assumed to be intraformational and synkinematic in character, was obviously intruded into an active shear zone. Similar dykes have been described from other schist sequences of the Svecofennian belt, e.g. by Haapala (1966) and Matisto (1971). Three metadasitic dykes were found at Ritovuori; the largest is up to 20 to 30 m in width and about 300 m in length. The rock is dark grey with patches of white plagioclase. The grain size of the phenocrysts varies from 1 to 4 mm. The matrix is fine-grained, the grain size being about 0.05 mm (Fig. 13). The mineral composition is: plagioclase (An_{20}) with some K-feldspar as phenocrysts, biotite aggregates with epidote, hornblende and titanite, and quartz only in fine-grained matrix. Accessories are apatite, muscovite, zircon, carbonate, chlorite and opaque minerals.

Pegmatite

Pegmatite dykes occur east of Kolimajärvi. A pegmatite dyke at Jousimäki (Fig. 2) intersects the porphyritic granite and amphibolite with agglomeratic texture. It is composed of microcline, quartz, biotite, muscovite, tourmaline and a few beryl crystals. The largest beryl crystal is 23 cm in diameter. Some beryl-bearing pegmatite dykes occur in the southeastern corner of the schist belt. In these pegmatites the beryl crystals do not exceed 1 cm in diameter.

RADIOMETRIC AGE DETERMINATIONS

U-Pb ages on minerals

The isotopic dating was made on rocks from the metavolcanic rock sequence and associated granitoids. The locations of the dated samples in the Pihtipudas area are shown on the map in Fig. 2. Table 1 gives the modal analyses for three metavolcanic rocks and Table 2 for four granitoids. Table 3 lists the U-Pb isotopic analyses including analyses of zircon and monazite from an orbicular quartz-dioritic rock, Viitasaari.

Daughter/parent ratios of zircons, titanites and one monazite are plotted on a conventional concordia diagram in Fig. 14. Eleven points for zircons from both metavolcanic rocks and granitoids yield results that define a linear pattern of discordance and give an interpreted age of 1883 ± 20 Ma. Titanites and monazite from the granitoids give an age of 1 800 Ma.

The dating of three zircon fractions from Ilosvuori granite gives fairly discordant ages (370 A, B, C) in Fig. 14. The modal analysis (Table 2) reveals that, since biotite is altered to chlorite, the rock has been affected by retrograde metamorphic alteration. The process has taken place without undergoing textural modification.

The dating of zircon from Tahkomäki granodiorite (259) in Fig. 14 also gives a clearly discordant age. The rock represents a marginal variety of the large granodioritic massif on the northern side of the schist belt. The texture is almost granoblastic. The marginal varieties tend to be reduced in grain size, the large grains being subdivided into a number of small grains that correspond to 'moderate' recrystallization (cf. Roddick *et al.* 1976).

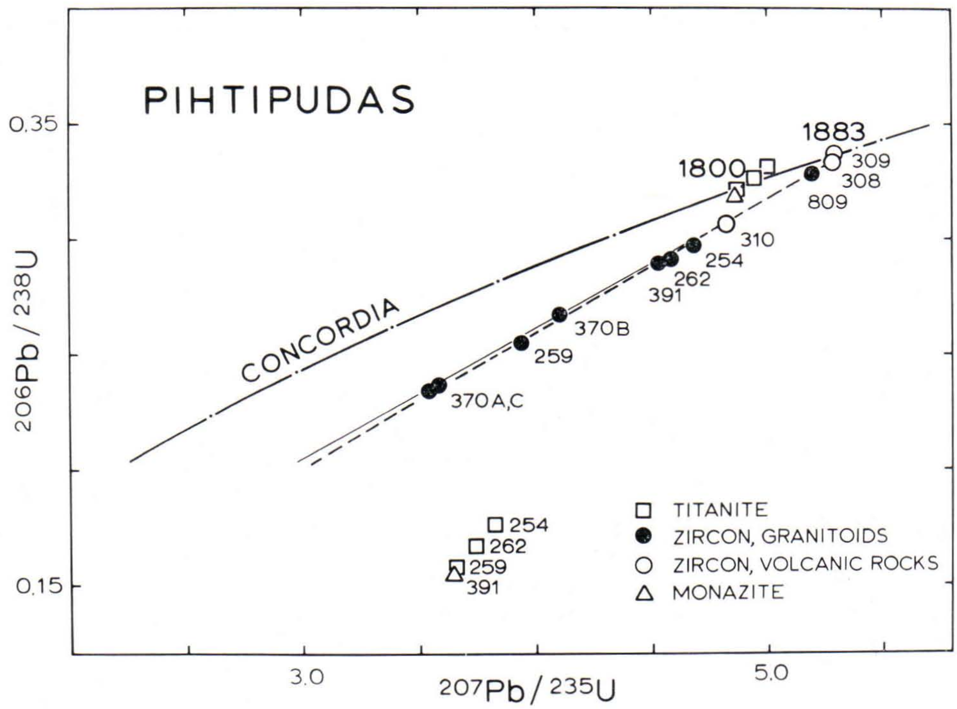

Fig. 14. Concordia diagram for U-Pb ratios of zircons and titanites from metavolcanic rocks and granitoids, Pihtipudas area, and of zircon and monazite (391) from an orbicular quartz-dioritic rock, Viitasaari.

Table 3. U-Pb isotopic results for zircons from metavolcanic rocks and granitoids, Pihtipudas and an orbicular quartz diorite, Viitasaari *). The decay constants for uranium: $^{238}U = 1.55125 \times 10^{-10}a^{-1}$ and $^{235}U = 9.8485 \times 10^{-10}a^{-1}$.

Sample No.	Locality	Rock type	^{238}U ppm	Radio-genic ^{206}Pb, ppm	$^{206}Pb/^{204}Pb$ measu-red	Isotopic abundance relative to ^{206}Pb (= 100)			Radiometric ages Ma			Mineral fraction (g.cm^{-3}/mesh size)	
						204	207	208	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$		
A 254	Koiravuori	granodiorite	576.4	148.65	660.32	.12673	13.109	12.875	1 681	1 763	1 863	Zr**)	total
»	»	»	87.0	24.91	175.1	.54457	18.378	22.719	1 841	1 820	1 797	Ti	total
A 259	Tahkomäki	granodiorite	1 224.6	271.24	486.4	.19348	13.805	16.660	1 468	1 623	1 830	Zr	total
»	»	»	126.0	35.07	779.5	.11579	12.578	23.53	1 797	1 798	1 800	Ti	total
A 262	Mustanpuronmäki ..	porphyritic granite	646.4	163.18	389.6	.25127	14.787	17.203	1 649	1 745	1 863	Zr	total
»	» ..	»	73.6	20.85	427.5	.18727	13.517	10.032	1 822	1 809	1 795	Ti	total
A 308	Pieni Kivimäki	felsite porphyry	584.2	168.65	1 712.67	.04803	12.153	12.867	1 855	1 866	1 880	Zr	total
A 309	Korppinen	»	947.2	275.85	628.57	.15213	13.460	16.354	1 869	1 867	1 865	Zr	total
A 310	Heinäsuonpää	»	626.2	165.98	1 312.14	.06439	12.296	11.613	1 722	1 788	1 868	Zr	total
A 370 A	Ilosvuori	granite	469.0	95.42	479.21	.17588	13.806	14.773	1 358	1 537	1 851	Zr	d > 4.2
A 370 B	»	»	321.3	74.26	666.32	.14697	13.438	13.838	1 526	1 652	1 858	Zr	d > 4.6
									± 4	± 4	± 10		
A 370 C	»	»	520.8	107.04	537.01	.18963	13.949	15.139	1 373	1 546	1 846	Zr	4.6—4.2
									± 5	± 5	± 15		
A 809	Ritovuori..........	metadasite	811.4	230.2	3 314.0	.27499	11.965	10.681	1 828	1 851	1 885	Zr	d > 4.2
									± 5	± 4	± 10		m > 200
A 391	Lahnanen, Viitasaari	orbicular quartz diorite	1 613.7	404.49	1 935.6	.0456	11.96	4.33	1 640	1 737	1 856	Zr	m > 200
»	»	»	2 190.7	606.1	4 966		11.03	388.63	1 787	1 795	1 805	MON	total

*) Map sheet 3311-11; co-ordinates x = 6999.60, y = 456.48
**) Zr = zircon, Ti = titanite, MON = monazite

The distance between the two granodiorites dated from Tahkomäki (259) and Koiravuori (254) is about 8 km (Fig. 2). The zircon from Koiravuori (254) gives a less discordant age than that of the marginal variety from Tahkomäki. Both granodiorites have almost similar mineral composition (Table 2).

The modal analysis (Table 2) of the porphyritic granite from Mustanpuronmäki (Fig. 2) indicates that the rock is the most silicic of the granitoids. The large intrusive breccia between this rock and the metavolcanic rocks points to a somewhat different character than that of the other synorogenic granitoids; nevertheless, the zircon ages are coeval.

One dating was made on the metadasitic dyke that intersects the metavolcanic rock sequence at Ritovuori. The zircon gives for this rock the most concordant granitoid age (809, in Fig. 14).

A monazite and a zircon from an orbicular quartz-dioritic rock from Viitasaari, some 25 km south of Pihtipudas, were analysed and plotted on the concordia diagram (Fig. 14). The orbicular rock from Viitasaari was included in the granitoids of the large batholith of Central Finland. The zircon shows that the age is the same as that of the granitoids in the Pihtipudas area.

Three titanites from the Pihtipudas granitoids and one monazite from the Viitasaari orbicular rock show fairly concordant ages, and have a younger intercept of 1 800 Ma than the zircons from the same rocks on the concordia curve (Fig. 14).

Age determinations made on several intrusive rocks of different composition in the Precambrian of Finland yield the same ages as titanites from Pihtipudas and monazite from Viitasaari, which are about 80 to 100 Ma younger than the zircon ages of the synorogenic granitoids. The late-or postorogenic intrusive rocks belong to an age group of about 1 750—1 850 Ma, e.g.: pegmatite granite, Kitee (Kouvo 1958); trondhjemite, Tohmajärvi (Nykänen 1968); granodiorite, Anttola (Korsman and Lehijärvi 1973); granite, Rovaniemi (Geologinen tutkimuslaitos 1972, p. 16); granodiorite, Kaavi (Geologinen tutkimuslaitos 1977, p. 16); granites, Lapland (Meriläinen 1976); and granites, Åland (Vaasjoki 1978).

The U-Pb ages on zircon for metavolcanic rocks were obtained from the felsic volcanic rocks (felsite porphyries). Because of the scarcity of zircons only one size fraction could be used.

The most discordant age for zircon from felsic volcanic rock is from Heinäsuonpää (310, in Fig. 14). The rock is intensely hybridized and thermally metamorphosed. The modal analysis (Table 1) shows muscovite instead of biotite. The felsite porphyries from Pieni Kivimäki (308) and Korppinen (309) in Fig. 14 have slightly discordant ages. The distance between these two dated samples is only 3 km. Microscopy studies reveal that the samples are similar in mineral composition (Table 1) and that texturally they differ only slightly from each other. The felsite porphyry from Pieni Kivimäki is clearly porphyritic, and the matrix is more fine-grained than that of the rock from Korppinen.

Pb-Pb whole-rock age

The whole-rock Pb-Pb isochron age for the metavolcanic rocks of Pihtipudas was determined using drill core samples. The drill hole chosen for this purpose intersects a metavolcanic rock sequence of mafic, intermediate and silicic rocks. The description of the samples is given in Table 4.

The lead was extracted, separated and purified in accordance with the method described by Sakko and Laajoki (1975). The analytical data

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of the isotopes are given in Table 5. The Pb-Pb isochron plot for whole-rock samples is shown in Fig. 15. The age calculated from the Pb-Pb whole-rock system is 1898 ± 26 Ma (using the decay constants given by Jaffey *et al.* 1971) and 1 912 ± 26 Ma, if weighted according to York (1966). The most primitive lead on the whole-rock isochron in Fig. 15 is that of the Pihtipudas galena, which was not included in the isochron regression.

On the basis of U-Pb and Pb-Pb geochronological data from the Pihtipudas area, the supracrustal stage of volcanism and the synorogenic stage of deformation, metamorphism and granitoidic magmatism occurred about 1 900 Ma ago. It may be concluded that the outpouring of magma took place only slightly before the intrusion of the granitoidic rocks. The differences in age is not significant and the synorogenic intrusives and metavolcanic rocks are obviously cogenetic.

Two types of volcanism were involved in the Svecokarelian orogenic cycle: basaltic Jatulian volcanism with an age of about 2 000—2 200 Ma (Sakko 1971; Sakko and Laajoki 1975) and intermediate and silicic Svecofennian volcanism slightly older than 1 900 Ma, which also includes the supracrustal rocks of the Pihtipudas area. The meta-andesitic lavas in the Pellinge region with an age of approximately 1930 Ma (Kouvo 1976), and the intermediate and silicic lavas in the Pyhäsalmi area with age of 1 909 ± 27 Ma (Helovuori 1979) also show roughly the same age as the metavolcanic rocks at Pihtipudas.

The time-span between these two volcanic events is about 100—300 Ma.

Table 4. Description of samples analysed for whole-rock Pb-Pb isochron age from metavolcanic rocks, Pihtipudas.

Sample No. A 598	Location (drill hole/depth)	Sample description
A	R 7/ 25.80 m	Plagioclase and uralite porphyrite
B	R 7/ 43.70 m	Tourmaline-bearing uralite porphyrite
C	R 7/ 81.20 m	Tourmaline-bearing felsite porphyry with quartz phenocrysts
D	R 7/100.10 m	Felsite porphyry
E	R 7/117.30 m	Felsite porphyry
F	R 7/126.55 m	Agglomerate with disseminated pyrrhotite and pyrite grains
G	R 7/137.20 m	Intermediate and hybridized plagioclase porphyrite
H	R 7/140.70 m	Plagioclase and uralite porphyrite
I	R 7/163.22 m	Felsite porphyry rich in muscovite

Table 5. Whole-rock data for metavolcanic rocks of the Pihtipudas area. Sample numbers refer to Table 4.

Sample No.	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
A 598 B	16.3207 ± 0.0087	15.3806 ± 0.0136	35.6591 ± 0.0523
A 598 A	16.4021 ± 0.0104	15.3915 ± 0.0241	35.7331 ± 0.0615
A 598 F	17.1201 ± 0.0111	15.4449 ± 0.0131	35.9938 ± 0.0385
A 598 H	17.7685 ± 0.0084	15.5240 ± 0.0095	36.4851 ± 0.0254
A 598 G	17.8656 ± 0.0068	15.5354 ± 0.0067	36.3403 ± 0.0182
A 598 I	19.0625 ± 0.0162	15.6970 ± 0.0201	37.9531 ± 0.0610
A 598 C	20.5429 ± 0.0182	15.8981 ± 0.0256	38.9350 ± 0.0695
A 598 D	25.0679 ± 0.0295	16.3760 ± 0.0225	42.0413 ± 0.0584
A 598 E	25.6188 ± 0.0175	16.4505 ± 0.0139	42.7751 ± 0.0363

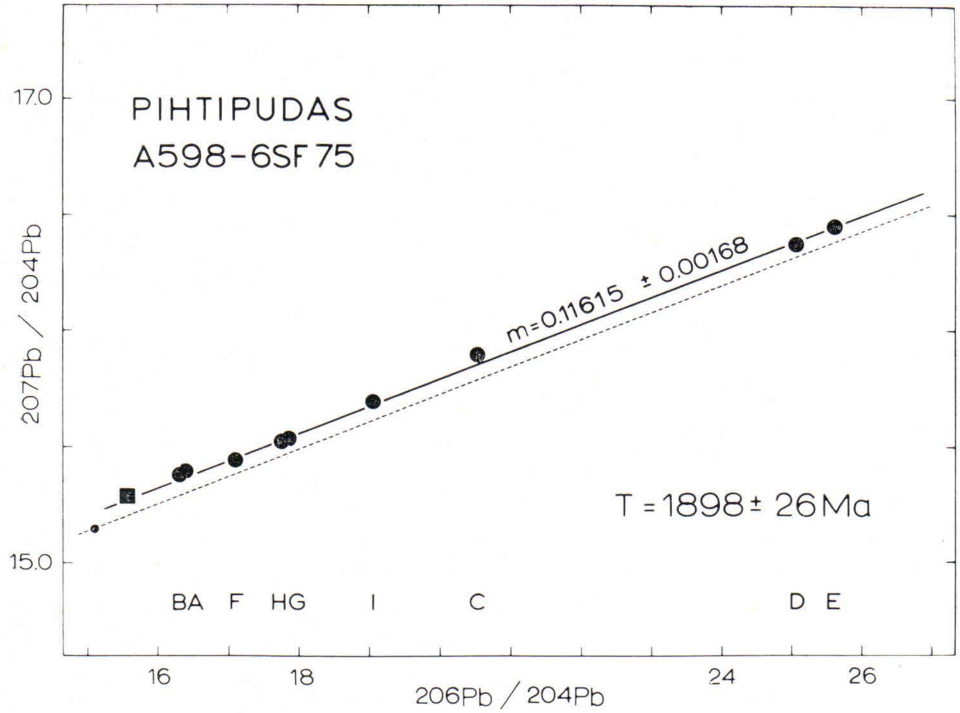

Fig. 15. Pb-Pb isochron plot for whole-rock samples from metavolcanic rocks, Pihtipudas: ●, metavolcanic rocks; ■, galena from Ritovuori, Pihtipudas; and •, galena from Pyhäsalmi (Stacey *et al.* 1977). Samples description is given in Table 4 and analytical data in Table 5. The reference isochron for Pyhäsalmi-Group volcanic rocks (Helovuori 1979) is shown for comparision.

Isotopic composition of lead in Pihtipudas galena

When lead is removed from its source and is included in minerals such as galena or feldspar, where the μ-value $^{238}U/^{204}Pb$ is close to zero, the model age of formation can be calculated from the measured $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ ratios because the evolution of the lead stops at the time of removal. This is possible, however, only if the geochemical history is known well enough. Problems arising from multistage histories, mixed sources, masked complex histories or changes affected by metamorphism have been discussed in numerous recent studies on common lead geochemistry.

It has long been recognized that the leads of many conformable deposits form an evolution curve within some surprisingly slight variations on the $^{238}U/^{204}Pb$ value. The deviations from this growth curve were often explained as due to inadequate analytical accuracy. Improved analytical techniques, however, have added more weight to the analyses along the isochrons, and not only along the growth curve. In other words, the genetic information obtained from the $^{238}U/^{204}Pb$ ratio, which reflects the sources of material (e.g. mantle/crust), can be considered as more reliable. The decreasing importance of common lead data as a tool for direct dating is still largely the fault of inadequate geological and genetic information.

Kouvo and Kulp (1961) were the first to report the isotopic composition of lead from Ritovuori deposit, Pihtipudas. The results pub-

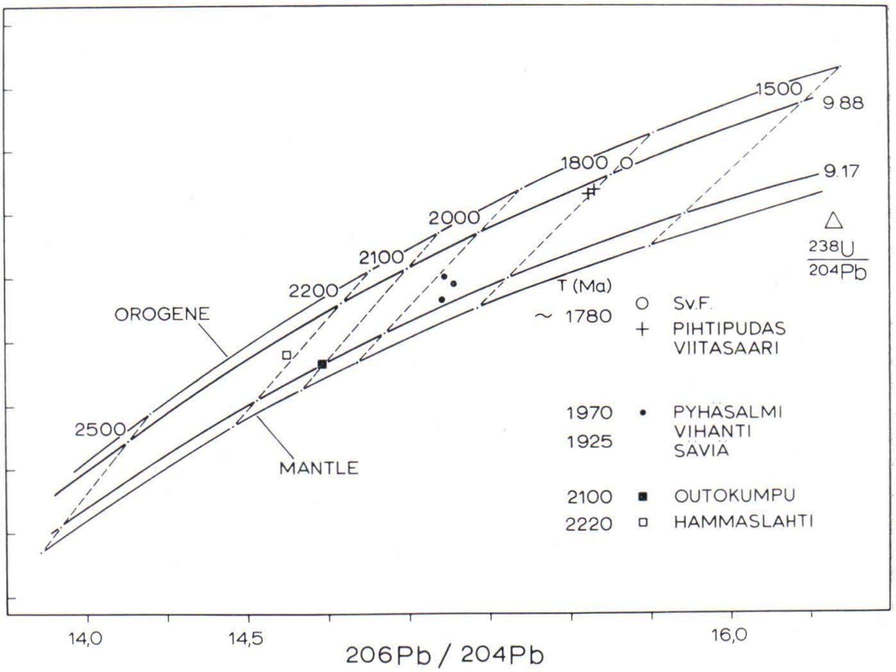

Fig. 16. Lead isotopic systematics and ages of some Finnish galenas including the Pihtipudas deposit (Simonen *et al.* 1978). O, Svecofennian in SW Finland.

lished then as well as the more accurate analyses published afterwards (Geologinen tutkimuslaitos 1974, p. 16; Stacey *et al.* 1977) showed that the isotopic composition of lead is not far from the Svecofennian lead included in several publications as a control point for the growth curve of conformable ore deposits. A different pattern of lead-isotopic ratios has been observed in the zinc-copper-lead ores in the Vihanti—Pyhäsalmi zone immediately north of Pihtipudas (Kouvo and Kulp 1961). A still more primitive isotopic composition of lead was found in the Outokumpu deposit (Kouvo 1958).

The principles of plumbotectonics proposed by Doe and Zartman (in press) offer a wide variety of genetic explanations based on time and uranium milieu, $^{238}U/^{204}Pb$. Stacey and coworkers (1977) have determined how well the principles of this plumbotectonic model could be extended into the Precambrian. Three Finnish ore deposits, Ritovuori, Pyhäsalmi and Outokumpu, were included in this study. Although lead isotope differences are much smaller in the Precambrian than in the Phanerozoic, the authors were able to identify bands of values between the mantle and upper crustal curves and the development of mantle lead. Figure 16 is based on the values given by Doe and Zartman (in press) and on the data given by Stacey *et al.* (1977):

	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Isochron model age
G16-GSF 61 Ritovuori, Pihtipudas	15.577	15.287	35.164	1800 Ma
G25b-GSF 61 Pyhäsalmi, Pyhäjärvi	15.111	15.147	34.835	1970 Ma
G30a-GSF 57 Outokumpu	14.731	15.016	34.476	2100 Ma

According to the authors mentioned above, a mantle origin is indicated for the Pyhäsalmi and Outokumpu deposits. The somewhat higher $^{207}Pb/^{204}Pb$ value for the Pyhäsalmi deposit exhibits a more continental character. The Pyhäsalmi area lies near the western edge of the Prekarelian craton and the numerous domes around the Outokumpu area indicate a near-continent environment as well. The small Ritovuori occurrence has been compared with similar lead in Broadway Mine, Wyoming, and in the 1700—1800 Ma old deposit of Arizona (Stacey *et al.* 1977). The data for the Pihtipudas deposit are not far below the orogene curve.

It has also been proved that the lead in the syngenetic deposits, in the Vihanti—Pyhäsalmi zone and in Outokumpu, does not fit the primary growth curve for terrestrial leads. Instead, the isotopic composition becomes more radiogenic to the west of the Prekarelian craton.

There are some other geochemical differences between these three groups of deposits with conspicuously different isotopic composition of lead. The most striking feature of decisive genetic significance common to Outokumpu-type deposits, and emphasized e.g. by Kouvo (1976), is that they are almost galena-free in contrast to the Vihanti—Pyhäsalmi-type zinc-copper-lead deposits and to the Pihtipudas deposit.

SUMMARY

The present study deals with an area in the Baltic Shield that, although relatively small, is of especial geological interest.

On the basis of U-Pb age determinations on zircon the synorogenic plutonic rocks in the Pihtipudas area are considered to be cogenetic with the metavolcanic rocks. All the rocks have been affected by the Svecokarelian orogeny, their emplacement having occurred approximately 1 883 $\pm$ 20 Ma ago. The whole-rock isochron age of 1 898 $\pm$ 26 Ma for the metavolcanic rocks in the Pihtipudas area indicates the age of Svecofennian volcanism, which is about 100—300 Ma younger than the Jatulian volcanism.

According to principles of the plumbotectonics model, the low $^{207}Pb/^{204}Pb$ value for Outokumpu ore places it on the mantle curve, the somewhat higher value for Pyhäsalmi ore points to a more continental character. The highest value for the Pihtipudas deposit are not far below the orogene curve.

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Appendix 1.

Chemical composition, Niggli values, CIPW norms (weight norms) of the metavolcanic rocks and granitoids from Pihtipudas area. XRF-analyses by Väinö Hoffrén.

	(308)*	(309)	(310)	(254)	(259)	(262)	(370)	(809)
SiO_2	69.77	69.10	71.10	65.39	64.97	66.89	69.65	67.12
Al_2O_3	15.41	14.03	12.95	14.85	14.93	14.27	14.29	14.95
Fe_2O_3 T	2.16	3.56	2.89	5.23	4.98	5.52	3.06	4.15
MgO	0.22	0.72	0.26	0.61	1.44	1.02	0.54	1.09
CaO	0.72	1.97	1.69	2.32	3.36	1.92	1.59	3.06
Na_2O	2.70	3.51	2.87	3.85	3.73	2.78	2.86	3.16
K_2O	6.71	3.50	2.94	3.16	3.13	3.70	4.41	2.68
MnO	—	0.06	0.07	0.08	0.09	0.09	0.05	0.07
TiO_2	0.23	0.34	0.25	0.45	0.51	0.61	0.34	0.40
P_2O_5	0.06	0.09	0.08	0.12	0.15	0.19	0.10	0.14
	97.98	96.88	95.10	96.06	97.29	96.99	96.89	96.82
Niggli values								
si	373	348	425	298	270	314	369	309
al	48.5	41.7	45.6	39.9	36.6	39.5	44.6	40.6
fm	10.4	19.1	15.6	22.4	24.8	27.0	16.7	22.1
c	4.1	10.6	10.8	11.3	15.0	9.6	9.0	15.1
alk	36.8	28.4	27.8	26.2	23.4	23.7	29.6	22.0
qz	125.5	134.9	213.7	93.6	77.3	119.3	150.8	121.6
mg	0.16	0.28	0.14	0.18	0.36	0.26	0.25	0.33
k	0.62	0.39	0.40	0.35	0.35	0.46	0.50	0.35
o	0.41	0.35	0.41	0.40	0.31	0.36	0.36	0.32
ti	0.92	1.29	1.12	1.54	1.59	2.15	1.35	1.38
p	0.13	0.19	0.20	0.23	0.26	0.37	0.22	0.27
Weight norms								
Q	26.68	30.24	39.37	23.36	22.57	31.46	32.20	30.69
C	2.54	1.10	2.16	1.16	—	2.65	2.16	1.62
or	39.65	20.68	17.37	18.67	18.49	21.86	26.06	15.83
ab	22.84	29.70	24.28	32.57	31.56	23.52	24.20	26.73
an	3.18	9.18	7.86	10.72	14.75	8.28	7.23	14.26
hy	0.54	1.79	0.64	1.51	3.58	2.54	1.34	2.71
hm	2.16	3.56	2.89	5.23	4.98	5.52	3.06	4.15
il	—	0.12	0.15	0.17	0.19	0.19	0.10	0.15
ti	—	—	—	—	0.66	—	—	—
ru	0.23	0.27	0.17	0.36	0.13	0.50	0.28	0.32
ap	0.14	0.21	0.18	0.28	0.35	0.45	0.23	0.33
Qu	29.92	37.51	48.59	33.10	31.08	40.94	39.05	41.90
Or	44.46	25.65	21.44	24.37	25.47	28.45	31.60	21.61
Ab	25.62	36.84	29.97	42.53	43.45	30.61	29.35	36.49
Qu	28.89	33.68	44.29	29.04	25.83	36.96	35.91	35.07
Or	42.93	23.03	19.55	21.38	21.17	25.68	29.05	18.09
Ab	24.74	33.07	27.32	37.30	36.12	27.63	26.98	30.55
An	3.44	10.22	8.84	12.28	16.88	9.73	8.06	16.29

*) Numbers refer to sample Nos in Table 3.
T = total Fe as ferric oxide

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