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The chronostratigraphy of southwestern Finland with special reference to Postjotnian and Subjotnian diabases

by Veli Suominen

Geologian tutkimuskeskus
Espoo 1991

ERRATA

page 12, line 5	**for** cm3 **read** cm^3
page 22, line 43	**for** SN **read** Sn
page 25, Fig.17a figure caption	**for** Zr **read** ZR
page 37, left column, line 9	**for** 00 **read** 200
page 52, fraction A029E	**for** HFe **read** HF
page 57, Fig. 43. figure caption	**for** 81-va **read** Åva
page 66, left column, line 5	**for** tint, **read** tint;
page 74, left column, line 15	**for** zircons **read** zircon
page 74, right column, line 8	**for** above **read** above mentioned
Appendix 5, Fig. 2, figure caption	**for** crystalization **read** crystallization

Appendix 5. Additional data for sample A920.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration $\mu g/g$ ^{238}U	Concentration $\mu g/g$ ^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A920-Kittuis, Houtskär: pyroxene granodiorite										
A920C	4.2<d<4.3; abr long crystals	662.0	180.96	5907	.01574	11.500	6.539	.3159 ± 17 1769	4.916 ± 27 1805	.11286 ± 5 1846
D	4.2<d<4.3; abr short crystals	661.7	179.00	5448	.01708	11.508	6.183	.3126 ± 16 1753	4.861 ± 26 1795	.11276 ± 11 1844

For symbols, see Table 3.

Geological Survey of Finland, Bulletin 356

THE CHRONOSTRATIGRAPHY OF SOUTHWESTERN FINLAND
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with 63 figures, 18 tables in
the text and 5 appendices

GEOLOGIAN TUTKIMUSKESKUS
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The intrusions and geological events characterizing the development of the Precambrian crust in southwestern Finland were dated by determining radiometric U-Pb ages on zircons, titanites, monazites, baddeleyites and one uraninite. The dated samples are from late Proterozoic (Postjotnian and Subjotnian) diabases, quartz porphyries, rapakivi granites and middle Proterozoic (synorogenic and late- and postorogenic Svecokarelian) granites, granodiorites, pyroxene granodiorites and gabbros.

The radiometric ages of rock formations in the Åland archipelago and adjacent areas in southwestern Finland are summarized and discussed.

The six oldest granitoid plutons dated in the Åland area are the synorogenic intrusions. They form an age group of 1880 ± 20 Ma.

The seven late-orogenic granites dated in southwestern Finland form a coherent age group of 1830 ± 10 Ma. The pyroxene granodiorites (1862 ± 6 Ma) mark an intraorogenic thermal pulse during that time. The postorogenic granites in the Åland archipelago are dated to an interval of 1770—1815 Ma.

A comparison is made with the Wiborg (Viipuri) rapakivi batholith (1630—1645 Ma) and the Salmi rapakivi intrusion (1539 ± 11 Ma).

The ages of the four quartz porphyry dykes dated are very close to the age of the Åland rapakivi intrusion. In the light of these results (1575 ± 10 Ma), the pyroxene diabases from the Föglö dyke set and the anorthositic variety of the Västersten diabase southwest of the Åland rapakivi area are coeval, within the limits of error, with the main phase of the Åland rapakivi granites.

The olivine diabases dated in western Finland are all of the same Postjotnian age (1260 ± 10 Ma).

Key words (GeoRef Thesaurus, AGI): radiometric ages, diabase, rapakivi, quartz porphyry, granites, granodiorites, U/Pb, Rb/Sr, Jotnian, Proterozoic, Finland.

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CONTENTS

INTRODUCTION

When introducing the term Jotnium for the youngest Precambrian formations in Fennoscandia, J.J. Sederholm (1897) included in it diabases, sandstones and rapakivi granite intrusions and the accompanying quartz porphyries, diabases, anorthosites and gabbros. Högbom (1910) called the lower Jotnian Subjotnian because the two formations were separated by an unconformity. Later, Sederholm (1927) divided the Jotnian into two groups: the Upper Jotnian, made up of sandstones overlain and intercalated by diabases, and the Lower Jotnian, comprising rapakivi granites with effusive members and the oldest mafic eruptives (ossipites). He coined the term Hoglandium for the Subjotnian rocks.

Jotnian sedimentary rocks occur in many parts of the Fennoscandian shield: in the U.S.S.R. on the south coast of the Kola peninsula (the Tersky coast), on the southwestern shore of Lake Onega, in the Salmi area in Soviet Karelia (Kairyak and Khazov 1967) and probably on the bottom of Lake Ladoga, also in Soviet Karelia (e.g. Hackman 1933); in Finland in Satakunta and Muhos (e.g. Simonen and Kouvo 1955); and in Sweden in the Lake Mälaren area (Gorbatschev 1962), the Gävle area (Gorbatschev 1967), Dalsland and the Nordingrå area (von Eckermann 1937).

Olivine diabases that are very similar in petrography and mode of occurrence occur as steeply dipping dykes or as sheet intrusions on both the Finnish and Swedish coasts of the Gulf of Bothnia (see Fig. 1 for sites and coordinates given in Appendix 1). In western Finland all these olivine diabases have been regarded as Postjotnian, although only in the Satakunta area do the olivine diabases overlie and cut the Jotnian sandstone (Sederholm 1934). The present work dates the Postjotnian diabases of Åland, Satakunta and Vaasa. From the results of palaeomagnetic measurements, these have been regarded as Jotnian by Neuvonen (1965, 1966) and Neuvonen and Grundström (1969).

Owing to their low zircon content, diabases have previously only been dated with K/Ar and Rb/Sr methods. However coarse-grained varieties of diabase, frequently contain enough zircon for dating with the U-Pb method, and samples of about 50 kg often seem to be large enough to give more than enough zircon for the analyses. In diabase pegmatoids, comagmatic with the whole diabase, zircon is concentrated in the parts rich in plagioclase, but the megacrysts do not contain as much zircon as does the matrix of the same sample (this also seems to apply to rapakivi granites). In some types of olivine diabase, baddeleyite is the principal zirconium mineral either together with zircon or alone (Siivola 1977 and this study).

The Föglö dyke set in the eastern archipelago of Åland is a Subjotnian diabase of special interest. This pyroxene diabase, which Sederholm (1934) called ossipite, has been considered older than not only the olivine diabases but also the rapakivi granites of the Åland Islands. Frosterus (1893), who first described the dyke, considered it younger than the rapakivi group, but Sederholm (1934) and Hausen (1964) later declared the pre-rapakivi age to be the more probable. The anorthositic varieties of pyroxene diabase, southwest of the Åland rapakivi, seem to be similar to the Föglö dyke set in many respects.

The quartz porphyry dykes around the Åland

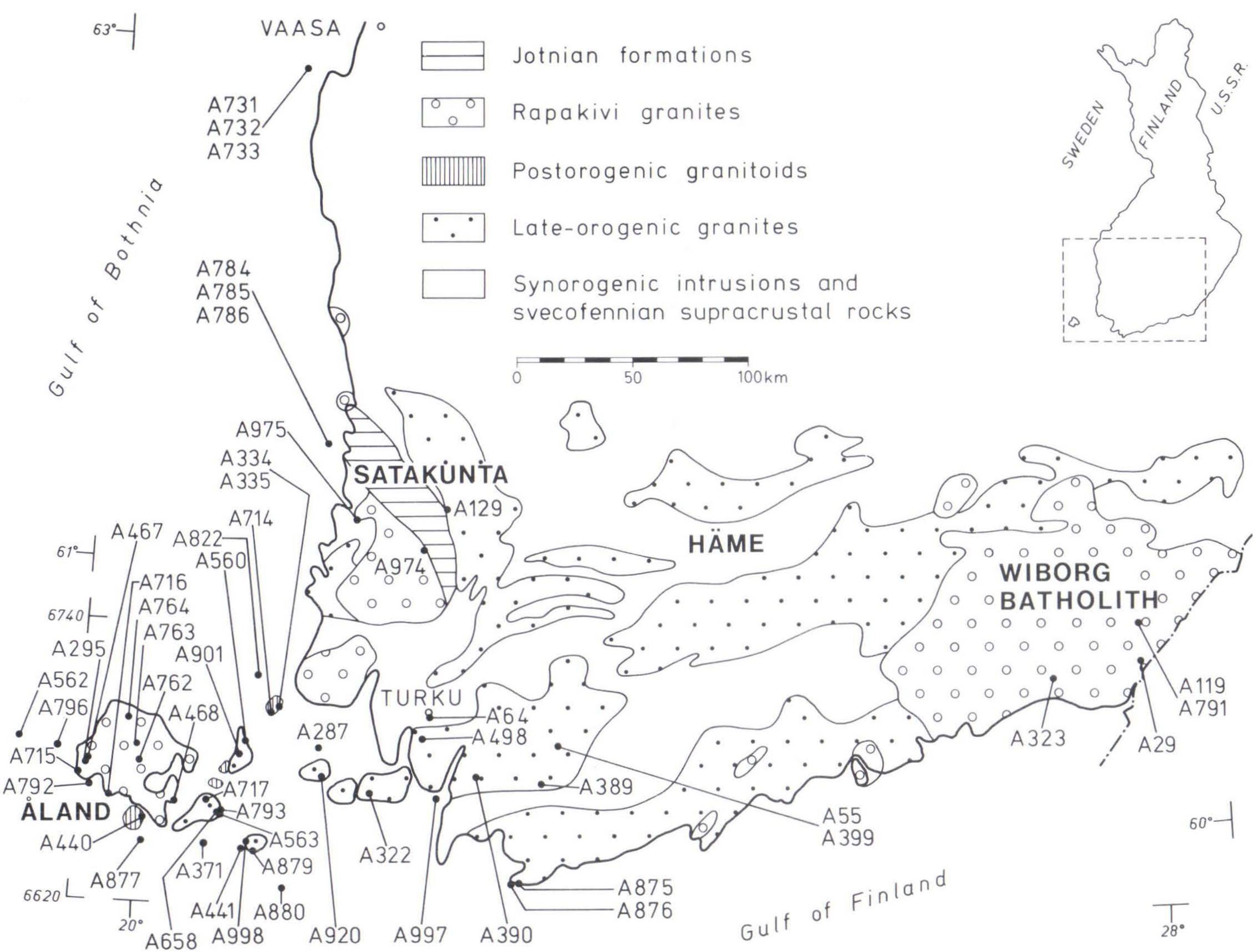

Fig. 1. Geological map of study area and sample sites referred to in text. The coordinates are given in Appendix 1. Map modified from Simonen (1980a).

rapakivi have been interpreted as contemporaneous with the main rapakivi phase of Åland (Vaasjoki 1977). Several authors (e.g. Sederholm 1934, Kaitaro 1953, Ehlers and Bergman 1984) have suggested that the quartz porphyries and pyroxene diabases are also coeval. Quartz porphyry dykes are known to cut some of the coarse-grained anorthositic diabases, but contact observations made southwest of the Åland rapakivi are ambiguous (cf. Bergman 1981).

The granitoids of southwestern Finland have traditionally been classified into four groups as compiled by Sederholm (1932) and recently updated by Nurmi and Haapala (1986). The youngest granitoids, rapakivi granites, belong to group IV; the postkinematic, coarse-grained porphyritic potassium granites to group III; the migmatite building potassium granites to group II and the (often gneissose) granites, granodiorites, tonalites and quartz diorites to group I. To provide insight into the magmatectonic evolution of southwestern Finland, new age data are given and the chronostratigraphy is discussed.

The characteristic features of the different granitoid groups are summarized in Table 1. One of the most distinctive features of the rapakivi granites (IV) is their high zircon content. The fluorite content is also high, and the titanium mineral is anatase. In the group III granites a high titanite content together with zircon is common, and the total iron content is relatively high. In the group II granites the accessory minerals are more diverse, and a high monazite content is often met together with only minor, if any, zircon and titanite. Rutile seems to be present instead of titanite. In the granitoids of group I, zircon and titanite are common accessory minerals.

The Åland rapakivi pluton is composed of several parts (see Bergman 1981, 1986). The main phase has been dated by Vaasjoki (1977). In the present study new zircon fractions were analysed from the rapakivi granites dated earlier and four additional specimens were dated to ascertain the age relations between the Subjotnian diabases, quartz porphyries and rapakivi granites.

The small rapakivi granite stock of Peipohja in Satakunta was previously dated by Kouvo (1958) and Vaasjoki (1977). Additional zircon fractions were now analysed from this reference rapakivi granite.

The rapakivi pluton of Kökarsfjärden and the rapakivi stock of Fjälskär in the southwestern archipelago, previously dated by Vaasjoki (1977), were redated with additional fractions and the latter with a new sample.

For comparison, some of the Wiborg rapakivi samples were dated with additional zircon fractions to verify the previously published data of Kouvo (1958) and Vaasjoki (1977). New reference ages for the Salmi rapakivi in Soviet Karelia were determined.

Several granite intrusions of postorogenic character, differing from the rapakivi granites in field relations and in mineral and chemical compositions, occur close to some of the intrusions dated here. They are cut by mafic dykes that are probably older than the diabases dated and dis-

Table 1. Granite groups of Sederholm with characteristics in southwestern Finland.

I	II	III	IV
Synorogenic	Late–orogenic	Postorogenic	Anorogenic
ass. pegmatite	ass. pegmatite	ass. pegmatite	rare
–	migmatite forming	–	–
rare	aplites	rare	aplites
zircon	(zircon)	zircon	zircon
titanite	rutile	titanite	anatase, rare
magnetite	magnetite	magnetite	magnetite
–	monazite	–	rare
–	–	rare	fluorite

cussed in this context. The Lemland intrusion south of Mariehamn has been dated by Vaasjoki (1977), who established that the rapakivis were significantly younger than the postorogenic granites of Åland. Neuvonen (1970), Vaasjoki (1977) and Patchett and Kouvo (1986) have presented age data on the Åva granite and »monzonite» intrusions. The Mosshaga intrusion has been dated by Vaasjoki (1977) and more recently by Welin et al. (1983); the Seglinge intrusion (1815 Ma) has also been dated by Vaasjoki (1977).

The Kumlinge granite was described by Sederholm (1934) as a good example of group II granites. Of the late-orogenic intrusions in southwestern Finland, the Perniö granite has been dated by Gast (1960) and Wetherill et al. (1962), and the Hanko granite by Hopgood et al. (1983) and Huhma (1986).

The present paper also gives age data for two synorogenic granodiorites, two granites and two gabbros in the eastern archipelago of Åland. The granitoids resemble those of Sederholm's group I. The Föglö dyke set cuts the granodiorite represented in this study by the Algersö sample, and the Bockholm granodiorite gives one additional point for the chronostratigraphy of the Åland area. Age data have earlier been published for the Mörskär and Svartgrund samples (Patchett et al. 1981, Patchett and Kouvo 1986).

The present paper documents the age relations of the diabase dykes in southwestern Finland and discusses the tectonic setting and emplacement time of these dykes and of some other Precambrian igneous rocks in that part of southwestern Finland.

ANALYTICAL PROCEDURES

All the isotopic analyses given in this paper were carried out in the laboratories of the Unit for Isotope Geology, Department of Petrology, Geological Survey of Finland. At the same time Rb-Sr dates were determined for some of the diabases discussed here and for some of the rapakivi granites by Dr Otto van Breemen at the Scottish Universities Research and Reactor Centre.

The analytical procedures used follow those of Krogh (1973) and have been described in detail by Vaasjoki (1977) and Huhma (1986). The few fractions fused earlier in borax were found to be comparable to fractions decomposed in hydrofluoric acid. Quartz and diamond paste abrasions were used in an unsuccessful attempt to improve the discordant zircon ages. To reduce the common lead of the zircons some fractions were crushed and washed in nitric acid (1 : 1 conc. $HNO_3 + H_2O$) and some were preleached in hydrofluoric acid. The air abrasion method described by Krogh (1982) was also used with a device developed and kindly supplied by Dr T.E. Krogh. The air pressure was 0.3 bar, and the time for abrasion ranged from 5 min. to 5 hr. The sample size of zircon for individual analyses ranged from 1 to 20 mg, that of monazite from 2 to 4 mg and that of titanite from 20 to 30 mg.

After removal of the blank (usually less than one nanogram), the remaining initial lead was assumed to have a model isotopic composition estimated from figures given by Doe and Stacey (1974). In no case was the initial lead isotopic composition critical. However, in the determination of ages on zircons from some rapakivi granites and quartz porphyries, the $^{206}Pb/^{204}Pb$ ratio was as low as 200—400 and, hence, the lead isotopic ratios were measured from coexisting K-feldspar and were corrected for 1575 Ma of inplace radioactive decay. The common lead corrections based on K-feldspar lead isotopic composition corrected for radiogenic component were applied only to the Åland rapakivi batholith and to one quartz-porphyry sample (see Table 2).

Table 2. Isotopic composition of lead in K-feldspar used for common lead correction.

Sample No.	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Concentration µg/g Pb	Concentration total U
A295	16.89	15.50	36.34	27.48	0.55
A762	16.96	15.46	36.17	21.67	0.36
A764	16.71	15.47	36.09	34.89	0.31
A715	17.60	15.54	36.05	30.37	0.21

For samples A468 and A763, the average isotopic composition of A295, A762 and A764 was used and for sample A467 that of the other Eckerö sample, A295. All these ages were also calculated from a model lead isotopic composition given by Doe and Stacey (1974).

Isotopic ratios were measured using conventional techniques. Pb- and U-isotope ratios were determined on microcomputed-controlled 9′, 60° thermal ionization mass spectrometers. The isotopic ratios were corrected for fractionation by comparison with analyses of CIT and NBS981 leads. The analytical errors were estimated largely with reference to Vaasjoki (1977, pp. 12—13).

The ages given in this paper were calculated using the decay constants recommended by the Subcommission on Geochronology (Steiger and Jäger 1977). The method developed by York (1969) was used to fit the regression line. Errors in the ages from the concordia intercepts are quoted at the 2-sigma level. The average precision of the $^{206}Pb/^{204}Pb$ ratio varies: if <1000 the ratio has an error of ± 1.6 %, if 1000—2000 it is ± 2.1 % and if >2000 ± 2.5 %; the average error is 1.9 %.

THE POSTJOTNIAN OLIVINE DIABASES OF WESTERN FINLAND

Jotnian formations in sensu lato cover large areas of the Fennoscandian shield. Jotnian sedimentary rocks, which are known to be cut by diabases, lie on rapakivi granites and associated rocks.

Jotnian olivine diabases form voluminous sills and dykes in three areas in western Finland: the western margin of the Åland islands, the Satakunta area and the Vaasa archipelago. In all these areas the olivine diabases are very alike in composition and texture; only in the Satakunta area do they overlie and cut the Jotnian sandstones. The Muhos siltstone, in northwestern central Finland, has been dated to 1362 Ma, I.R. = 0.704 (unpublished preliminary Rb-Sr isochron; Dr O. Kouvo, pers. communication) and to about 1200 Ma on the basis of biotype (Tynni and Uutela 1984). The Jotnian sediments in Satakunta have been dated by the K-Ar method to 1130—1318 Ma, (assumed new Soviet constants, 1097 Ma—1278 Ma if conversed after Harland et al. 1982) and the argillaceous siltstone in Muhos to 1280 — 1318 Ma (Simonen 1960, Polkanov and Gerling 1961a). These ages, with assumed new Soviet constants, if conversed after Harland et al. 1982, would be 1242—1278 Ma.

In earlier papers the term Jotnian was applied to all olivine diabases on petrographic criteria; strictly speaking they should be called Postjotnian.

Märket, Eckerö

In the Åland Sea the olivine diabase crops out on five small islands and skerries around the tiny lighthouse island of Märket, on the border between Finland and Sweden. In all these outcrops the olivine diabase is a dark brownish grey, coarse-grained, ophitic rock. No contacts with

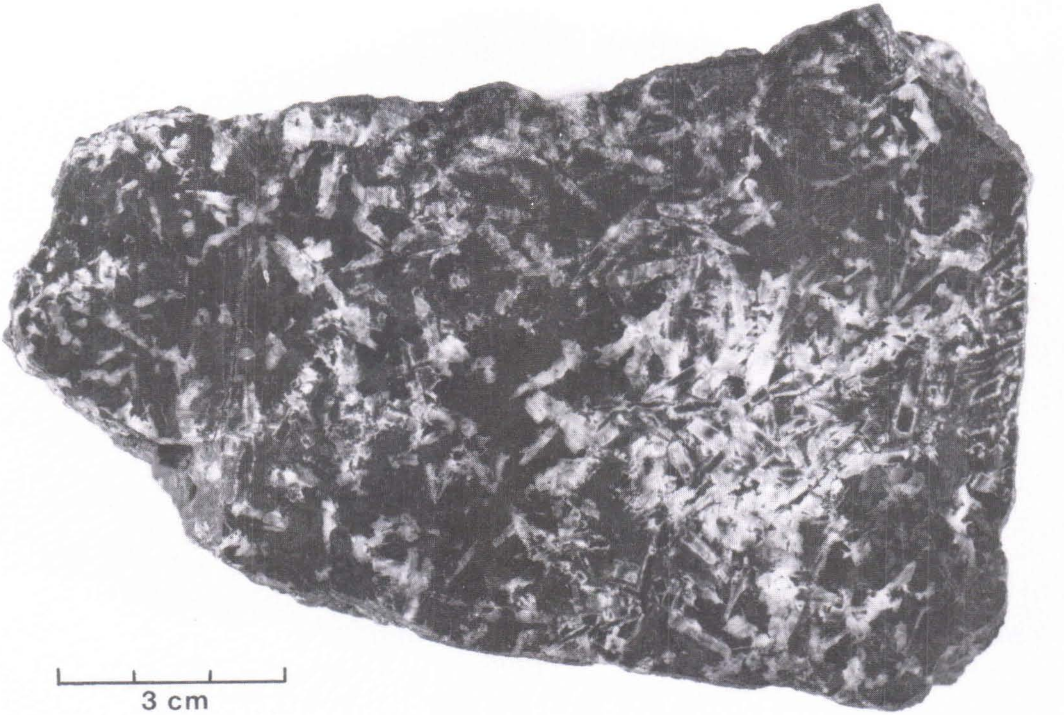

Fig. 2. Coarse-grained ophitic olivine diabase from Märket with characteristic small patches of accumulated plagioclase. Actual size. Polished surface.
Photo Erkki Halme.

adjacent rocks have been found. Using topographic criteria, Hausen (1964) interpreted the diabase body as a sill lying on sandstone, which in turn overlies rapakivi granites. To the east, the bedrock consists of rapakivi granite of the Åland area and to the west of older Svecokarelian supra- and infracrustal rocks. A similar olivine diabase is met with on the island of Halsaren off the nearby Swedish coast, some 15 km southwest of Märket (Åhman 1947). According to chemical and modal analyses, the olivine diabase on Märket (Sederholm 1934, Bergman 1981, Suominen 1987a) is similar to the Halsaren diabase (Åhman 1947) and is of the Swedish Åsby type.

Sample A562 is from south of the lighthouse on Märket. The main constituents are zonal or polysynthetically twinned plagioclase (An 55—60), clinopyroxene (pigeonite-augite) and olivine, often altered to iddingsite or serpentine. The main opaque minerals are magnetite and ilmenite. The accessories include biotite, apatite as long, acicular, clear, transparent crystals, titanite, quartz, zircon and baddeleyite. Hornblende, epidote and sericite occur as alteration products in abundances of up to 3—4 % in some thin sections. The main and accessory mineral compositions of the samples in this study are summarized in Appendices 2 and 3.

The grain size of diabase sample A562 is typical of the area, but the plagioclase content is slightly higher than usual and the rock in the outcrop has a faint reddish tint. No real diabase pegmatoids are found on Märket or in the adjacent diabase outcrops. Only some small dot-like clusters of plagioclase are scattered here and there in the normal, coarse-grained type of diabase

Fig. 3. Microphotograph of olivine diabase from Märket with typical skeletal magnetite and ophitic texture. + nicols. Photo Erkki Halme.

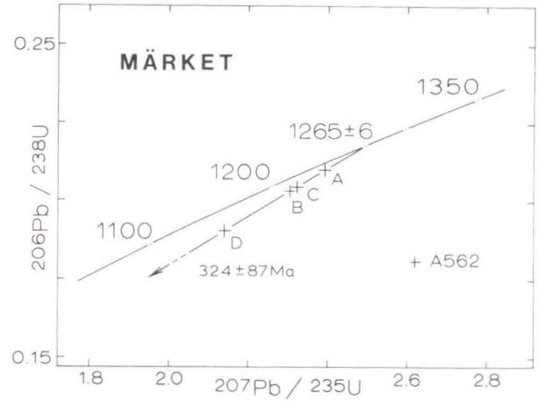

Fig. 4. Concordia diagram and U-Pb isotope ratios for zircon fractions from the Märket diabase (A562). Each zircon fraction is indicated by a letter referred to in Table 3.

(see Fig. 2). Olivine is irregularly distributed in the Märket diabase, and its abundance seldom reaches 2 %. The magnetite content is high, ca. 10 %, and the mineral occurs together with ilmenite lamellae as skeletal aggregates (see Fig. 3).

The Märket diabase is free from country-rock inclusions. No xenoliths of sandstone have been met with, but the diabase is cut by small, narrow rheomorphic dykelets that bear a close resemblance to the rheomorphic dykes described from Halsaren by Åhman (1947).

The zircon grains in sample A562 are large, and the fractions studied consist of fragments of transparent, faint, pinkish crystals.

The upper intercept age of the four zircon fractions on a concordia diagram is 1265 ± 6 Ma (see Fig. 4). The isotopic data and the apparent radiometric ages are given in Table 3.

Säppi, Luvia

Various types of diabase have been described from the Satakunta area (A. Laitakari 1925, 1928, Kahma 1951, Hämäläinen 1987, Pihlaja 1987). The olivine diabases are sills or dykes but, according to the results of palaeomagnetic measurements, there is no difference between the olivine diabases of vertical dykes and sills (Neuvonen 1965).

The olivine diabases of the Satakunta area (see Fig. 1) are represented by samples from Säppi, Hankkila and Ämmänpelto. Säppi is an island in the Gulf of Bothnia, off the town of Pori. Hankkila is in the northernmost corner of the Sorkka diabase, some 35 km south-southeast of Säppi, and Ämmänpelto is roughly the same distance east of Hankkila.

Table 3. U-Pb isotopic data on Postjotnian olivine diabases.

Sample No.	Fraction[1] d=density, g/cm3 Ø=grain size, μm	Concentration μg/g ^{238}U	^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A562-Märket, Eckerö: olivine diabase										
A562A	d>4.0	688.4	125.30	887	.10698	9.756	73.280	.2104	2.391	.08244
								± 12	± 16	± 21
								1230	1239	1256
B	3.8<d<4.0	1038	182.47	1109	.08759	9.464	77.855	.2032	2.305	.08225
	Ø>130							± 12	± 14	± 10
								1192	1213	1251
C	3.8<d<4.0	971.2	171.88	930	.10464	9.716	78.387	.2045	2.323	.08237
	70<Ø<130							± 12	± 15	± 20
								1199	1219	1254
D	3.6<d<3.8	1156	190.58	671.5	.14613	10.218	79.859	.1905	2.140	.08150
	light-coloured							± 11	± 15	± 25
								1123	1161	1233
A784-Säppi, Luvia: megaophitic olivine diabase										
A784A	4.0<d<4.2	935.3	166.96	4162	.02075	8.463	51.830	.2063	2.324	.08170
	Ø>160							± 11	± 13	± 11
								1209	1219	1238
B	d>4.2;	588.3	106.32	3579	.02436	8.618	40.432	.2089	2.383	.08274
	Ø>70							± 11	± 14	± 12
								1222	1237	1263
C	4.0<d<4.2	968.2	175.29	5205	.01687	8.481	51.491	.2092	2.378	.08242
	Ø>160							± 11	± 13	± 8
								1224	1235	1255
D	baddeleyite	252.7	46.50	4205	.02097	8.576	2.388	.2127	2.428	.08280
								± 16	± 20	± 14
								1242	1250	1264
A785-Säppi, Luvia: megaophitic olivine diabase										
A785A	4.0<d<4.2	970.0	174.36	3960	.01931	8.520	68.567	.2077	2.362	.08247
								± 11	± 14	± 16
								1216	1231	1256
B	3.8<d<4.0	1357	234.97	5319	.01474	8.413	74.516	.2002	2.265	.08205
	Ø>70							± 11	± 13	± 11
								1176	1201	1246
C	3.6<d<3.8	1450	234.36	2968	.02958	8.564	77.802	.1868	2.098	.08145
	Ø>70							± 10	± 12	± 11
								1103	1148	1232
A786-Säppi, Luvia: megaophitic olivine diabase										
A786A	d>4.2;	502.8	90.45	2169	.04151	8.878	41.688	.2079	2.377	.08291
	Ø>160							± 11	± 14	± 15
								1217	1235	1267
B	4.0<d<4.2	770.4	136.81	1568	.05996	9.069	50.732	.2053	2.327	.08222
	Ø>160							± 11	± 14	± 19
								1203	1220	1250

Table 3. (continued)

A786C	4.0<d<4.2	808.0	143.73	1538	.06206	9.086	51.543	.2056	2.327	.08208
	Ø>160							± 11	± 13	± 12
								1205	1220	1247
A975–Hankkila, Eurajoki: olivine diabase pegmatoid										
A975A	4.2<d<4.6	411.3	74.88	1666	.05492	8.984	74.356	.2104	2.381	.08207
								± 11	± 15	± 19
								1231	1236	1247
B	4.0<d<4.2	774.0	139.21	1760	.05399	8.983	82.808	.2079	2.356	.08220
								± 18	± 23	± 34
								1217	1229	1250
C	3.8<d<4.0	1222	214.35	1416	.07011	9.175	91.606	.2028	2.288	.08183
								± 15	± 18	± 20
								1190	1208	1241
D	baddeleyite	264.1	49.10	4298	.02077	8.551	4.183	.2149	2.447	.08258
								± 32	± 37	± 11
								1254	1256	1259
E	d>4.0;	722.4	131.85	1148	.08496	9.450	82.864	.2110	2.399	.08250
	abr 5 h							± 17	± 20	± 16
								1233	1242	1257
A974–Ämmänpelto, Kauttua: olivine diabase pegmatoid										
A974A	4.0<d<4.2	–	–	6355	.01574	8.449	44.156	–	–	.08226
										1252
B	baddeleyite	268.6	48.72	6234	.01333	8.451	2.124	.2097	2.388	.08263
								± 12	± 14	± 11
								1227	1239	1260
A731–Svall, Korsnäs (Moikipää area): megaophitic diabase										
A731A	total	907.6	159.68	1432	.06898	9.244	69.843	.2034	2.319	.08270
								± 11	± 15	± 28
								1193	1217	1262
B	baddeleyite	153.3	28.59	1100	.08298	9.559	7.575	.2156	2.493	.08388
								± 16	± 21	± 27
								1258	1269	1290
A732–Norrgrynnan, Korsnäs (Moikipää area): megaophitic diabase										
A732A	d>4.2;	486.8	85.62	1566	.05516	9.048	60.950	.2033	2.317	.08268
	Ø>70							± 11	± 15	± 24
								1192	1217	1261
B	4.0<d<4.2	843.9	143.07	829	.11709	9.925	66.945	.1959	2.234	.08271
	Ø>130							± 10	± 14	± 21
								1153	1191	1262
C	4.0<d<4.2	791.8	134.11	630.9	.15513	10.410	71.649	.1958	2.218	.08217
	70<Ø<130							± 10	± 12	± 13
								1152	1186	1249
D	3.8<d<4.0	1154	179.25	568.9	.17209	10.642	72.155	.1795	2.031	.08209
	Ø>70							± 9	± 12	± 21
								1064	1126	1247

Table 3. (continued)

A732E	3.6<d<3.8	1100	164.41	546.1	.17895	10.687	73.423	.1727	1.942	.08155
	Ø>70							± 9	± 12	± 25
								1026	1095	1234
F	4.0<d<4.2	818.1	138.04	631.0	.15487	10.408	72.457	.1950	2.210	.08218
	70<Ø<130							± 10	± 26	± 77
								1148	1184	1250
A733-Norrgrynnan, Korsnäs (Moikipää area): spotted diabase										
A733A	3.8<d<4.0	1044	173.80	3647	.02460	8.522	83.454	.1925	2.169	.08174
								± 10	± 12	± 15
								1134	1171	1239

The following decay constants (DC) were used (Steiger & Jäger 1977):
$DC^{238}U = 1.155125 \times 10^{-10}/a$
$DC^{235}U = 9.8485 \times 10^{-10}/a$
atomic ratio $^{238}U/^{235}U = 137.88$

[1] all fractions are zircon unless otherwise indicated
[2] recalculated from Vaasjoki (1977)
borax = borax fusion
HF = preleached in hydrofluoric acid
cr = crushed material, powder preleached in 1:1 HNO_3
abr = air abraded
abr quartz = abraded with quartz
abr diamond = abraded with diamond paste
Errors in atomic ratios refer to two last significant digits.

The sampling sites on Säppi are on the northwestern shore of the island. The olivine diabase is a differentiated sill (Eskola 1936, Inkinen 1963) showing several varieties. All the types are coarse-grained and exhibit clear contacts with each other. Igneous layering is met with in some places on the northern shore of Säppi. No contacts with the country rocks have been found.

For the age determinations, samples were taken from the megaophitic variety (see Fig. 5), which occurs as lenticular bodies, often with sharp, loop-formed contacts (see Fig. 6 and 7) to the adjacent olivine diabase. Eskola (1936) considered them pipes, but they are more likely inhomogeneity pockets such as occur in cast iron. They seem to be comagmatic, like the pegmatoids in the gabbros of the Tammisaari area (Hopgood et al. 1983), and free from country-rock assimilation.

The normal type of olivine diabase contains ca. 14 % olivine (Inkinen 1963), but the megaophitic variety lacks olivine (Eskola 1936). The other constituents are the same, and are irregularly distributed within the megaophitic bodies (see Figs. 5, 6 and 7).

On the northern shore of Säppi the main type is pyroxene diabase, but pegmatoids with K-feldspar also occur. The pyroxene diabase exhibits a fluidal parallel orientation around these pegmatoids but since they may have assimilated material from the country rock they were not sampled.

When the Säppi diabases were sampled for the first time, the lightest type, which is the richest in plagioclase (see Fig. 8) and occurs in a homogeneous part of the »spotty diabase» (Inkinen 1963), was chosen. However, it yielded a baddeleyite concentrate and very little zircon; the normal olivine-bearing type also produced only scant zircon. New samples were collected from the palest parts of the megaophitic diabase pegmatoid pockets, where the plagioclase laths are commonly 2 cm, often 5 cm, long.

The main minerals are plagioclase (An 60),

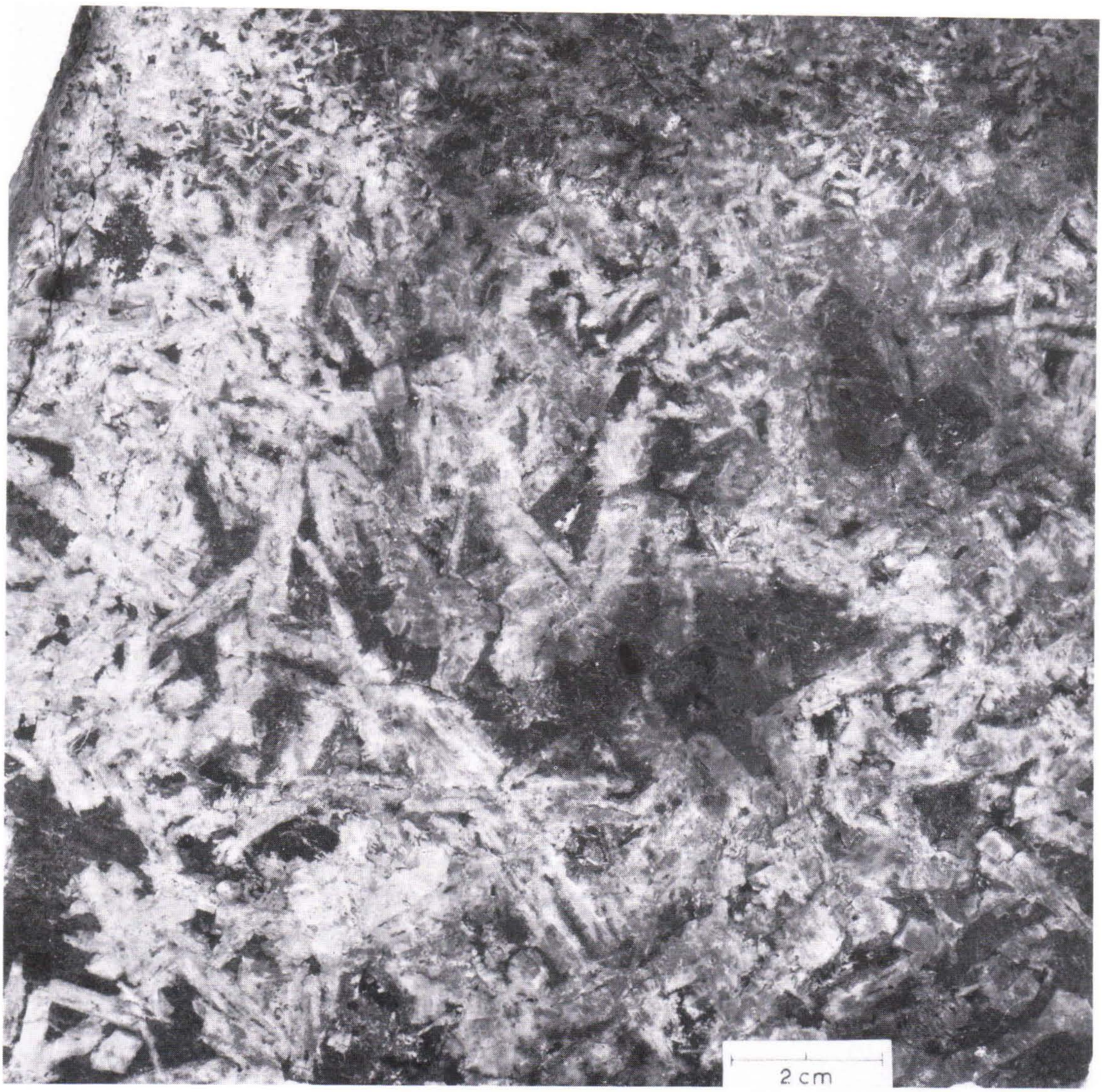

Fig. 5. Megaophitic diabase pegmatite (A785) on the western shore of Säppi. Glacial polished surface. Photo Helena Halme.

augite and ilmenite + magnetite. The accessory minerals include apatite, zircon and baddeleyite. For chemical analyses and modes, see Eskola (1936), Inkinen (1963) and Suominen (1987a).

The zircons analysed from samples A784, A785 and A786 are mostly fragments of large, short (length/breadth = L/B ratio 1—2), transparent prisms with a zonal growth structure (see Fig. 9).

The analytical data are given in Table 3. The upper intercept age for the data points of the zircon fractions in a concordia diagram (see Fig. 10) for Säppi is 1264 ± 12 Ma. The data point of the A784 D baddeleyite falls on the regression line.

Fig. 6. Loop contact between megaophitic diabase pegmatoid (A786) and olivine diabase on the western shore of Säppi. Length of ruler 20 cm. Photo Veli Suominen.

Fig. 7. Unevenly distributed light and dark minerals in megaophitic pegmatoid diabase on the western shore of Säppi. Photo Veli Suominen.

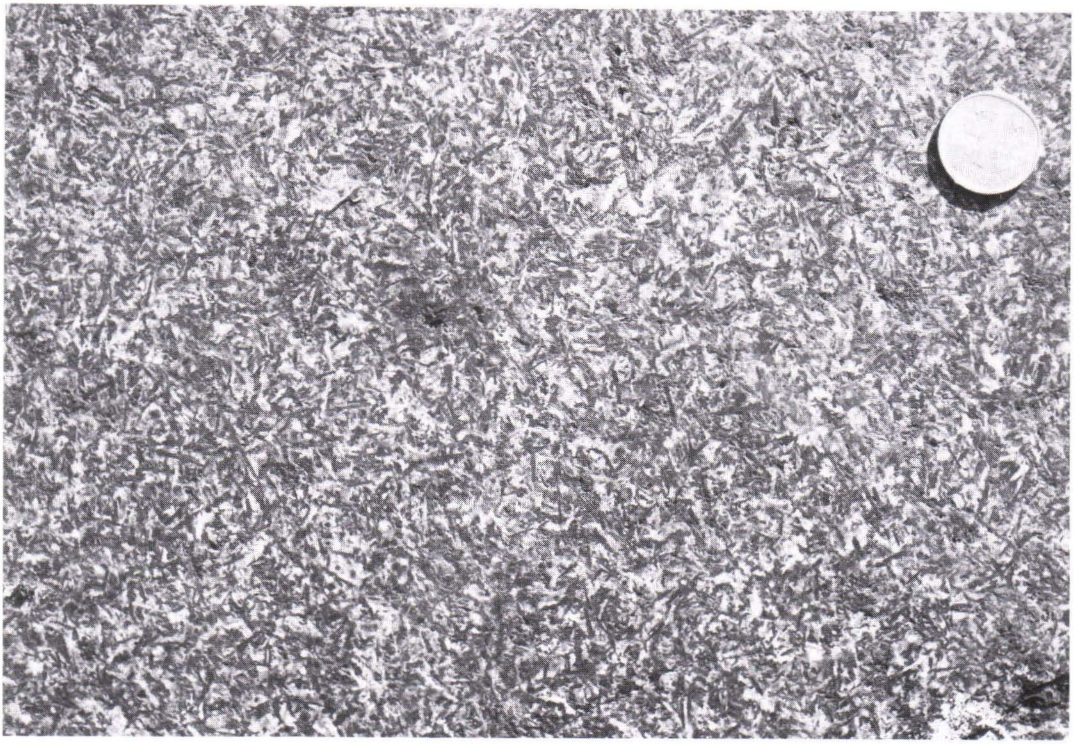

Fig. 8. Coarse-grained ophitic olivine diabase, »spotty diabase», containing baddeleyite and scant zircon. Diameter of coin 2.4 cm. Säppi, northwestern shore.
Photo Veli Suominen.

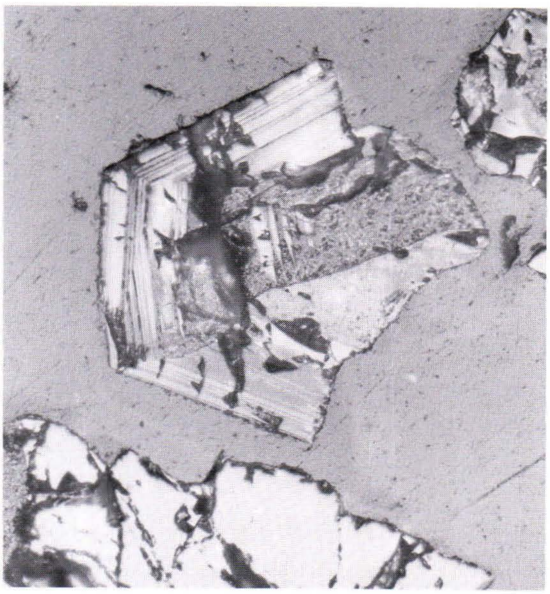

Fig. 9. Microphotographs (reflected light) of HF-etched zoned zircon crystals from sample A786 of the Säppi diabase. Length of zoned fragment 0.3 mm.
Photo Veli Suominen.

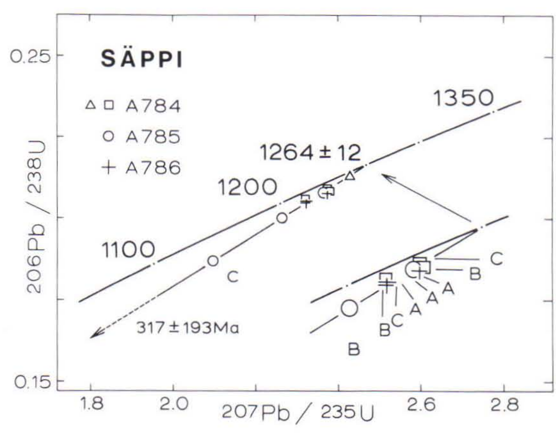

Fig. 10. Isotope ratios and age of zircon fractions from the megaophitic diabase of Säppi. The data point for A784D-baddeleyite is marked with a triangle.

Hankkila, Eurajoki

The sample from the olivine diabase of Hankkila, Eurajoki (A975) is a pegmatoidic variety of coarse-grained olivine diabase. Hankkila is located in the northernmost part of the flat-lying Sorkka diabase, which covers an area of 24 km². The olivine diabase overlies the Eurajoki rapakivi granite (Haapala 1977).

The Hankkila diabase has been described by A. Laitakari (1925) and the palingenic contact phenomena have been discussed by A. Laitakari (1928) and Kahma (1951). The diabase represents the same type as the other olivine diabases in the Satakunta area. According to A. Laitakari (1928), the composition of the flat-lying diabases is like that of the steeply dipping dykes. The main constituents are labradorite, olivine, brownish violet augite, ilmenite, magnetite and biotite. The ophitic texture of the coarse-grained diabase is well developed. For chemical analyses, see Rämö (1990).

The zircon crystals in density fraction 3.8—4.0 g/cm³ from sample A975 are translucent, white fragments of large crystals. The baddeleyite crystals are translucent, reddish brown, long monoclinic needles with characteristic striae on the prism faces.

The five data points (Fig. 11) plotted on a concordia diagram yield an upper intercept age of 1258 ± 13 Ma and a lower intercept of 384 ± 307 Ma. For analytical data, see Table 3. If the data point for the Ämmänpelto (A974) baddeleyite is included, the corresponding ages are 1264 ± 25 Ma and 462 ± 434 Ma.

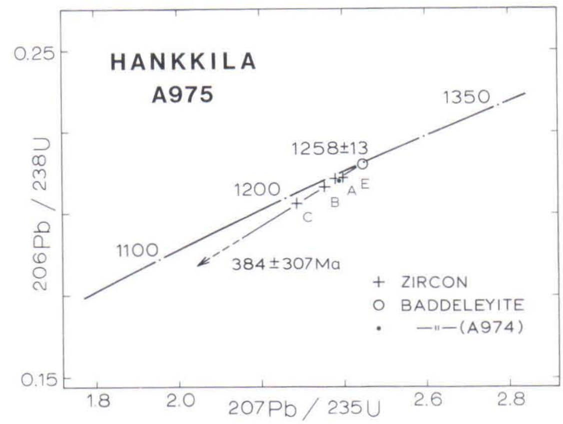

Fig. 11. Concordia plot for zircon fractions from the Hankkila diabase pegmatoid, northernmost part of Sorkka diabase.

The Rb-Sr age of biotite, 1263 ± 18 Ma (see Table 16) of the Sorkka diabase in Satakunta is more compatible with the U-Pb results than is the K-Ar age of 970 Ma earlier reported for the Sorkka and Säppi diabases by Savolahti (1964).

Ämmänpelto, Eura

In this study the Eura diabases are represented by the Ämmänpelto diabase in Kauttua. Sample A974 is a diabase pegmatoid, but the zircon content is so low that only one zircon fraction could be analysed. This sample contains abundant baddeleyite, which occurs as acicular, red-brown, translucent crystals.

The analysis of the only zircon fraction of A974 gave a $^{207}Pb/^{206}Pb$ age of 1252 Ma (see Table 3). The Rb-Sr biotite age of the nearby Kiperinoja sample is 1251 ± 18 Ma (Dr O. van Breemen, pers. communication)

Moikipää, Korsnäs

Moikipää is the collective name of two small islands, Svall and Norrgrynnan, which here represent the well preserved Postjotnian diabases in the Vaasa archipelago described by Saksela

(1933), A. Laitakari (1942), Nykänen (1960b) and Aro (1987).

The diabases in the Moikipää area and on the island of Säppi are petrographically very alike. Mafic pegmatoids are a common feature (Nykänen 1960b). The Ulvö diabases, about 125 km west of Moikipää, are similar in composition and texture, but well developed magmatic layering has not been met with on the Finnish side (cf. Lundqvist and Samuelsson 1973, Lundqvist 1979, 1990, Larson 1973, 1980).

As shown by the geological sketch map (Fig. 12), the diabase dykes in the Moikipää area cut the mica gneisses at a low angle.

All the types of diabase encountered in the area are medium to coarse-grained and ophitic in texture. The main constituents are zoned plagioclase (An 40—70), monoclinic and rhombic pyroxenes, olivine, magnetite and ilmenite. Amphiboles, biotite, apatite, titanite, sulphides, zircon and baddeleyite occur as accessory minerals.

The diabase pegmatoids are very similar to the megaophitic diabase pegmatoids on Säppi and, like them, are without olivine but contain hornblende. Individual plagioclase laths are often 5 cm long. For chemical analyses and modes, see

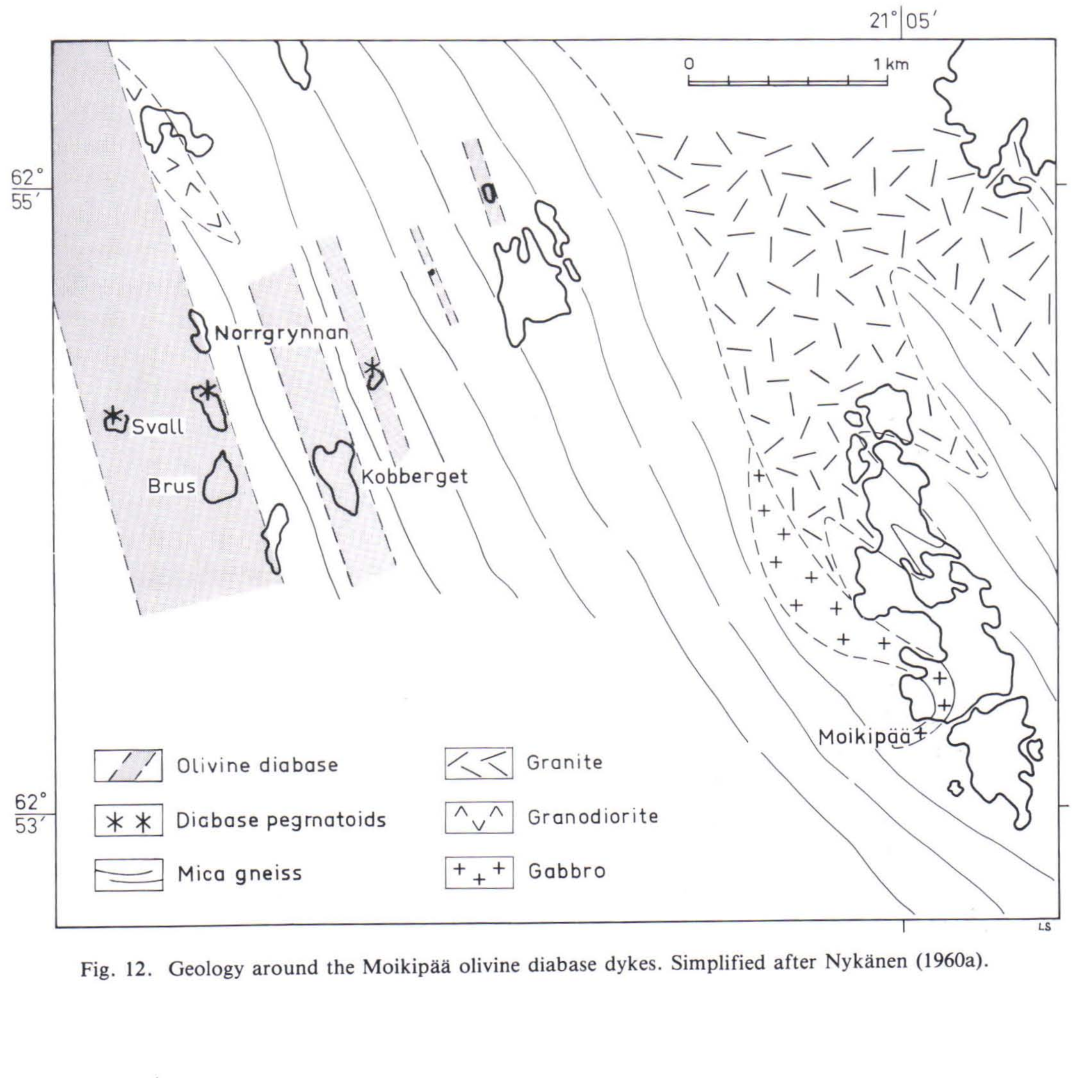

Fig. 12. Geology around the Moikipää olivine diabase dykes. Simplified after Nykänen (1960a).

Nykänen (1960b) and Aro (1987).

The olivine diabase on Svall is medium to coarse-grained with ophitic texture. Sample A731 was taken from a megaophitic lens in the southwestern corner of the island. The zircon crystals from the sample are large, long (L/B ratio 4—6), prismatic, sharp-edged, transparent or translucent and show a faint pinkish tint. A dull core is visible in some crystals. Baddeleyite has the same grain size and the same, or an even more acicular, habit.

The main rock type on Norrgrynnan is a medium to coarse-grained ophitic olivine diabase enclosing a megaophitic diabase pegmatoid (sample A732). The zircons from sample A732 are small, translucent, milky white or clear, transparent, acicular prisms with L/B ratio 3—6.

In the middle of Norrgrynnan, the ophitic, coarse-grained diabase is paler and resembles the »spotted diabase» on Säppi; sample A733, which contains abundant baddeleyite, is of this type. The zircon crystals from sample A733 are small, acicular, simple prisms. They are transparent, faint pinkish or milky white and translucent. The baddeleyite crystals are long needles.

The isotopic data are given in Table 3.

The U-Pb daughter/parent ratios plotted on a concordia diagram yield an age of 1268 ± 13 Ma (Fig. 13). This is consistent with the Rb-Sr age of biotite, 1253 ± 18 Ma (Dr Otto van Breemen, pers. communication) and the palaeomagnetic results of Neuvonen (1965 and 1966). The K-Ar age (isochron for whole rock, biotite, K-feldspar, plagioclase and pyroxene) of the diabases in the nearby Nordingrå area in Sweden is 1215 Ma (Welin and Lundqvist 1975, Welin 1980). The palaeomagnetic directions of the Vaasa and Ulvö diabases are the same (Magnusson and Larson 1977, Magnusson 1983).

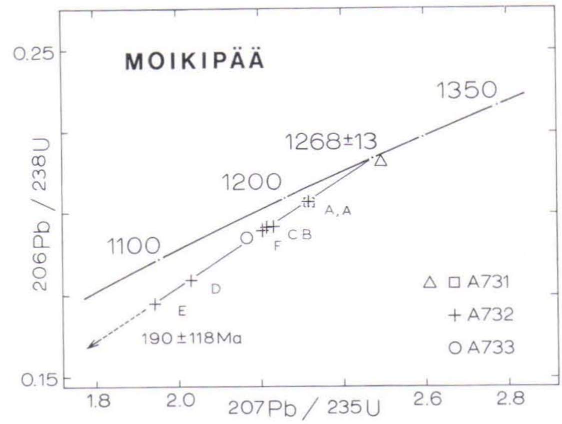

Fig. 13. Concordia diagram for U-Pb isotope ratios of zircon fractions from diabase pegmatoids A731-Svall (triangle is for baddeleyite), A732-Norrgrynnan and »spotty diabase» A733-Norrgrynnan in the Moikipää area. The age given is for zircon fractions only. If baddeleyite were included, the upper intersection would be 1275 ± 15 Ma.

SUBJOTNIAN FORMATIONS

The Subjotnian formations in southwestern Finland comprise diabase dykes, rapakivi granites, anorthosites and quartz porphyry dykes. The abundance of anorthosite is very low compared with that in other rapakivi areas. The diabases, rapakivi granites and other associated rocks must be older than the Jotnian sandstones, which overlie them in places and are cut by the Postjotnian diabases. Of the plutonic rock formations in southern Finland, the rapakivi granites cover large areas. To establish the age relations between these rocks a number of age determinations were made to supplement the field observations, which, owing to the lack of contact relations, were scarce at their best.

The Föglö pyroxene diabase dyke set

The large Föglö dyke consists of a tholeiitic set, 35 km long, occurring en echelon (Suominen 1980, 1981) in outcrops where the widest dykes reach 300 m. The Föglö dykes lie 11 km east of

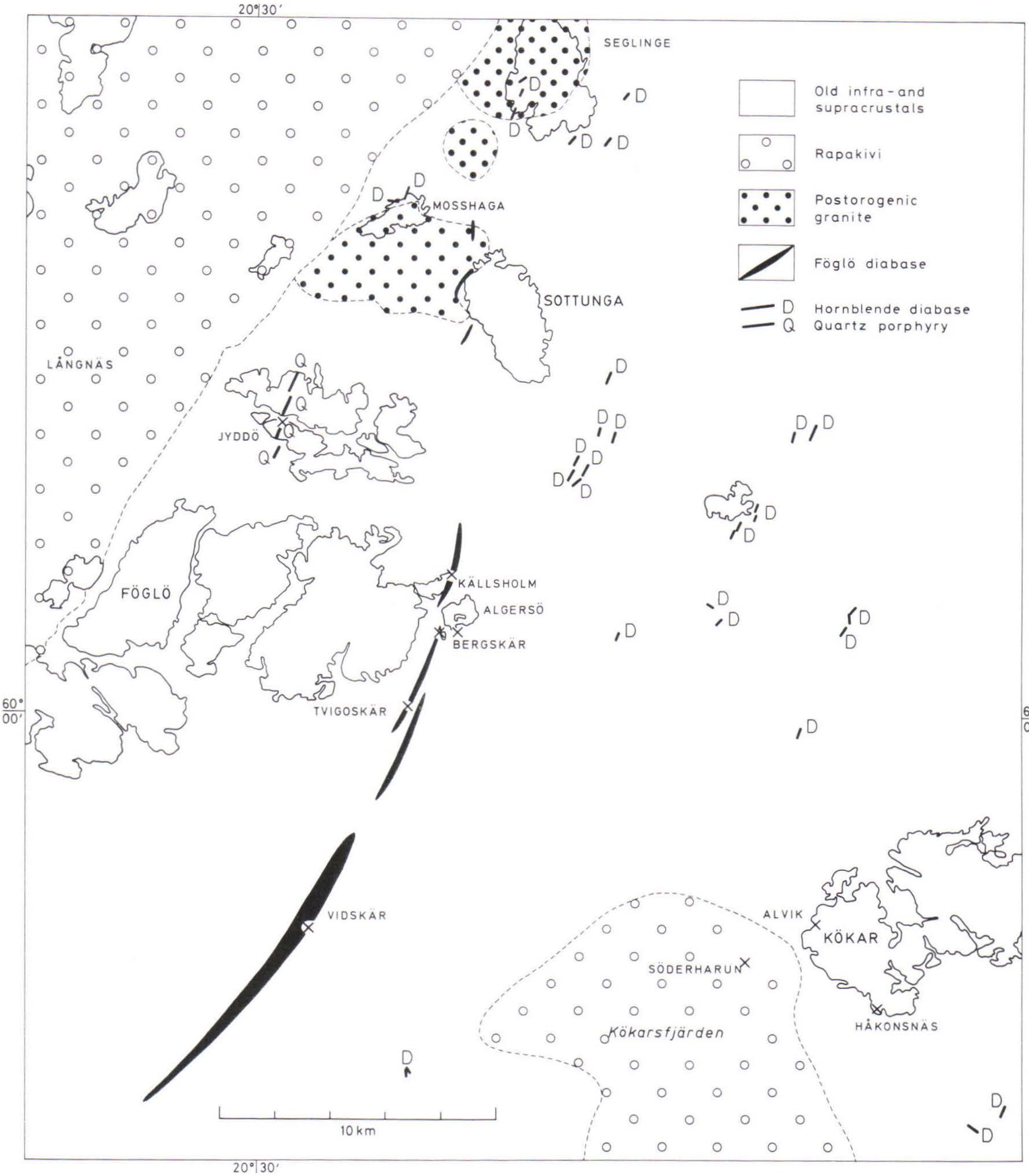

Fig. 14. Geology around the en-echelon pyroxene diabase dyke set in Föglö, Åland islands with sampling sites. Simplified after Suominen (1980, 1981).

the Åland rapakivi intrusion, subparallel to its eastern contact, and 8—10 km northwest of the Kökarsfjärden rapakivi pluton (see Fig. 14). In its northernmost outcrop, the Föglö diabase cuts the 1788 ± 11 Ma old (Welin et al. 1983) granite intrusion of Mosshaga. The country rock of the Föglö diabase dykes is usually a Svecofennian granodiorite of 1899 ± 8 Ma age, as reported later in this paper (A563-Algersö) and in Welin et al. (1983). Interesting parts of the Föglö dyke are encountered on the islands of Källsholm and Bergskär. The Föglö dyke set is of special interest due to its coarse-grained varieties and zircon content providing material for age determination. In the course of a hundred years this dyke set has drawn geologists' attention to the large outcrops. Petrography has profited a good deal, but the age relations are still less well understood than those of other intrusions of assumed Subjotnian age.

Frosterus (1893), who was the first to describe this diabase, considered it younger than the Åland rapakivi. Later, however, Sederholm (1934), who termed it ossipite, and Hausen (1964) stated that a pre-rapakivi age was more correct.

Table 4. Chemical composition of the pyroxene diabase of Föglö (Nos. 1 - 2) and the olivine diabase of Märket (Nos. 3 - 4), and CIPW norms. Oxides in weight %, elements in ppm.
Analyst: Pentti Ojanperä.

	1	2	3	4		1	2	3	4
SiO_2	52.23	53.18	44.43	46.48	Q	4.22	7.67	-	-
TiO_2	1.43	1.94	4.60	3.92	or	6.60	9.97	5.12	7.83
Al_2O_3	17.20	15.01	11.85	12.90	ab	24.90	24.65	22.07	28.96
Fe_2O_3	2.07	2.67	5.77	4.70	an	31.12	23.81	18.67	16.58
FeO	8.45	9.43	12.06	12.81	di en	2.03	1.83	6.88	3.49
MnO	0.12	0.14	0.30	0.29	fs	2.28	2.73	5.61	5.63
MgO	4.17	3.28	4.98	3.41	wo	4.36	4.53	12.90	9.00
CaO	8.57	7.28	10.20	8.27	mt	3.05	3.96	8.52	6.94
Na_2O	2.90	2.85	2.56	3.36	il	2.76	3.77	8.90	7.58
K_2O	1.10	1.65	0.85	1.30	ap	0.58	0.82	0.80	1.42
P_2O_5	0.24	0.34	0.33	0.59	z	-	-	0.02	0.03
CO_2	0.00	0.00	0.00	0.00	sal	66.84	66.10	45.86	53.37
H_2O^+	1.16	1.78	1.09	1.09	fem	15.06	17.64	43.63	34.09
H_2O^-	0.10	0.20	0.33	0.61	Qu	11.81	18.14	-	-
Sum	99.74	99.75	99.34	99.92	Or	18.48	23.58	18.83	21.28
					Ab_{100}	69.71	58.29	81.17	78.72
Sc	45	40			Qu	6.31	11.60	-	-
V	160	190			Or	9.88	15.08	11.16	14.66
Cr	115	85			Ab	37.25	37.29	48.12	54.27
Co	43	41			An_{100}	46.56	36.02	40.72	31.07
Ni	76	74							
Cu	56	84							
Ga	32	36							
Y	340	210							
Mo	10	10							
Zn	1700	2300							
SN	3	3							
Pb	10	11							

Analysis No.	Sample No.	Locality	Map sheet	Grid coordinates
1.	355/LEM/75	Föglö	1014 04	6659.40-1479.42
2.	351/LEM/75	Föglö	1014 04	6659.18-1479.22
3.	1/VOS/76	Märket	0043 07	6688.24-1563.00
4.	2/VOS/76	Märket	0043 07	6688.25-1562.90

The grid coordinates refer to the Finnish national grid.

Eskola (1963) wrote, »The Föglö dike is believed to be of pre-rapakivi age as are the intrusions of gabbros, ossipites and anorthosites around the Åland rapakivi area.»

The Föglö diabase exhibits variations in both texture and composition. In colour, it is a dark brownish grey although some light, coarse-grained portions also exist. Ophitic types predominate.

The main constituents are plagioclase (An 45—50), augite, chlorite, magnetite, ilmenite and apatite. Olivine occur in the most fine-grained types (randomly distributed), biotite, hornblende, quartz, epidote and K-feldspar. Titanite, zircon and baddeleyite are the accessory minerals. Zircon and quartz occur together.

Although the Föglö dykes are postmetamorphic, the diabase is to some extent altered. Plagioclase is sericitized, pyroxene is partly altered to hornblende, and the very rare olivine to iddingsite and serpentine. Biotite is chloritized (for modes see Suominen 1987a). The chemical composition (see Table 4) is clearly different from that of the Postjotnian Märket diabase and the Häme dykes (see Rämö 1990). Note that the Föglö dyke is quartz normative. The chemical composition resembles that of the labrador-porphyrites of Someri (Sommarö), an island in the Gulf of Finland, at the southern margin of the Wiborg rapakivi batholith, and that of Öster-Höggrund, west of the Åland rapakivi intrusion (Wahl 1938).

For radiometric dating, samples were collected from Källsholm (A793) and Bergskär (A658), on both of which islands chilled aphanitic contacts are visible. Some metres from the contact the rock is, however, medium to coarse-grained and ophitic in texture. Samples A658 and A793 are from plagioclase-rich parts (see Figs. 15 and 16) that may represent autoliths. There are no clear contacts between the autoliths and the normal type of diabase (see Fig. 15). Near the autoliths, there are often large angular megacrysts of plagioclase with the same An content as the plagioclase in the autoliths. This shows that the diabase crystallized slowly, with a state of equilibrium prevailing between the megacrysts and the matrix (Mäkipää 1979).

The zircon crystals are large, long (L/B ratio 4—6), transparent or translucent, simple prisms

Fig. 15. Contact between normal coarse-grained ophitic pyroxene diabase and the plagioclase-enriched autolithic pocket (A658) on the western shore of Bergskär, Föglö. Compass plate 6.5 × 10.7 cm. Photo Veli Suominen.

Fig. 16. Partly rounded and corroded plagioclase crystals in the autolithic diabase pegmatoid (A793) on Källsholm, Föglö. Photo Veli Suominen.

with pyramid faces developed at the terminations. In some crystals the pyramid is obtuse angled, and in some there is a dull growth nucleus. Baddeleyite occurs within the zircons. The zircon grains in the fractions analysed are often fragments of large crystals.

For analytical data, see Table 5. A concordia plot of the U-Pb isotope ratios yields an age of 1577 ± 12 Ma for sample A793-Källsholm alone (baddeleyite excluded from calculations; see Fig. 17a). The data points of the Bergskär sample, A658, do not form a coherent chord (see Fig. 17b). Linear regression of nine zircon fractions out of ten gives an intercept on the concordia curve of 1540 ± 12 Ma (2 sigma). The point for zircon fraction bE (density 4.0—4.2 g/cm^3) plots near the chord of sample A793 and was omitted. The uranium content of this fraction is the lowest and the density correspondingly the highest found in sample A658. The most concordant abraded fraction, bJ, is the next most dense (3.8—4.0 g/cm^3) and plots between the two chords. In addition, the total fraction, aA, which was only analysed for the isotopic composition on lead, yields a $^{207}Pb/^{206}Pb$ age of 1558 Ma, which is as high as that of fraction bE and higher than that of the bulk of sample A793. The scatter of the remaining data points about the chord of 1540 ± 12 Ma (2-sigma), however, is no greater than the analytical error. The two trajectories denoting ages of 1540 ± 12 and 1577 ± 12 Ma are insufficient to explain the age relation between the Åland rapakivi and the Föglö mafic dyke, because the Bergskär sample has some fractions older than 1540 Ma, thus suggesting that at least part of the Bergskär dyke is coeval with Källsholm, which, on the other hand, gives the same age as the Åland rapakivi (see later in this study).

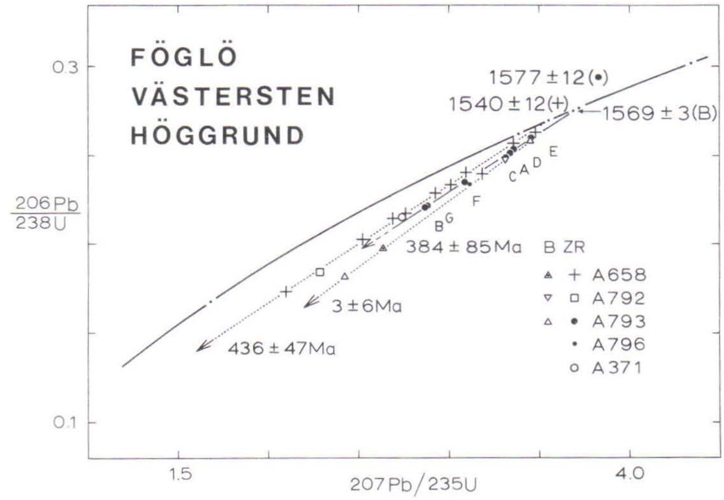

Fig. 17a. Concordia plot for zircon (Zr) and baddeleyite (B) fractions from pyroxene diabases A658-Bergskär, A793-Källsholm and A371-Vidskär in Föglö, and from anorthositic pyroxene diabases A792-Västersten in Hammarland and A796-Höggrund in Eckerö.

The lowei intercept of the Bergskär chord is higher than that of the Källsholm sample. Finally there is evidence of later disturbance during tectonic movements along the fracture line immediately west of Bergskär. The chord for the four baddeleyite fractions from three different samples yields an age of 1569±3 Ma (see Fig. 17a). The data point of the baddeleyite fraction of the Bergskär sample lies below the regression line for zircons (see Fig. 17b) thus showing that the zircon fraction bE and the baddeleyite fraction are older and have not been affected by tectonic movements.

The Rb-Sr whole-rock age for the Vidskär sample of the Föglö dyke set is 1523±34 Ma, and for the Tvigoskär samples of the same dyke set 1556±34 Ma (Dr O. van Breemen, pers. communication).

It is known from the contact relations that the olivine diabase dyke swarm of Häme (Fig. 1) is older than the rapakivi of Wiborg and its satellite plutons. This is particularly clear in Lovasjärvi, where the dyke and the Wiborg rapakivi (Siivola 1977, 1987, Rämö 1990) give the same age for the dyke and rapakivi within the limits of error. However, the Wiborg rapakivi clearly cuts the mafic dyke. The intrusion of the Häme olivine diabase dyke swarm is in temporal and causal connection with the intrusion of the Wiborg rapakivi batholith (I. Laitakari 1969, 1987, Haapala 1985, Siivola 1987, Vaasjoki and Sakko 1989).

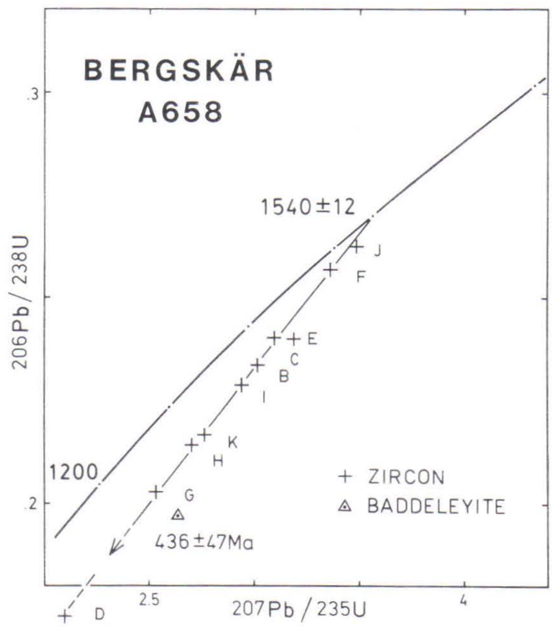

Fig. 17b. Concordia diagram for the U-Pb ratios of zircon and baddeleyite fractions of the A658-Bergskär sample of the Föglö dyke set.

The Breven dyke in Sweden resembles the

Table 5. U–Pb isotopic data on the Subjotnian pyroxene diabase of Föglö and the anorthosites of Västersten and Höggrund.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration μg/g ^{238}U	^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A658–Bergskär, Föglö: pyroxene diabase pegmatoid										
A658aA	total	–	–	3498	.02860	10.047	39.196	–	–	.09651 ± 9 1558
aB	total	2538	512.86	2230	.04355	9.962	41.608	.2335 ± 12 1352	3.012 ± 17 1410	.09356 ± 17 1499
bC	3.6<d<3.8 Ø>70	2354	489.62	3340	.02785	9.730	41.259	.2404 ± 12 1388	3.096 ± 17 1431	.09343 ± 8 1496
bD	3.5<d<3.6 Ø>70	2450	366.62	1295	.07450	9.846	43.530	.1730 ± 9 1028	2.099 ± 12 1148	.08802 ± 9 1383
bE	4.0<d<4.2	1086	225.54	1774	.05237	10.362	34.111	.2400 ± 16 1386	3.189 ± 23 1454	.09635 ± 22 1554
bF	3.6<d<3.8 abr	2128	472.79	2641	.03598	9.987	43.724	.2568 ± 15 1473	3.359 ± 21 1494	.09487 ± 16 1525
bG	3.5<d<3.6 abr	2442	428.45	1696	.05821	9.846	44.876	.2028 ± 33 1190	2.526 ± 42 1279	.09033 ± 25 1432
bH	3.6<d<3.8 abr	2196	406.99	1262	.07816	10.217	43.982	.2142 ± 13 1251	2.695 ± 22 1327	.09126 ± 43 1452
bI	3.6<d<3.8 cr	2113	418.28	4370	.02143	9.596	43.832	.2288 ± 14 1328	2.933 ± 20 1390	.09298 ± 28 1487
bJ	3.8<d<4.0 abr	1509	343.23	1494	.06616	10.526	40.195	.2629 ± 17 1504	3.483 ± 25 1523	.09608 ± 26 1549
bK	3.5<d<3.6 abr	1647	309.25	1059	.09314	10.538	45.566	.2171 ± 14 1266	2.765 ± 20 1346	.09240 ± 27 1475
bL	baddeleyite	579.4	98.66	1109	.08904	10.940	6.042	.1968 ± 15 1158	2.633 ± 20 1309	.09705 ± 16 1568
A793–Källsholm, Föglö: pyroxene diabase pegmatoid										
A793A	4.0<d<4.2 Ø>70	945.5	205.84	5149	.01749	9.874	36.596	.2516 ± 13 1446	3.341 ± 19 1490	.09632 ± 12 1554

Table 5. (continued)

A793B	3.6<d<3.8 Ø>70	1396	266.44	2814	.03324	9.890	40.244	.2206 ± 11 1285	2.868 ± 16 1373	.09428 ± 15 1513
C	d>3.8	784.8	169.08	1166	.07730	10.729	37.960	.2490 ± 13 1433	3.315 ± 21 1484	.09657 ± 23 1559
D	3.6<d<3.8 Ø>70 abr	1371	300.92	1985	.04965	10.304	41.020	.2536 ± 14 1457	3.362 ± 20 1495	.09615 ± 14 1550
E	3.6<d<3.8 Ø>70 abr	1480	332.67	2926	.03197	10.085	40.650	.2597 ± 14 1488	3.453 ± 19 1516	.09641 ± 15 1555
F	3.6<d<3.8 cr	1306	265.05	2323	.04173	10.142	38.686	.2346 ± 16 1358	3.093 ± 22 1430	.09563 ± 15 1540
G	3.6<d<3.8	1430	274.35	1617	.06090	10.272	41.395	.2217 ± 13 1291	2.881 ± 22 1377	.09425 ± 41 1513
H	baddeleyite	651.0	102.08	1625	.05856	10.520	5.802	.1812 ± 13 1073	2.426 ± 19 1250	.09709 ± 36 1569
I	baddeleyite	1402	312.92	2491	.03829	10.240	3.221	.2580 ± 18 1479	3.454 ± 27 1516	.09709 ± 28 1569
	A371–Vidskär, Föglö: pyroxene diabase									
A371A	3.6<d<4.0 abr	950.7	176.70	949	.10375	10.714	74.214	.2148 ± 21 1254	2.745 ± 29 1340	.09269 ± 39 1481
	A792–Västersten, Hammarland: anorthosite									
A792A	3.5<d<3.6	1463	232.90	804	.11483	10.608	47.450	.1839 ± 10 1088	2.283 ± 16 1207	.09003 ± 31 1426
B	baddeleyite + zircon	433.1	92.706	809.4	.11711	11.338	10.288	.2474 ± 24 1424	3.313 ± 35 1484	.09715 ± 34 1570
	A796–Höggrund, Eckerö: anorthosite									
A796A	3.6<d<4.0 abr	1232	248.86	3009	.02663	10.058	57.482	.2334 ± 15 1352	3.118 ± 28 1437	.09689 ± 52 1565

For symbols, see Table 3.

Föglö dykes. It is of the same 1560—1510 Ma age (Patchett 1978), and its geology, as described by Wikström (1985), has many similar features. However, the Föglö dyke is not known to be associated with granophyres.

The Västersten and Höggrund anorthositic varieties of pyroxene diabase

On Västersten, Danten and Östersten, three islands in Hammarland, southwest of the Åland rapakivi area, the most common rock type is a very coarse-grained anorthositic variety of pyroxene diabase (Bergman 1979, 1981). It was inferred to belong to the same age group as the Föglö dykes by Sederholm (1934), Eskola (1963) and Hausen (1964). Similar anorthositic diabases occur on several islands west and southwest of the Åland rapakivi complex (see Sederholm 1934, who called it ossipite). Hausen (1964) reported a cutting rapakivi dyke in anorthosite on Västersten. On Höggrund and Blåklobb quartz porphyry cuts the anorthositic diabase, but in some localities at the southern margin of the Åland rapakivi the contact relations are ambiguous (cf. Bergman 1981). The anorthositic rocks of the Åland area are similar to the gabbro-anorthosites described from the Wiborg rapakivi area by Sederholm (1934), Wahl (1938), Savolahti (1956, 1966), Kranck (1968) and Tyrväinen (1986).

Sample A792 from Västersten was taken from the coarse-grained anorthositic variety shown in Fig. 18. The main constituents are plagioclase, hornblende (partly altered to chlorite), serpentine, opaque minerals and quartz. The accessory minerals include apatite, epidote, zircon and baddeleyite.

Much of the Västersten island consists of a very coarse-grained, breccia-like rock (see Fig. 19) with rounded plagioclase fragments 20—40 cm in diameter. It is probably an autolithic breccia.

The zircon grains of sample A792 are dull,

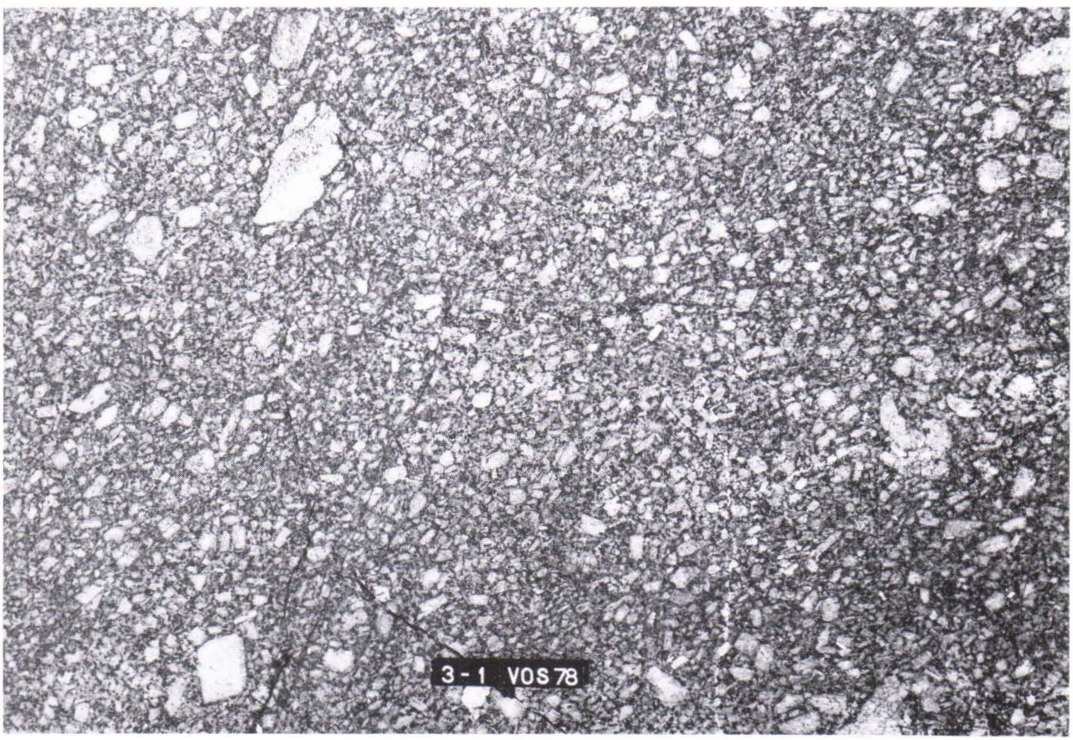

Fig. 18. Anorthositic pyroxene diabase (A792) dated from the western shore of Västersten, Hammarland, Åland islands. Length of tag 12 cm.
Photo Veli Suominen.

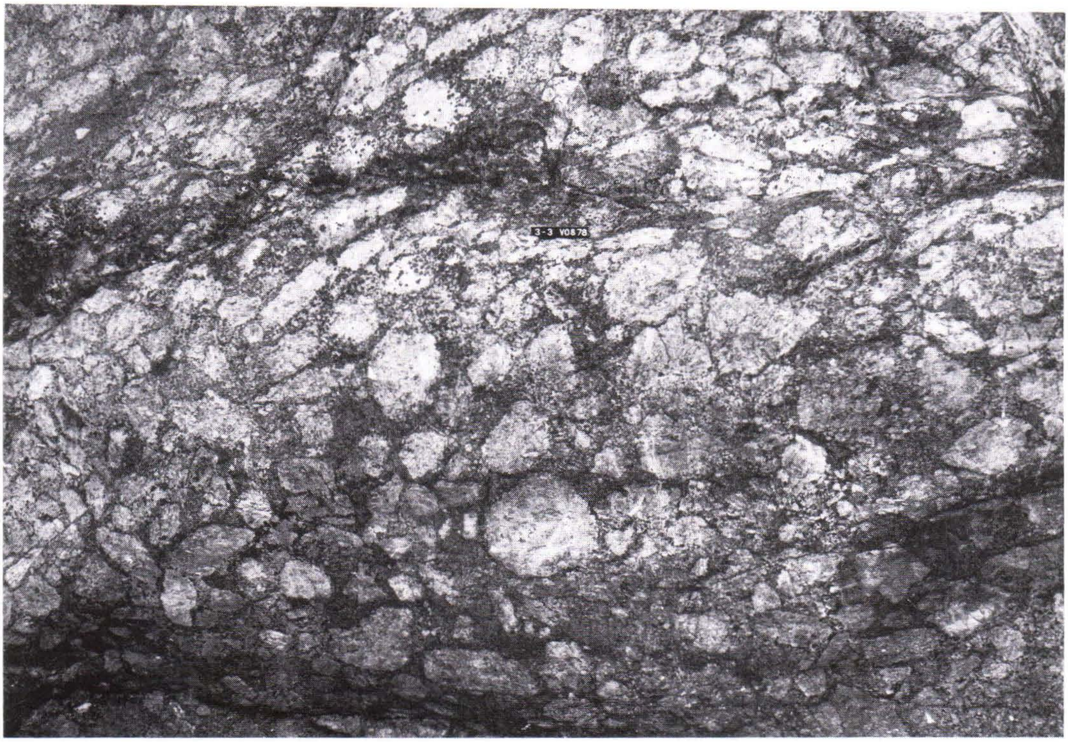

Fig. 19. Rounded autolithic anorthosite pegmatite fragments on the northwestern shore of Västersten. Length of tag 12 cm.
Photo Veli Suominen.

translucent fragments of large crystals.

The single zircon fraction analysed from Västersten seems to fall within the data points on the best-fit lines of the Källsholm and Bergskär dykes. Hence, it is highly probable that the age is 1540—1577 Ma (see Fig. 17a). The zircon crystals are light coloured. For analytical data, see Table 5. The data-point of A792-Västersten does not fall on any rapakivi or quartz porphyry chord of the Åland area. The thorium content is slightly higher than that in the other pyroxene diabases and quartz porphyry samples analysed, and clearly higher than that in the Ylijärvi, Ylämaa anorthosite, Wiborg batholith (see Table 10), as indicated by the $^{208}Pb/^{206}Pb$ ratio. The closest is the Åva quartz porphyry on Källholm.

To check whether the zircon fractions of the anorthosites are different from those of the diabases, the hafnium, yttrium and zirconium contents in the zircons from the anorthosites of Västersten and Ylämaa, the pyroxene diabase of Föglö and the olivine diabase of Säppi were analysed with an electron microprobe. The analyses were carried out on the central parts of the undamaged crystals where no inclusions were visible. For the analytical results and HfO_2/ZrO_2 and Y_2O_3/ZrO_2 ratios, see Table 6. There does not seem to be any clear characteristic difference between the zircon crystals analysed.

Table 6. Electron microprobe analyses on zircons from the Västersten anorthosite (A792), Föglö pyroxene diabase (A658b and A793), Säppi olivine diabase (A785) and Ylämaa anorthosite (spectrolite quarry) (A119).
Analyst: Anu Karessuo.

Sample	Anal.	SiO_2	FeO	CaO	ZrO_2	HfO_2	Y	Σ	HfO_2/ZrO_2	Y_2O_3/ZrO_2
A658b	1	32.2	0.05	0.45	61.5	1.30	0.30	95.86	0.0211	0.0048
	2	32.2	0.01	-	64.1	1.09	0.86	98.39	0.0170	0.0134
A793	1	32.4	-	0.01	65.2	1.34	0.53	99.52	0.0205	0.0081
	2	33.1	0.05	-	64.2	1.57	0.16	99.23	0.0244	0.0024
	3	31.7	0.09	-	63.4	1.48	0.65	97.48	0.0233	0.0102
	4	32.6	0.04	0.10	61.4	1.52	0.21	95.92	0.0247	0.0034
	5	32.9	-	-	65.7	1.28	0.43	100.43	0.0194	0.0065
	6	32.3	-	-	65.3	1.39	0.47	99.57	0.0212	0.0071
A792	1	29.0	-	1.18	52.8	1.16	2.04	86.26	0.0219	0.0386
	2	29.2	-	3.29	55.3	1.07	0.46	89.41	0.0193	0.0083
	3	29.9	-	4.59	53.0	0.84	0.43	88.96	0.0158	0.0081
A785	1	32.9	-	-	62.5	1.07	1.92	98.41	0.0171	0.0307
	2	34.4	-	-	63.3	1.56	1.34	100.80	0.0246	0.0211
	3	32.8	0.05	-	62.0	1.39	2.23	98.67	0.0224	0.0359
	4	32.4	0.01	-	64.1	1.22	1.88	99.67	0.0190	0.0293
A119	1	33.3	-	0.05	65.9	1.33	0.02	100.63	0.0201	0.0003
	2	33.1	-	0.01	65.5	1.27	0.10	100.04	0.0193	0.0015
	3	33.2	-	-	65.4	1.22	0.77	100.04	0.0186	0.0117
	4	33.3	-	0.01	66.6	1.12	0.00	101.20	0.0168	-
	5	33.5	0.01	-	66.1	1.37	0.00	101.04	0.0207	-

Hornblende diabases in the southwestern archipelago of Finland

The Åland area would appear to have undergone at least three different periods of postmetamorphic mafic dyke intrusion. The third type, discussed here only briefly, comprises the fine to medium-grained ophitic hornblende diabase dykes that abound in the archipelago of southwestern Finland and were earlier called trapdiabases (Sederholm 1927, 1934, Ehlers and Ehlers 1977). Sederholm (1927) considered the hornblende diabases older than the rapakivi granites. The multiple intrusion of hornblende diabases, as described by Ehlers and Ehlers (1977), indicates the existence of diabases of different ages, although the age difference may be only slight.

On Kungsholm, Jomala, a hornblende diabase dyke cuts the rapakivi of Åland (Bergman 1981). The diabase contains very little zircon and, what is worse, the fraction with the few zircon grains obtained was contaminated, some of the zircon grains obviously deriving from the country rock. Because of the low zircon content and the lack of mafic coarse-grained varieties in this type of diabase, U-Pb dating was not possible.

The type area of the hornblende diabase dykes is Kumlinge (Ehlers and Ehlers 1977). The Koklápp (near Börsskär, Kumlinge) dykes form a typical, small dyke set striking NE-SW and dipping steeply.

The Rb-Sr whole-rock age of the Kumlinge dykes is 1599±26 Ma (see Table 16). According to the palaeomagnetic studies of Neuvonen (1978), the Kumlinge dykes are of 1650 Ma age and, according to Pesonen et al. (1985), their palaeomagnetic poles plot on the Subjotnian loop (1650—1300 Ma), close to the Åland rapakivi poles of the apparent polar wander curve (Bylund and Pesonen 1987).

The pyroxene diabase on Korsö, Brändö, south of the Åva intrusion (Springert 1951, Neuvonen 1970, Ehlers and Ehlers 1978, 1981), yielded an age of 1600 Ma with the Rb-Sr whole-rock method (Dr O. van Breemen pers. communication).

These figures permit some earlier stratigraphic standpoints and palaeomagnetic results to be re-evaluated.

The age obtained for the Föglö dykes with the Rb/Sr whole-rock method, 1556 ± 34 Ma (see Table 16), seems to confirm the existence of an age difference between the various diabases.

Quartz porphyry dykes in the Åland area

The rock association of rapakivi granite, quartz porphyry dykes and diabases in the southwestern archipelago of Finland has been discussed by Sederholm (1934), Kaitaro (1953), Bergman (1981) and Ehlers and Bergman (1984). Vaasjoki (1977) assumes that the quartz porphyry dykes near the Åland rapakivi intrusions are associated with the main phase of the Åland rapakivi.

Blåklobb, Eckerö

The quartz porphyry on the small island of Blåklobb, Eckerö, close to the western contact of the Åland rapakivi, is in contact with a granodiorite and with a diabase of the same type as that of Föglö (see Sederholm 1934, p. 60 for map and p. 67 for chemical analysis). Wahl (1936) and Hausen (1964) used the term labrador porphyrite for the very coarse-grained Blåklobb diabase with rounded and fragmented plagioclase crystals in a greenish-black, fine-grained matrix.

The quartz porphyry has aphanitic contacts against the diabase and granodiorite. It contains fragments of these two rock types and sends apophyses into them. It has blue, euhedral, acicular quartz crystals and K-feldspar phenocrysts in a brown-red matrix.

The zircons from sample A715 are prismatic, transparent, reddish crystals with partly corroded surfaces. The L/B ratio varies from 2 to 5.

Vaasjoki (1977) dated the quartz porphyry with three zircon fractions. In the present study eight new zircon fractions were analysed. The 11 data points plotted on a concordia diagram (see Fig. 20 and for analytical data Table 7) yield an age of 1590 ± 14 Ma. If data points B, C and I with $^{206}Pb/^{204}Pb$ ratio < 500 are omitted from the calculations, the age is 1574 ± 6 Ma for the 8-point best-fit line.

The analytical results for the original fractions are discordant, but the new data points for heavier zircon fractions are more concordant than the A, B, C fractions analysed earlier. Treating the crushed material in nitric acid, leaching in hydrofluoric acid and air abrasion remove common lead and seem to yield more concordant data points, as is seen in Fig. 20.

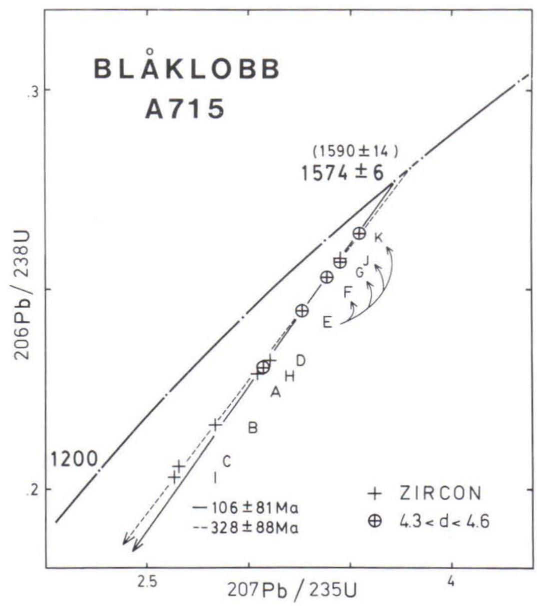

Fig. 20. Concordia plot for various zircon fractions from the Blåklobb quartz porphyry (A715), Eckerö. N.B. the treatment of zircons in the series: E untreated, F preleached in HF, G crushed and washed in HNO_3, J air abraded (d > 4.2 g/cm^3), and K air abraded. Chord, drawn with full line, is for data points having $^{206}Pb/^{204}Pb$ > 500.

Table 7. U-Pb isotopic data on the Subjotnian quartz porphyries of the Åland area.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration μg/g ^{238}U	^{206}Pb radiog.	^{206}Pb/^{204}Pb measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: ^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb
A714–Källholm, Åva, Brändö: quartz porphyry										
A714A	d>4.2; Ø>70	266.7	59.02	178.0	.51634	16.892	47.626	.2557 ± 16 1467	3.441 ± 72 1513	.0976 ± 14 1578
B	d>4.2; Ø<70	237.1	51.27	384.3	.21720	12.742	36.997	.2500 ± 15 1438	3.357 ± 60 1494	.0974 ± 12 1575
C	3.8<d<4.2	848.3	169.32	417.4	.22636	12.680	33.992	.2307 ± 12 1338	3.036 ± 26 1416	.09545 ± 50 1537
E	4.3<d<4.52 HF	213.1	49.72	357.4	.27757	13.532	39.573	.2697 ± 22 1539	3.605 ± 39 1550	.09694 ± 62 1566
F	4.2<d<4.3 HF	376.0	85.67	682.6	.14518	11.677	33.474	.2634 ± 17 1507	3.511 ± 30 1529	.09669 ± 48 1561
G	4.3<d<4.52 abr quartz	217.0	48.28	407.4	.24205	13.026	38.518	.2572 ± 14 1475	3.432 ± 27 1511	.09679 ± 47 1563
H	4.3<d<4.52	210.4	45.70	278.5	.35712	14.595	40.929	.2510 ± 17 1443	3.342 ± 28 1490	.09656 ± 42 1558
A715–Blåklobb, Eckerö: quartz porphyry										
A715aA[2]	d>4.1; Ø<220	672.0	133.13	718.0	.10697	11.116	18.808	.2290 ± 13 1329	3.042 ± 41 1418	.09636 ± 85 1554
aB[2]	3.8<d<4.1	1206	225.30	465.5	.20946	12.422	23.229	.2159 ± 12 1259	2.833 ± 18 1364	.09518 ± 24 1531
aC[2]	3.6<d<3.8	987	175.58	332.5	.28250	13.291	26.123	.2056 ± 11 1205	2.655 ± 25 1316	.09367 ± 54 1501
aD	d>4.2; Ø<160	571.7	114.88	575.5	.16232	11.938	20.648	.2322 ± 12 1346	3.104 ± 22 1433	.09693 ± 35 1566
bE	4.3<d<4.6	367.8	77.86	1170	.08395	10.843	16.974	.2447 ± 17 1411	3.266 ± 30 1473	.09682 ± 54 1563
bF	4.3<d<4.6 HF	333.4	73.11	2136	.04540	10.304	15.300	.2535 ± 23 1456	3.382 ± 32 1500	.09676 ± 23 1562

Table 7. (continued)

A715bG	4.3<d<4.6 cr	330.0	73.46	2646	.03607	10.232	14.938	.2573 ± 15 1476	3.453 ± 24 1516	.09733 ± 36 1573
bH	4.3<d<4.6 cr abr quartz	374.8	74.71	869.3	.11345	11.251	18.277	.2304 ± 15 1336	3.075 ± 28 1426	.09682 ± 56 1563
bI	3.6<d<3.8 abr quartz	1572	276.78	313.6	.31785	13.819	27.349	.2034 ± 12 1193	2.639 ± 38 1311	.0941 ± 11 1509
bJ	d>4.2; Ø<160 abr	352.7	78.77	1985	.04843	10.365	15.495	.2581 ± 16 1480	3.450 ± 23 1515	.09695 ± 17 1566
bK	4.3<d<4.6 abr	381.6	87.27	1674	.05770	10.526	16.295	.2643 ± 15 1511	3.545 ± 21 1537	.09728 ± 16 1572
A716–Hammarudda, Hammarland: quartz porphyry										
A716A	d>4.2; Ø>130	404.9	88.22	2073	.04344	10.268	15.727	.2518 ± 13 1447	3.356 ± 20 1494	.09666 ± 21 1560
B	4.0<d<4.2 Ø>130	956.9	202.21	2156	.04461	10.266	16.138	.2442 ± 17 1408	3.249 ± 25 1468	.09648 ± 23 1557
C	d>4.6	178.0	39.63	3620	.02498	10.036	13.641	.2573 ± 24 1476	3.438 ± 32 1513	.09690 ± 14 1565
D	d>4.6; HF	163.2	37.94	4386	.02015	9.966	13.227	.2687 ± 18 1534	3.588 ± 26 1546	.09687 ± 23 1564
E	4.2<d<4.6 abr	522.0	119.94	7063	.01234	9.847	15.432	.2655 ± 20 1518	3.543 ± 30 1536	.09676 ± 37 1562
F	4.2<d<4.6 abr	406.6	92.89	8241	.01064	9.867	15.250	.2641 ± 22 1510	3.539 ± 31 1535	.09720 ± 28 1571
A717–Jyddö, Föglö: quartz porphyry										
A717 A	d>4.2	82.06	18.74	369.5	.25331	13.273	23.915	.2640 ± 14 1510	3.554 ± 35 1539	.09765 ± 65 1579
B	4.0<d<4.2	91.47	20.40	148.7	.65516	18.703	37.015	.2578 ± 14 1478	3.416 ± 54 1508	.0961 ± 12 1550
C	d>4.6	74.59	17.21	201.2	.49215	16.450	31.932	.2667 ± 24 1523	3.537 ± 44 1535	.09622 ± 73 1552
D	d>4.6; HF	74.73	17.46	194.9	.50648	16.824	32.739	.2700 ± 17 1540	3.652 ± 72 1560	.0981 ± 16 1588

Table 7. (continued)

A717 E	d>4.6;	77.22	17.64	162.6	.61160	18.141	36.277	.2640	3.516	.0966
	Ø>70							± 22	± 67	± 15
								1510	1530	1559
F	d>4.6;	71.88	17.48	1027	.09175	10.970	18.343	.2811	3.759	.09698
	HF							± 22	± 44	± 74
	cr							1596	1583	1566
G	d>4.6;	72.70	16.79	390.1	.25004	13.186	23.732	.2670	3.578	.0972
	Ø>70							± 24	± 72	± 16
	abr							1525	1544	1571

For symbols, see Table 3.

Hammarudda, Hammarland

On Hammarudda the quartz porphyry is in contact with rapakivi (see Bergman 1979, 1981). The well preserved quartz porphyry represents the adjacent quartz porphyries in contact with rapakivi and diabase. The complex contact relations have been discussed in detail by Frosterus (1892), Sederholm (1934), Hausen (1964) and Bergman (1981).

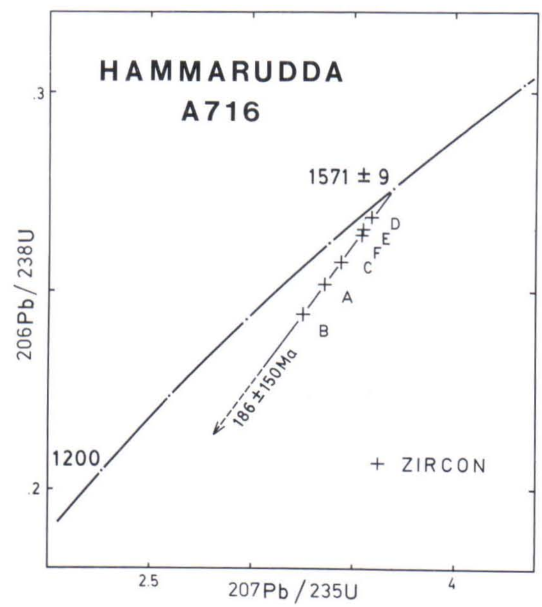

Fig. 21. Concordia diagram for U-Pb isotope ratios of zircons from the Hammarudda quartz porphyry (A716). Data points A, E and F represent the same density fraction, E and F were air abraded. Data points C and D are of the same density fraction but fraction D was preleached in HF.

The zircons from sample A716 are clear and sharp-edged with glossy crystal faces. The L/B ratio varies from 3 to 5, but can be up to 10. The crystals are simple tetragonal prisms with well developed pyramid faces. Crystals with zonal growth are not uncommon. Inclusions are frequent and many of them are located along growth zones. Parallel to the c-axis there are long acicular inclusions, some of which seem to be filled with gas or liquid.

The six zircon fractions plotted on a concordia diagram (see Fig. 21) yield an age of 1571 ± 9 Ma. Data point D represents zircons preleached in hydrofluoric acid; fractions E and F were air abraded. For analytical data, see Table 7. The age obtained is close to that of the other quartz porphyries in the Åland area.

Jyddö, Föglö

The Jyddö quartz porphyry forms an en-echelon dyke set parallel to the eastern contact of the Åland rapakivi. It runs parallel to the Föglö diabase dyke set, and hence the age relations could not be confirmed with field observations. The 2—6 m wide dykes lie about 3 km east of the Åland rapakivi (see Fig. 14).

The zircons of the Jyddö quartz porphyry are poor in uranium but relatively rich in common

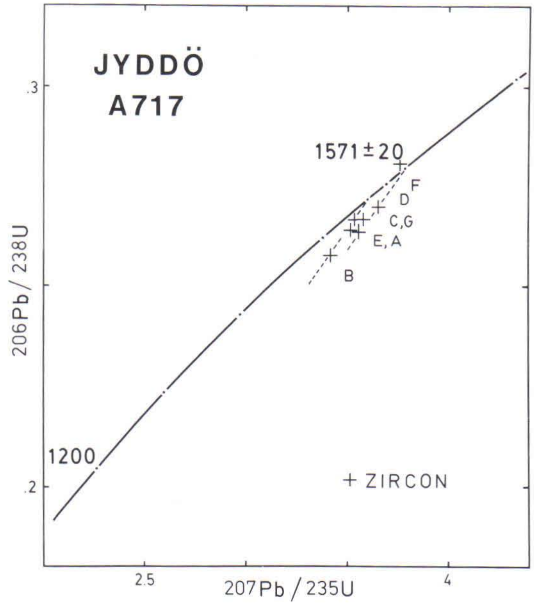

Fig. 22. Concordia plot for U-Pb isotope ratios of zircon fractions from the Jyddö quartz porphyry (A717). Fraction C was untreated, D preleached in HF, F crushed and preleached in HF, and G air abraded.

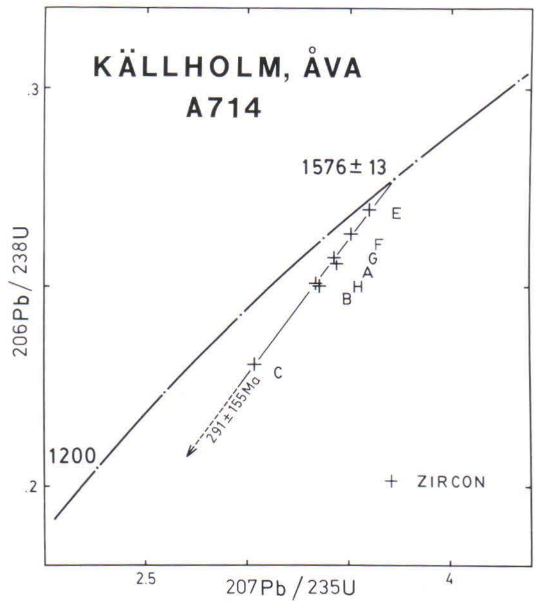

Fig. 23. Concordia plot showing U-Pb isotope ratios of zircon fractions from the Åva quartz porphyry (A714), Källholm, Brändö, Åland.

lead. Molybdenite was found during the refining processes. The zircons are transparent and euhedral.

When plotted on a concordia diagram, the U-Pb isotope ratios (see Table 7) for seven zircon fractions cluster in a rather small area near the concordia and do not form a clear chord. The ages remain within 1571 ± 20 Ma (see Fig. 22) if extrapolated according to the near-linear interval of continuous diffusion curves (Wasserburg 1963).

Källholm, Åva, Brändö

In the Åva area, quartz porphyry dykes cut the 1797 ± 4 Ma old (Patchett and Kouvo 1986) postorogenic group III granite and its granodioritic (earlier referred to as monzonitic) varieties. Ehlers and Ehlers (1977, 1981) regarded the quartz porphyry dykes in the Åva area as coeval with the Korsö pyroxene diabase.

Sederholm (1934) and Kaitaro (1953) have described the field relations between the hornblende and pyroxene diabase dykes and the quartz porphyry dykes of the Åva area. These dykes have a parallel trend, and some of them, e.g. the Källholm dyke near the Korsö diabase, are known to lie in succession (Kaitaro 1953). The age relations are not clear as far as the contact relations are concerned, but Kaitaro (1953), when stating that »they belong to the same sequence», seems to favour a slightly older age for the diabases. »Quartz porphyry cannot be older than the diabase as suggested by Sederholm (1934, p. 53) or we must assume the existence of two generations of quartz porphyries,» writes Kaitaro (1953, p. 58). The quartz porphyry dykes are associated with, but are younger than, the diabases (Ehlers and Bergman, 1984 p. 181).

The zircons of sample A714 are small, acicular, transparent, clear or faint, pinkish prisms with L/B ratio 4—8. The crystal surfaces are glossy.

The upper intercept age (see Fig. 23) on a concordia diagram from the seven zircon fractions is 1576 ± 13 Ma. Note that the most concordant fractions, E and F, were preleached in hydrofluoric acid and lie slightly on the younger side of the best-fit line.

For analytical data, see Table 7.

The Åland rapakivi area

The Åland rapakivi is composed of several textural types representing different intrusion pulses. The terminology used to describe the textural types closely follows that applied to the Wiborg rapakivi batholith (e.g. Wahl 1925). The terms may not exactly correspond to those used by Wahl (e.g. megacryst size, chemical and mineral compositions and textures) but they are not all that different either. The Åland rapakivi area was recently remapped and described by Bergman (1978a, 1978b, 1979, 1981 and 1986). Vaasjoki (1977) has given ages for two types of Åland rapakivi. The earlier rapakivi U-Pb ages given on zircons are based on only a few, often very discordant, fractions. With additional fractions more concordant data were obtained.

The main granite types are coarse-grained normal rapakivi with mantled ovoids (wiborgite), coarse-grained rapakivi with predominantly unmantled ovoids (pyterlite), porphyritic rapakivi and even-grained rapakivi. Quartz-porphyritic varieties also exist, and there are some minor aplitic intrusions (Bergman 1981, 1986).

Böle and Vabbängarna, Eckerö

Rapakivi sample A467 from Böle, Eckerö is from the main phase of the intrusion. Even when recalculated and with additional zircon fractions (altogether 11 fractions were analysed, see Fig. 25 and Table 8), the age of the main phase of the rapakivi is still ambiguous. A new sample, A295, was therefore taken from Vabbängarna, south of Storby, Eckerö, from close to the Böle sample.

Sample A295 represents the hornblende-bearing rapakivi type and hence the main phase of the Åland rapakivi (Bergman 1986). According to Bergman (1979, 1986), it belongs to the same part of the intrusion as does sample A467 from Böle. The rock is deep red in colour and partly granophyric in texture. The unmantled ovoids are ca. 2 cm in diameter. For chemical analysis, see Rämö (1991) and for the mode and chemical analysis of a sample from a nearby outcrop, see Bergman (1981 p. 32 mode no. 20, and p. 47 analysis no. 14).

The zircon crystals of A467 (see Fig. 24) and A295 are mostly euhedral and sharp-edged with glossy surfaces. The L/B ratio is up to 5. The nonmagnetic fraction is conspicuously clean. The crystals are transparent and the primary inclusions are small, possibly partly filled with gas or liquid. As the large magnetic fraction is rich in coatings, at least some of the inclusions or coatings must be magnetic. Some pinkish, multifaced, short crystals were encountered. Rhythmic crystallization might explain the new layer visible in some of the crystals.

During refining of the heavy fractions one grain of galena and a few grains of molybdenite were found in the heaviest fraction.

The five zircon fractions analysed from sample A295 form a good chord (see Fig. 25), which yields an upper intercept age of 1575 ± 11 Ma and a lower intercept of 198 ± 113 Ma at the 2-sigma level. The best-fit line is ruled by the data points

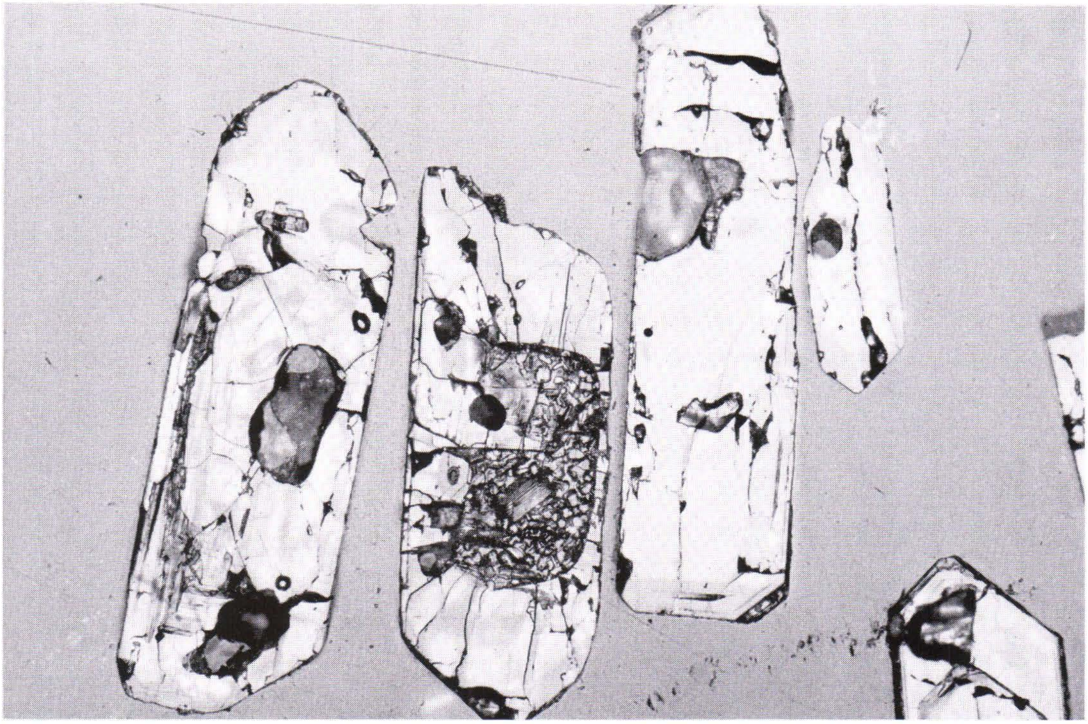

Fig. 24. Microphotographs of HF-etched zircon crystals from sample A467-Böle. The largest zircon is 0.5 mm long. Note the zonal growth and nucleus.
Photo Veli Suominen.

of density fraction 4.3—4.6 g/cm^3. Point A refers to the untreated fraction. To improve the discordant result the zircons were treated as follows: B was crushed and washed in HNO_3, D was preleached in hydrofluoric acid and E was air abraded for 2 hr as described by Krogh (1982). For analytical results, see Table 8. Note the decreasing uranium content due to the treatment: 262—232—220—00 μg/g. These results were more concordant. The common lead content exhibits an interesting variation in the $^{206}Pb/^{204}Pb$ ratio: 659—921—1135—882. Common lead was removed during the acid treatment. The most concordant fraction is that cleaned by air abrasion.

The eleven fractions of sample A467-Böle fit a chord intersecting the A295 best-fit line and yield an upper intercept age of 1560 ± 14 Ma. Despite all efforts to improve the concordance and the number of fractions, the age is still ambiguous. Fractions H and I (see Table 8) were preleached in hydrofluoric acid, a procedure that is known occasionally to result in selective lead loss, moving the isotope ratios to the left on the concordia diagram. The anomalous lower intercept, 23 ± 74 Ma, may be a result of that. The common lead content is high as it is in the quartz porphyries, but the uranium content is surprisingly low, a feature that should favour more concordant results.

Table 8. U–Pb isotopic data on the rapakivi granites of the Åland batholith.

Sample No.	Fraction[1] d=density, g/cm³ Ø=grain size, μm	Concentration μg/g ^{238}U	Concentration μg/g ^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, $^{206}Pb = 100$: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A467–Böle, Eckerö: pyterlitic rapakivi granite, main phase										
A467A[2]	d>4.2	370.4	57.99	510.9	.15752	11.874	17.751	.1810	2.418	.0969
								± 11	± 40	± 11
								1072	1247	1565
B	d>4.6	266.3	42.98	501.6	.19549	12.438	18.664	.1865	2.502	.0973
								± 12	± 43	± 14
								1102	1272	1573
C	4.2<d<4.6	408.5	63.40	404.0	.24249	13.039	20.849	.1794	2.393	.09677
								± 9	± 14	± 21
								1063	1240	1562
D	4.0<d<4.2	940.5	149.54	325.7	.30488	13.762	23.681	.1838	2.414	.09528
								± 10	± 16	± 32
								1087	1246	1533
E	d>4.6; HF	215.3	41.08	879.9	.11087	11.236	15.347	.2206	2.950	.09700
								± 13	± 32	± 78
								1284	1394	1567
F	d>4.6 cr	231.2	41.25	490.7	.20097	12.407	18.357	.2062	2.735	.09619
								± 14	± 24	± 43
								1208	1337	1551
G	4.2<d<4.6 cr	372.6	65.29	460.8	.21521	12.659	19.852	.2026	2.702	.09675
								± 13	± 30	± 79
								1189	1328	1562
H	4.2<d<4.6; HF	300.4	59.66	805.8	.12232	11.253	16.346	.2295	3.024	.09554
								± 16	± 34	± 78
								1332	1413	1538
I	4.2<d<4.6; HF cr	219.3	50.39	808.4	.12073	11.329	16.188	.2656	3.535	.09655
								± 15	± 31	± 56
								1518	1535	1558
J	4.2<d<4.6 abr	327.9	70.17	528.0	.18521	12.190	19.637	.2473	3.281	.09621
								± 13	± 35	± 79
								1424	1476	1552
K	d>4.2 abr	262.0	55.45	1062	.09117	10.946	15.442	.2446	3.265	.09682
								± 13	± 18	± 14
								1410	1472	1563
A295–Vabbängarna, Storby, Eckerö: pyterlitic rapakivi										
A295A	4.3<d<4.6	262.1	53.65	659.3	.14959	11.724	26.132	.2366	3.147	.09649
								± 17	± 38	± 87
								1368	1444	1557

Table 8. (continued)

A295B	4.3<d<4.6	231.6	48.95	921	.10636	11.161	15.941	.2443	3.262	.09687
	cr							± 13	± 20	± 25
								1408	1472	1564
C	4.2<d<4.3	612.1	119.78	769.3	.12879	11.377	19.148	.2262	2.990	.09589
								± 14	± 21	± 28
								1314	1405	1545
D	4.3<d<4.6	220.0	48.02	1135	.08587	10.850	15.144	.2523	3.360	.09659
	HF							± 16	± 29	± 51
								1450	1495	1559
E	4.3<d<4.6	199.9	46.30	881.5	.11040	11.238	16.390	.2678	3.584	.09708
	abr							± 19	± 30	± 39
								1529	1545	1568
A762–Godby, Finström: wiborgitic rapakivi										
A762 A	d>4.5	200.8	39.79	414.9	.23837	12.985	20.328	.2290	3.060	.09691
								± 17	± 28	± 46
								1329	1422	1565
B	d>4.5	188.0	38.34	780.1	.12536	11.416	15.686	.2357	3.146	.09683
	cr							± 13	± 26	± 56
								1364	1444	1564
C	d>4.5;	167.9	38.65	754.7	.12994	11.499	16.009	.2661	3.560	.09704
	HF							± 17	± 25	± 25
								1521	1540	1568
D	4.3<d<4.5	338.9	66.80	285.7	.34842	14.505	25.922	.2278	3.044	.09690
								± 17	± 33	± 69
								1323	1418	1565
E	4.3<d<4.5	297.5	61.63	1063	.09212	10.964	16.099	.2394	3.200	.09691
	cr							± 21	± 29	± 25
								1383	1456	1565
F	4.2<d<4.3	572.7	107.42	785.0	.12594	11.350	17.911	.2168	2.872	.09608
	abr							± 14	± 24	± 46
	cr							1264	1374	1549
G	d>4.2	434.8	73.26	640.0	.15190	11.687	18.082	.1948	2.574	.09585
								± 10	± 15	± 18
								1147	1293	1545
H	d>4.5	165.4	38.51	508.2	.19422	12.422	19.265	.2691	3.614	.09740
	abr							± 15	± 28	± 46
								1536	1552	1575
I	d>4.5	158.3	36.68	1110	.08640	10.903	14.144	.2679	3.586	.09709
	70<Ø<130							± 20	± 32	± 40
	abr							1529	1546	1569
J	4.3<d<4.5	274.4	59.13	214.6	.46239	16.166	33.642	.2491	3.360	.09783
	Ø>130							± 16	± 28	± 46
	abr							1433	1495	1583

Table 8. (continued)

A762 K	4.3<d<4.5	264.0	58.28	931.0	.10559	11.128	16.380	.2552	3.402	.09668
	abr							± 15	± 23	± 26
	cr							1465	1504	1561
A763–Åsbacka, Saltvik: even-grained rapakivi granite										
A763 A	d>4.2;	328.0	71.00	86.2	1.1597	25.781	57.469	.2502	3.36	.0973
	Ø>70							± 20	± 13	± 32
	abr							1439	1494	1573
B	4.0<d<4.2	814.4	175.02	202.0	.49351	16.476	32.271	.2484	3.301	.09639
	Ø>160							± 14	± 24	± 40
	abr							1430	1481	1555
A764–Getabergen, Geta: wiborgitic rapakivi										
A764 A	d>4.2	397.4	81.93	2539	.03512	10.153	13.813	.2383	3.175	.09667
								± 12	± 18	± 12
								1377	1451	1560
B	4.0<d<4.2	1127	232.32	1036	.09420	10.928	19.108	.2383	3.162	.09622
								± 16	± 25	± 36
								1378	1447	1552
C	4.3<d<4.6	325.8	64.73	969	.10164	11.039	15.885	.2297	3.049	.09630
								± 14	± 21	± 26
								1332	1419	1553
D	4.3<d<4.6	278.9	59.70	1495	.06523	10.550	14.492	.2474	3.290	.09646
	Ø>70;							± 15	± 21	± 22
	cr							1425	1478	1556
E	4.3<d<4.6	278.8	60.43	2782	.03438	10.151	13.396	.2505	3.341	.09675
	Ø>70;							± 18	± 24	± 11
	HF							1440	1490	1562
F	4.3<d<4.6	263.9	60.03	2442	.03901	10.240	14.289	.2630	3.516	.09699
	70<Ø<160							± 16	± 24	± 30
	abr, cr							1504	1530	1567
G	4.3<d<4.6	275.5	63.47	5549	.01603	9.972	13.885	.2663	3.579	.09750
	abr							± 17	± 24	± 13
								1521	1544	1576
A468–Långnäs, Lumparland: pyterlite (biotite-rich, partly porphyritic) rapakivi granite										
A468A^2	d>4.2	376.6	69.98	197.3	.48413	16.326	29.695	.2155	2.848	.0962
								± 14	± 46	± 12
								1254	1368	1551
B	4.3<d<4.5	371.8	70.79	262.6	.37925	14.857	25.623	.2200	2.912	.09600
								± 13	± 27	± 62
								1282	1385	1547
C	4.3<d<4.5	313.0	65.18	291.2	.34197	14.318	24.004	.2407	3.178	.09576
	cr							± 17	± 27	± 38
								1390	1451	1543
D	4.3<d<4.5	282.3	61.57	503.1	.19687	12.371	18.603	.2521	3.351	.09644
	Ø>130							± 16	± 25	± 37
	abr							1449	1493	1556

Table 8. (continued)

A468 E	4.3<d<4.5 HF	346.6	71.36	136.5	.73138	19.742	38.348	.2379 ± 18 1375	3.151 ± 34 1445	.09606 ± 67 1548
F	4.0<d<4.2 Ø>70 cr	792.5	160.21	190.2	.52505	16.832	31.659	.2337 ± 17 1353	3.076 ± 38 1426	.09550 ± 84 1538
G	4.3<d<4.5 abr	272.4	61.17	637.1	.15280	11.757	16.427	.2595 ± 15 1487	3.449 ± 24 1515	.09640 ± 30 1555
H	4.3<d<4.5 HF	292.6	62.64	552.7	.17911	12.113	18.008	.2474 ± 15 1424	3.285 ± 26 1477	.09632 ± 46 1554
I	4.3<d<4.5 abr, 5h cr	337.0	74.57	613.9	.15897	11.860	17.372	.2557 ± 15 1467	3.405 ± 27 1505	.09659 ± 44 1559

For symbols, see Table 3.

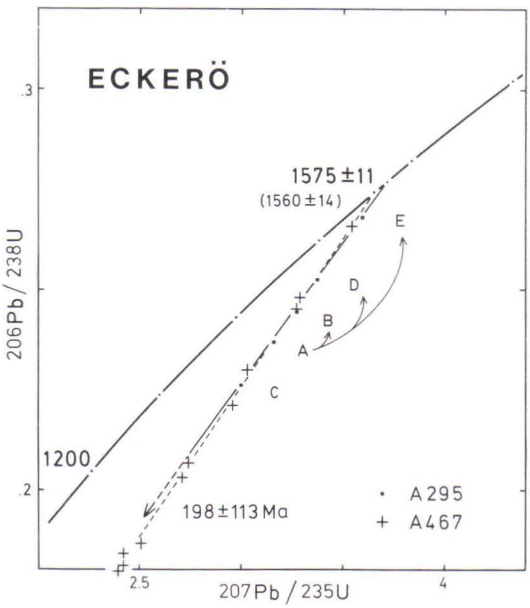

Fig. 25. Concordia diagram for U-Pb isotope ratios of zircon fractions from rapakivi samples A295-Vabbängarna and A467-Böle, Eckerö. Fraction A/A295 was untreated, B crushed and washed in HNO_3; D preleached in HF, and E air abraded (fraction 4.3<d<4.6 g/cm³). Fractions from sample A467: in order of growing discordance are: IJKHEFGBDAC

The age of the Eckerö rapakivi is the same as that of the nearby Blåklobb quartz porphyry and the other rapakivis in the Åland area.

Godby, Finström

Sample A762 is from Godby, Finström. It is a wiborgitic textural type of rapakivi in which orthoclase ovoids are mantled with oligoclase (for chemical analysis, see Rämö 1991).

The zircon crystals of sample A762 (see Fig. 26) are mostly simple euhedral prisms with numerous small inclusions of biotite on their crystal faces; otherwise the faces are clear. Multifaced zircons also occur. The crystals are transparent but grey. Some of the heaviest zircon fractions are translucent and milky white, yellowish or reddish. The L/B ratio is 2—3 but often even 2—5.

The uranium content in zircons is less than 200 ppm (see Table 8), and the $^{206}Pb/^{204}Pb$ ratio is low due to the content of common lead.

The best-fit line through 11 data points (see

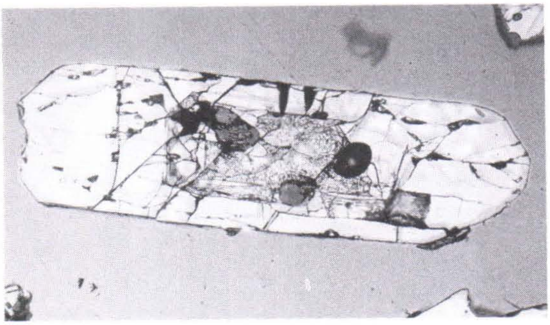

Fig. 26. Microphotograph of a 0.6 mm long zircon crystal from sample A762-Godby. Note the multi-layered U + Th-rich nucleus and new layers of zircon. Photo Veli Suominen.

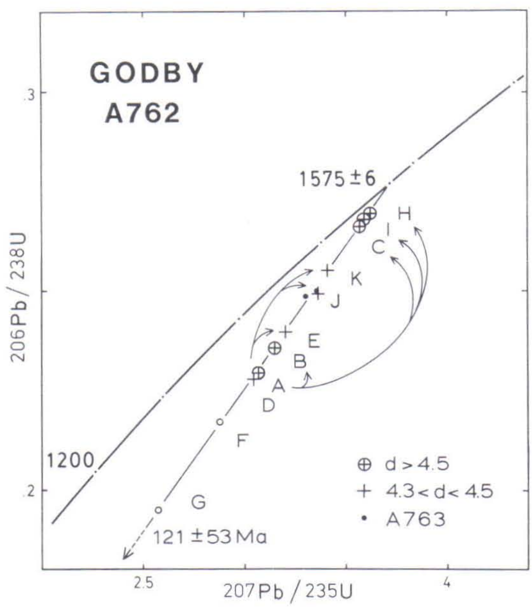

Fig. 27. Concordia diagram for U-Pb isotope ratios of zircon fractions from the Godby wiborgitic rapakivi (A762). Zircon fraction A was untreated, B the same fraction crushed and washed in HNO_3, C preleached in HF, and H and I were air abraded. Fraction D was untreated, E crushed and washed in HNO_3, J air abraded large zircons; and K air abraded. N.B. data points for A763 Åsbacka fractions are not included in calculation.

Fig. 27) yields an age of 1575 ± 6 Ma for the Godby wiborgite (N.B. the zircons of sample A763 are not included in the calculations of this chord, see later in this paper). The untreated zircon fractions (A, D, G) are quite discordant. To improve the accuracy, fractions B, E, F were crushed and washed in nitric acid, fraction C was preleached in hydrofluoric acid, and fractions H, I, J, K were air abraded.

The age obtained for the Godby wiborgite is the same, within the limits of error, as that for the Eckerö rapakivi. The Godby wiborgite is younger than the wiborgite of the Wiborg rapakivi area (see further in this paper).

Åsbacka, Saltvik

The Åsbacka sample (A763), from the Ödkarby intrusion in Saltvik, represents the even-grained rapakivi granites in the north of the Åland islands (see Bergman 1978b). This rock type was termed Haga granite by Frosterus and Sederholm (1890). The granite is deep red and medium-grained. For mode and chemical analysis, see Bergman (1981 and 1986).

Sample A763 contains less zircon than the wiborgitic types, a common feature of even-grained rapakivi granites according to Nurmi and Haapala (1986). The other characteristic accessory minerals are black anatase and bastnaesite (with intergrown fluocerite). Cerussite was found for the first time in Finland (Lindqvist and Suominen 1988). Lead from three tiny cerussite crystals (unwashed) from sample A763 was analysed, and its isotopic composition is $^{206}Pb/^{204}Pb = 21.407$; $^{207}Pb/^{204}Pb = 16.005$; $^{208}Pb/^{204}Pb = 40.302$. A considerable amount of radiogenic lead is incorporated in this lead. K-feldspar lead was used for common lead correction in age calculations of zircons (see p. 9).

The zircon crystals with density fraction d > 4.2 g/cm^3 are fragments of transparent, colourless or pale pinkish and yellow, simple prisms. Some zircons have small black inclusions on their faces. In density fraction $4.0 < d < 4.2$ g/cm^3 the zircon grains are fragments of translucent, milky or faint, pinkish, simple prisms, often with corroded faces.

The data points of the two zircon fractions analysed (see Table 8 and Fig. 27) fall close to the chords of nearby Godby and Getabergen (see below), which evidently belong to the same 1575 Ma age group.

Getabergen, Geta

Sample A764, from Getabergen, Geta in the northern part of the Åland rapakivi, is a wiborgitic variety (see Bergman 1978b, 1981 and 1986).

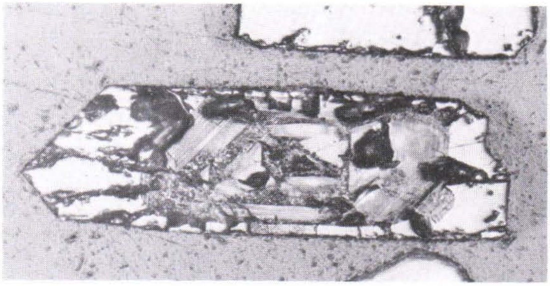

Fig. 28. Microphotograph of a 0.55 mm long zircon crystal from sample A764-Getabergen. Note the several metamict layers.
Photo Veli Suominen.

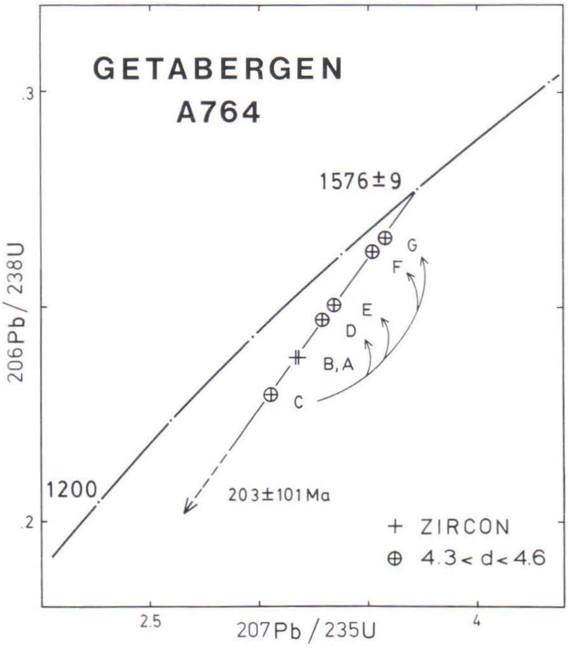

Fig. 29. Concordia plot for the zircon fractions from sample A764-Getabergen. Fraction C was untreated (4.3 < d < 4.6 g/cm^3), D crushed and washed in HNO_3, E preleached in HF, F air abraded large zircons, and G air abraded.

The zircons from this sample (for microphotograph, see Fig. 28) exhibit zonal growth with many inclusions. Some of the zircons are sharp-edged, fully clear and transparent. The pyramid faces at the terminations are well developed in some of the crystals. The crystal faces are glossy, and the L/B ratio varies from 2 to 7.

Density fraction 4.3 < d < 4.6 g/cm^3 was analysed five times. Data point C of Fig. 29 represents the original fraction. The same fraction crushed and washed in nitric acid (D) is clearly more concordant, and fraction E, which was preleached in hydrofluoric acid, is even more so. The most concordant fractions are F (air abraded and crushed and the powder preleached in 1 : 1 HNO_3) and G (air abraded until the grains were completely rounded).

The U-Pb isotope ratios of the seven zircon fractions plotted on a concordia diagram (see Fig. 29) yield an age of 1576 ± 9 Ma. For analytical data, see Table 8. (Note the high $^{206}Pb/^{204}Pb$ ratio).

Långnäs, Lumparland

The Långnäs rapakivi sample, A468, represents the pyterlitic textural type of the Åland rapakivi intrusion. The rock, which is rich in biotite, often has a porphyritic texture. This type of rapakivi occurs near the eastern margin of the Åland rapakivi area. For mode and chemical analyses, see Bergman (1981, 1986). A striking feature is the presence of greisen dykes in the rock.

The zircons from sample A468 are small, reddish, transparent and mostly short (L/B ratio 2—6) tetragonal prisms at obtuse angles to the pyramid faces (see Fig. 30) and with zonal growth. The crystal faces are glossy on the whole, but some have a characteristic striation parallel to the c-axis and some are corroded.

Sample A468 was dated earlier by Vaasjoki (1977). With additional zircon fractions the age obtained from a 9-point best-fit line is 1559 ± 8 Ma (lower intercept 102 ± 92 Ma). If data points A and B are omitted from calculations, the age

Fig. 30. Microphotographs of zircon crystals from sample A468-Långnäs. The largest zircon is 0.6 mm long. Note the growth nucleus surrounded by metamict layers. Photo Veli Suominen.

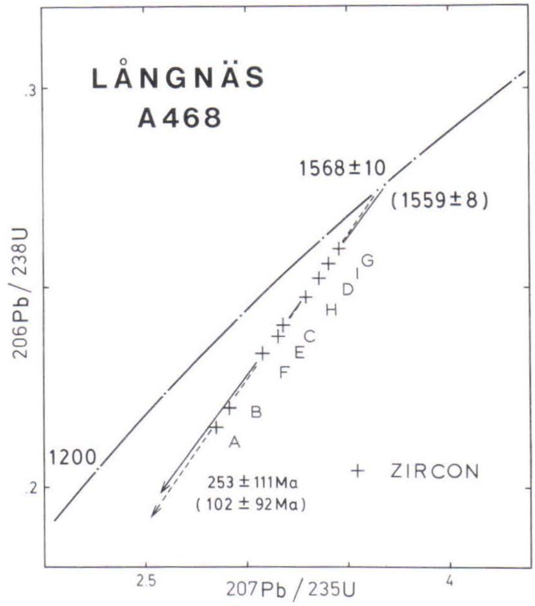

Fig. 31. Concordia diagram for U-Pb isotope ratios of zircon fractions from rapakivi granite A468-Långnäs. B is an untreated (4.3 < d < 4.5 g/cm^3) fraction, C was crushed and washed in HNO_3, D air abraded, E preleached in HF, G air abraded, H preleached in HF, and I air abraded and crushed zircons. The chord drawn with a full line is for treated zircon fractions.

obtained from the seven zircon fractions treated is 1568 ± 10 Ma, with a lower intercept of 253 ± 111 Ma (see Fig. 31). The treated and more concordant fractions have a higher $^{206}Pb/^{204}Pb$ ratio and are more reliable than fractions A and B. Thus the age yielded by the acid-treated and air-abraded zircons is the most probable for the Långnäs sample. For analytical data, see Table 8.

A slight rotation of the array from the intercept ages of 1568 ± 10 Ma/253 ± 253 Ma to 1570 ± 10 Ma/285 ± 111 Ma occurred if the model lead isotope ratios $^{206}Pb/^{204}Pb = 16.169$, $^{207}Pb/^{204}Pb = 15.430$ and $^{208}Pb/^{204}Pb = 35.838$ were used instead of the average K-feldspar lead (16.853, 15.479, 36.201, respectively) from samples A295, A762 and A764.

The Kökarsfjärden rapakivi granite

The Kökarsfjärden rapakivi pluton crops out only on some outer islands and skerries in the Baltic Sea, southwest of the island of Karlby, Kökar (see Fig. 14). On Söderharun (sample A441) the rapakivi has a porphyritic texture, and unmantled orthoclase ovoids are common. The megacrysts are often angular, twinned grains. The matrix is medium to coarse-grained, and the unmantled ovoids are often 5—8 cm in diameter. The euhedral blue quartz is acicular. Although

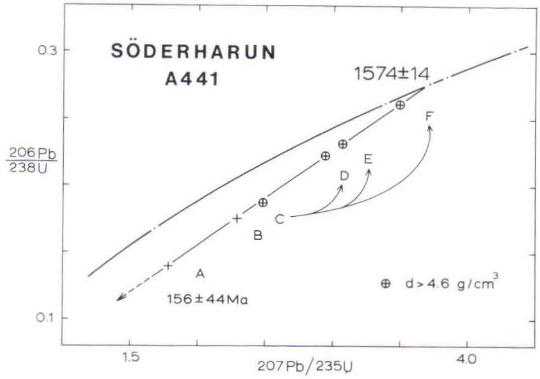

Fig. 32. Concordia plot for zircon fractions of Kökarsfjärden rapakivi granite sample A441-Söderharun. C is an untreated fraction, D crushed, E preleached in HF, and F air abraded. If fraction C is omitted from the calculation the data define a chord with intercepts at 1571±4 Ma and 162±12 Ma.

the grain size and texture vary within the pluton, the prevailing texture is trachytoid. The scarcity of outcrops led Sederholm (1924, 1934) to suspect that the pluton is divided into two separate intrusions. On aeromagnetic maps the strong negative anomaly over the rapakivi is continuous, and thus the intrusion is interpreted as being one single pluton (see Suominen 1981). However, it may comprise two or more intrusive phases, especially if they are similar in texture and composition. Interpreted from aeromagnetic maps, the pluton covers an area of some 500 km^2.

No contacts are known, but angular granodiorite inclusions occur on Norrharun, in the northeastern part of the pluton, suggesting the proximity of a contact against the granodiorite to the north. Near the interpreted western contact, granite fragments are met with in the rapakivi.

The zircon crystals of sample A441-Söderharun are translucent, the majority being transparent, euhedral and sharp-edged. The crystal faces are glossy. Inclusions are common. The L/B ratio is up to 7. Some pinkish, multi-faced zircons were found in the zircon population, in which red-pigmented crystals are also common. Molybdenite and two small grains of galena were found during the refining process.

The Kökarsfjärden rapakivi on Söderharun was earlier dated by Vaasjoki (1977). With additional zircon fractions the upper intercept age from the six-fraction best-fit line is 1574±14 Ma (see Fig. 32). The age is the same as that obtained for the main phase of the Åland rapakivi massif. For analytical data, see Table 9.

The Fjälskär rapakivi stock, Houtskär

The small rapakivi stock of Fjälskär (see Fig. 1 and Fig. 62) was previously dated by Vaasjoki (1977). A new sample, A287, was taken from the middle of the stock, from the island of Fjärdskär. The Fjälskär stock plays an important role in comparisons of the rapakivi granites and post-orogenic granites, e.g. the Åva intrusion, both of which are circular intrusions of the same size.

First described by Sederholm (1924), the rapakivi of Fjärdskär is a two-mica granite with porphyritic texture. Muscovite is not a common mineral in the rapakivi granites (Sederholm loc. cit. p. 130). Topaz veinlets and pegmatitic miarolitic cavities containing topaz and columbite occur near the sharp-cutting contacts against the Svecofennian rocks. For modes and chemical analyses of the Fjälskär granite, see Bergman (1986). The fluorite content is high, even for a rapakivi, 0.3 — 2.9 % (Bergman 1986).

In the course of heavy mineral separation, fluocerite was found in the magnetic fraction with a density of >4.6 g/cm^3. This was the first time fluocerite, first described by Berzelius (1818) from Finnbo and Broddbo near Falun, Sweden, was identified with certainty in Finland.

Fluocerite (tysonite) occurs together with fluorite as inclusions, intergrowths or individual grains, often partly altered to bastnaesite. The

Table 9. U–Pb isotopic data on the rapakivi granites of southwestern Finland.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration μg/g ^{238}U	 ^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100 204	 207	 208	Atomic ratios and radiometric ages, Ma $^{206}Pb/^{238}U$	 $^{207}Pb/^{235}U$	 $^{207}Pb/^{206}Pb$
A441–Söderharun, Kökarsfjärden, Kökar: porphyritic rapakivi granite										
A441A[2]	3.8<d<4.0 Ø>160 borax	1856	224.09	977	.08651	10.443	12.846	.1396 ± 9 842	1.778 ± 16 1037	.09238 ± 45 1475
B[2]	d>4.0; Ø>160 borax	585.3	88.69	516.9	.15501	11.631	16.501	.1751 ± 11 1040	2.288 ± 38 1208	.0948 ± 11 1523
C	d>4.6	263.7	42.76	455.9	.21690	12.617	19.905	.1874 ± 11 1107	2.482 ± 22 1266	.09608 ± 58 1549
D	d>4.6 cr	204.4	39.36	289.5	.34236	14.353	24.707	.2225 ± 15 1295	2.946 ± 25 1393	.09602 ± 47 1548
E	d>4.6 HF	201.4	40.35	278.3	.35710	14.572	25.831	.2315 ± 17 1342	3.070 ± 25 1425	.09618 ± 31 1551
F	d>4.6 abr	146.0	33.00	760.4	.12781	11.464	18.497	.2612 ± 16 1495	3.490 ± 26 1525	.09692 ± 34 1565
A287–Fjärdskär, Houtskär: even-grained rapakivi										
A287A	4.3<d<4.6 Ø>70	463.8	76.51	81.4	1.2273	26.545	65.476	.1907 ± 13 1124	2.495 ± 34 1270	.0949 ± 10 1526
B	4.3<d<4.6 Ø>70 abr 1h	516.1	92.26	132.2	.75507	19.978	45.318	.2066 ± 14 1210	2.702 ± 31 1328	.09485 ± 79 1525
C	4.3<d<4.6 Ø>70 abr 2h	453.5	87.97	116.7	.85537	21.538	48.501	.2242 ± 14 1304	2.992 ± 86 1405	.0968 ± 25 1563
D	4.3<d<4.6 Ø>70 abr 5h	277.5	66.80	366.2	.26582	13.498	29.699	.2782 ± 17 1582	3.766 ± 45 1585	.09819 ± 91 1590
E	4.3<d<4.6 Ø>70 HF	602.9	130.34	70.4	1.419	29.372	75.086	.2499 ± 42 1437	3.342 ± 64 1490	.09701 ± 80 1567
F	4.3<d<4.6 Ø<70; HF cr	196.8	42.30	785.6	.12398	11.363	34.032	.2485 ± 15 1430	3.304 ± 22 1481	.09644 ± 21 1556
G	fluocerite	32.84	6.76	354.5	.27405	13.250	9652	.2381 ± 20 1376	3.098 ± 76 1432	.0944 ± 20 1516

Table 9. (continued)

A287G	fluocerite	24.07	5.69	141.1	.61586	18.181	10067	.273	3.63	.0964
								± 11	± 27	± 51
								1556	1556	1555
A129–Peipohja, Kokemäki: porphyritic rapakivi granite										
A129A²	total borax	310.4	67.91	360.9	.24503	13.075	27.215	.2529	3.376	.0968
								± 30	± 70	± 13
								1453	1498	1563
B²	d>4.2; Ø>160	499.2	77.82	511.0	.16914	11.890	20.316	.1802	2.371	.09543
								± 11	± 30	± 78
								1067	1233	1536
C	d>4.6; Ø>70 abr diamond	239.1	47.15	928	.10605	11.093	21.151	.2279	3.025	.09624
								± 14	± 30	± 68
								1323	1413	1552
D	d>4.6; Ø>70	259.6	48.21	822	.11737	11.337	21.259	.2146	2.874	.09713
								± 11	± 17	± 20
								1253	1375	1569
E	4.2<d<4.6 Ø>70 abr diamond	722.2	121.69	1065	.09326	10.882	16.168	.19472	2.575	.09589
								± 10	± 18	± 38
								1146	1293	1545
F	d>4.6; Ø>70 abr diamond	258.0	46.46	592.4	.16452	11.815	22.250	.2081	2.734	.09530
								± 11	± 17	± 26
								1218	1337	1534
G	d>4.6; Ø>70 HF	161.3	37.29	10081	.007596	9.816	18.821	.2672	3.578	.09711
								± 15	± 21	± 14
								1526	1544	1569

For symbols, see Table 3.

mineral association, fluocerite-bastnaesite-fluorite, where bastnaesite is an alteration product of fluocerite, is characteristic (Geijer 1921a, 1921b, Goddard and Glass 1940). In Fig. 33 the above-mentioned mineral paragenesis is seen with zircon in the middle. The results of a detailed study of the Fjärdskär fluocerite have been published by Lahti and Suominen (1988).

The other heavy accessory minerals are zircon, topaz, bastnaesite, cerianite and columbite.

The zircon crystals from sample A287-Fjärdskär, density fraction 4.2—4.3 g/cm³, are transparent to translucent, milky or very slightly pink, simple tetragonal prisms with L/B ratio 3—6. The crystals of this fraction vary in size. In some of the zircon grains there are short tetragonal (L/B ratio 1.5—2.5) zircon crystals as inclusions with pyramids at both ends. These inclusions are clear and slightly yellowish but transparent. Yellowish crystals of the same habit are common in the fraction studied. They may have crystallized earlier from the same magma or have been inherited from the country rock through which the rapakivi granite intruded.

The zircon crystals of density fraction 4.3—4.6 g/cm³ are clearly different from those of fraction 4.2—4.3 g/cm³. They are clear and transparent and have a faint reddish tint. The size of the zircon crystals varies. The habit is the same as in the previous fraction. L/B is 3—5. Gas or liquid inclusions are visible in some of the crystals. As inferred from colour and density, this

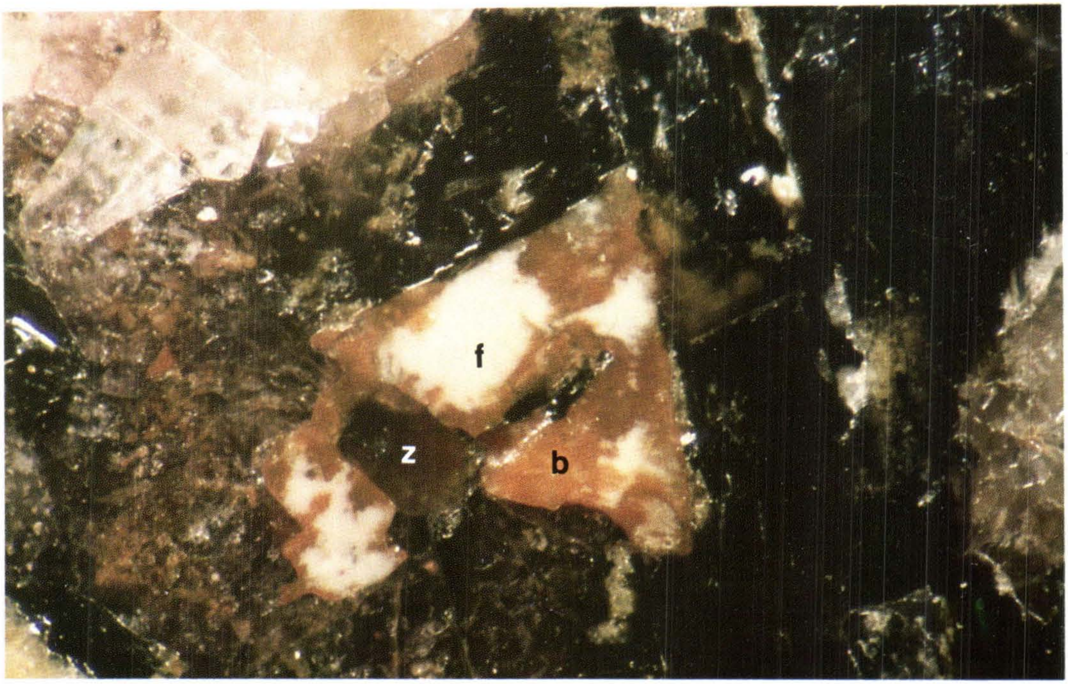

Fig. 33. Fluocerite from sample A287-Fjärdskär. Fluocerite (almost white = f), bastnaesite (red-brown = b), fluorite (violet), zircon (dark-brown = z, within bastnaesite and fluocerite) with radial cracks in biotite, K-feldspar and quartz. Inclined illumination, polished sample.
Photo Veli Suominen.

fraction is less radioactive than the previous one.

The zircon content of the Fjärdskär sample is not as high as it normally is in rapakivi granites. Some galena and molybdenite were found during refining processes. Lead isotope ratios of $^{206}Pb/^{204}Pb = 23.23$, $^{207}Pb/^{204}Pb = 16.33$ and $^{208}Pb/^{204}Pb = 35.32$ were measured for galena. From the isotopic composition it can be concluded that some radiogenic lead must be involved.

The isotope ratios of six zircon fractions plotted on a concordia diagram yield an age of 1579 ± 13 Ma (see Fig. 34; for analytical data, see Table 9). Isotope ratios for the two fluocerite fractions are given in Table 9. The fluocerite is probably contaminated by its alteration product, bastnaesite. The common lead content in the zircon crystals is high.

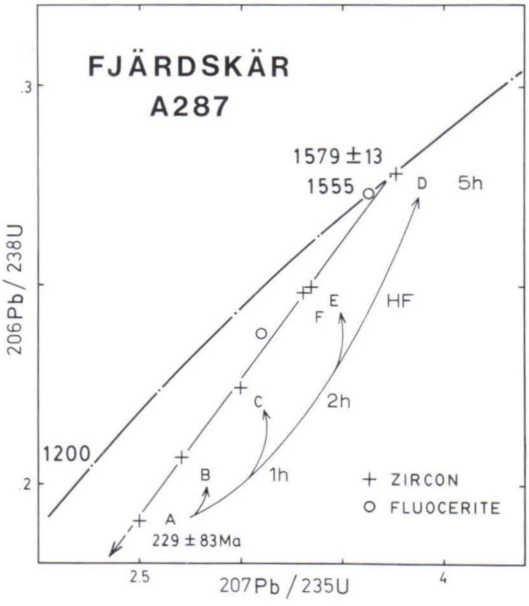

Fig. 34. Concordia plot for zircon fractions and fluocerite from rapakivi granite sample A287-Fjärdskär. Fractions B,C and D are air abraded, E and F preleached in hydrofluoric acid.

The Peipohja rapakivi stock, Kokemäki

The small porphyritic rapakivi stock in Peipohja, Kokemäki (sample A129) was previously dated by Kouvo (1958; $^{207}Pb/^{206}Pb$ age on zircon) and, with an additional fraction, by Vaasjoki (1977). The petrography and chemical characteristics have been described by Vorma (1976). In many respects the Peipohja rapakivi is similar to that at Eurajoki (Haapala 1977), which continues beneath the Jotnian sandstone of Satakunta as discussed by A. Laitakari (1925) and Kahma (1951). During recent fieldwork the area of the Kokemäki rapakivi was revised making use of aeromagnetic map interpretations (Hämäläinen 1985).

The U-Pb isotope ratios of the seven zircon fractions plotted on a concordia diagram (see Fig. 35) yield an age of 1573 ± 20 Ma. For analytical data, see Table 9. The age obtained is the same as that reported for the Laitila rapakivi (Vaasjoki 1977).

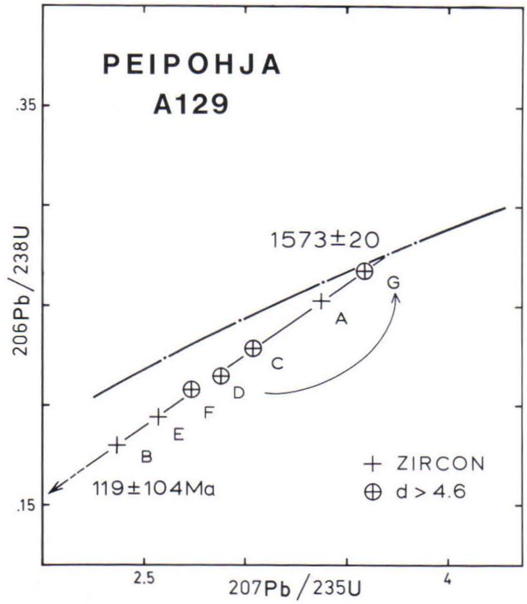

Fig. 35. Concordia plot for the seven zircon fractions analysed from Peipohja rapakivi granite in Kokemäki (A129). D is the original fraction, C abraded with diamond paste, and G preleached in HF.

Comparison with the Wiborg and Salmi rapakivi areas

The rapakivi granites in Fennoscandia have traditionally been correlated with the largest and, in many respects, best known rapakivi area, that of Wiborg (Viipuri). The Salmi rapakivi on the northeastern shore of Lake Ladoga in Soviet Karelia offers one more possibility for correlating the ages of the rapakivi intrusions in the Fennoscandian (Baltic) Shield.

The Wiborg rapakivi area

The Wiborg (Viipuri) rapakivi area in southeastern Finland is composed of several textural types representing different intrusion phases. The rock names used in Finland for these different textural types refer to those of the Wiborg rapakivi as defined by Wahl (1925). Even if there are differences in chemical characteristics, the rock names refer to texture only, as suggested by Sahama (1945).

The Wiborg rapakivi was earlier dated by Kouvo (1958) using the U-Pb method on zircon and the Rb-Sr method on biotite; by Gerling and Polkanov (1958) using the K-Ar method on biotite; by Polkanov and Gerling (1961b) with the same method and by Vaasjoki (1977) using the U-Pb method on zircon. New age data with additional zircon fractions were reported for the Wiborg rapakivi area by Tyrväinen (1986); for the rapakivi-like Onas granite of the same age by Laitala (1984) and for the Östersundom granite porphyry by Törnroos (1984). There does not seem to be a clear age difference between the gabbro-anorthosite and rapakivi varieties and the

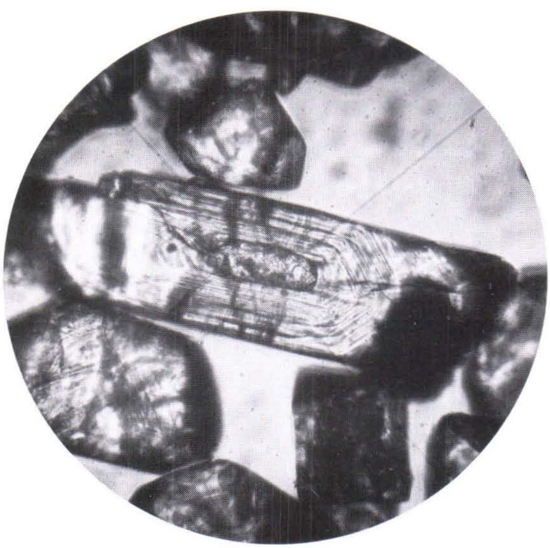

Fig. 36. Microphotograph of zircon crystals from wiborgite sample A29 with growth nucleus, characteristic zoning and clear interfaces.
Courtesy Olavi Kouvo.

quartz porphyry dykes; within the limits of error they are of the same age, about 1640 Ma. These recent rapakivi ages are summarized in Vaasjoki et al. (1989, 1991). The Hamina quartz porphyry dyke is slightly younger, as reported later in this paper.

For comparison with the Åland area, a wiborgitic variety of the Wiborg rapakivi, A29 Falin, Muurikkala, Miehikkälä, was reanalysed. The anorthosite sample, A119-Ylijärvi, Ylämaa, and the dark coloured rapakivi granite sample A791-Ylijärvi, Ylämaa, are from the same quarry. For chemical analysis of samples A29 and A119, see Rämö (1991).

Zircon from anorthosite (A119) occurs as large, clear, transparent, prismatic crystals with L/B ratio 2.5—6. The surfaces are mostly glossy but contain small opaque impurities. Some surfaces seem to be corroded. Gem-like multifaced

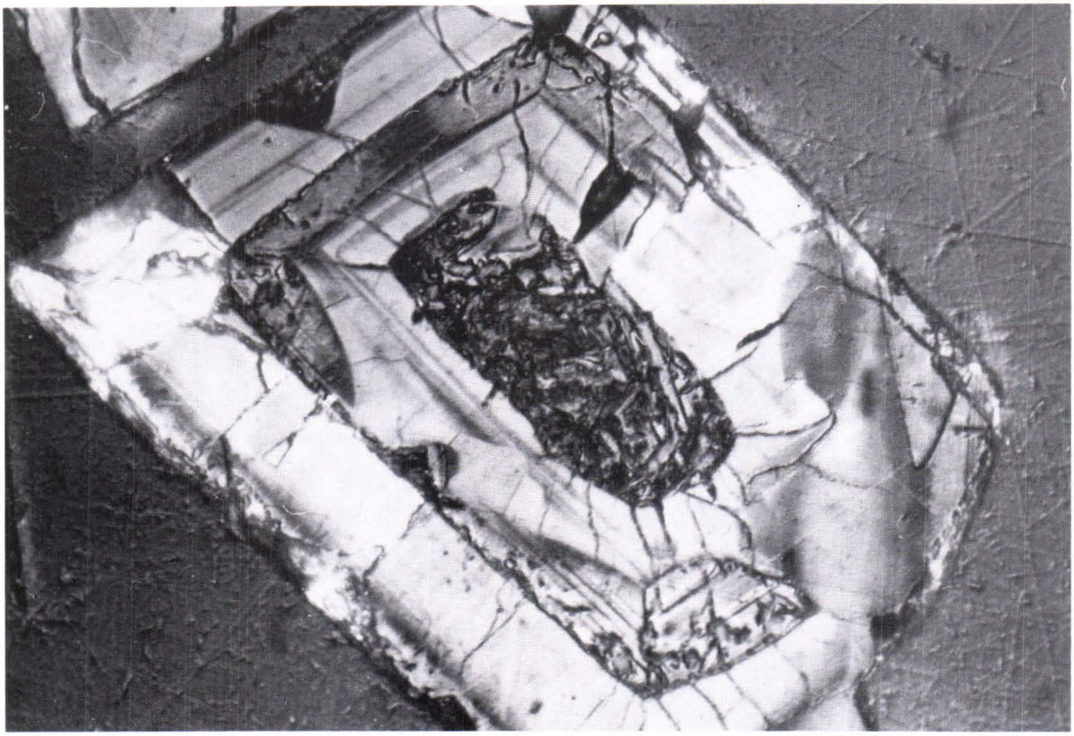

Fig. 37. Microphotograph of an etched zircon crystal from sample A29.
Courtesy Olavi Kouvo.

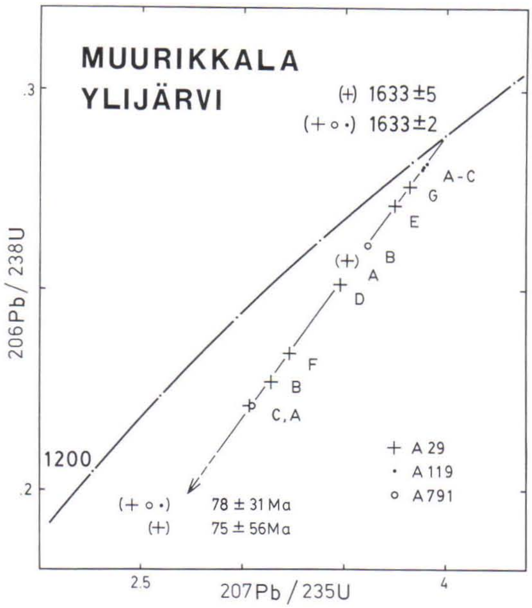

Fig. 38. Concordia diagram for zircons from reference samples A29-Muurikkala (wiborgite), A119-Ylijärvi (anorthosite) and A791-Ylijärvi dark-coloured rapakivi granite of the Wiborg rapakivi area.

zircons occur. Acicular inclusions parallel to the c-axis are common.

The zircon crystals of A29 Falin are long and prismatic with polysynthetic twinning most often around a disharmonically twinned core (see Fig. 36 and 37). The zirconium and hafnium contents of the marginal parts (ZrO_2 61 % and HfO_2 1.6 %) and central parts (ZrO_2 64 % and HfO_2 0.9 %) differ clearly (electron microprobe analyses by Tuula Paasivirta).

The data points of the U-Pb isotope ratios are plotted on the same concordia diagram in Fig. 38. For analytical data, see Table 10. With six zircon fractions (data point A omitted from the calculations) an age of 1633 ± 5 Ma was obtained for A29 (see Fig. 38). The K-Ar age reported by Gerling and Polkanov (1958) on biotite is 1620 Ma, (new Soviet constants; 1569 Ma if conversed after Harland et al., 1982). The same was obtained by Kouvo (1958) with the Rb-Sr method on biotite (1610 ± 40 Ma; 1576 Ma if the decay constant recommended by Steiger and Jäger (1977) is used).

The quartz porphyry dyke of Hamina

One of the quartz porphyry dykes in the Wiborg rapakivi area, the Hamina dyke, cuts both the wiborgitic and the pyterlitic varieties of rapakivi (see Simonen 1973, 1987). It was previously dated and described by Vaasjoki (1977) and after additional radiometric measurements, a new age was reported by Neuvonen (1986) and by Vaasjoki et al. (1991).

The zircon crystals from sample A323-Hamina are pinkish, transparent or red translucent, simple tetragonal prisms with pyramid faces. The L/B ratio is 3—5. Small impurities are common on corroded crystal faces.

For analytical results, see Table 10. Plotted on a concordia diagram, the data points form two

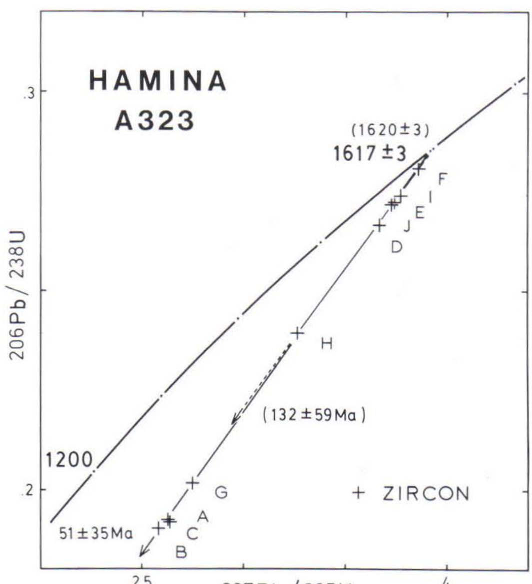

Fig. 39. Concordia diagram for U-Pb ratios of zircon fractions from sample A323, Hamina quartz porphyry dyke. Fractions A, B, C and G were not treated in acid or abraded. The upper group, treated with HF acid or air abrasion, is the most concordant. The ages of the treated fractions are in parentheses.

Table 10. U–Pb isotopic data on the rapakivi granites and quartz porphyry of the Wiborg batholith.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration μg/g ^{238}U	Concentration μg/g ^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A29–Falin, Muurikkala, Miehikkälä: wiborgite										
A029A		ref. Kouvo 1958								
B[2]	d>4.1	530.0	104.17	880	.08961	11.256	16.641	.2272	3.139	.10022
								± 14	± 33	± 63
								1319	1442	1628
C[2]	3.8<d<4.1	952.4	182.31	782	.10748	11.427	16.745	.2212	3.034	.09946
								± 13	± 30	± 54
								1288	1416	1614
D	d>4.6; Ø>160	277.8	60.40	1119	.08786	11.237	15.003	.2513	3.475	.10027
								± 13	± 19	± 12
								1445	1521	1629
E	d>4.6; HFe	230.0	53.98	3286	.02849	10.421	12.521	.2712	3.750	.10029
								± 14	± 21	± 13
								1546	1582	1629
F	4.2<d<4.6 Ø>160	464.0	94.10	1473	.06699	10.917	13.977	.2344	3.229	.09994
								± 12	± 18	± 16
								1357	1464	1623
G	4.2<d<4.6 Ø>160 HF	353.1	84.33	6696	.01398	10.225	11.640	.2760	3.818	.10032
								± 14	± 21	± 8
								1571	1596	1630
A119–Ylijärvi, Ylämaa: anorthosite										
A119A	d>4.6; Ø>70	293.3	71.25	7742	.009096	10.166	19.611	.2808	3.887	.10041
								± 15	± 21	± 12
								1595	1611	1631
B	d>4.2; Ø>160	529.2	128.94	9961	.007155	10.148	20.793	.2816	3.902	.10049
								± 15	± 21	± 8
								1599	1614	1633
C	4.0<d<4.2	748.4	181.50	9322	.009123	10.166	19.909	.2803	3.880	.10040
								± 15	± 21	± 8
								1592	1609	1631
A791–Ylijärvi, Ylämaa: dark-coloured rapakivi granite										
A791A	d>4.6; Ø>160	330.0	63.23	83.5	1.1980	26.499	57.341	.2215	3.044	.0997
								± 13	± 54	± 17
								1289	1418	1618
B	d>4.6; Ø<160 HF	226.9	51.21	804	.12264	11.734	17.834	.2608	3.612	.10043
								± 16	± 29	± 47
								1494	1552	1632
A323–Hamina: quartz porphyry										
A323A[2]	d>4.2	370.7	61.69	145.0	.63899	18.747	37.184	.1924	2.630	.0992
								± 13	± 63	± 17
								1134	1309	1608

Table 10. (continued)

A323B²	3.8<d<4.1	542.3	89.28	219.5	.41933	15.638	25.134	.1903 ± 12 1122	2.581 ± 43 1295	.0984 ± 11 1593
C²	total borax	410.8	68.19	145.7	.67130	19.235	37.825	.1919 ± 16 1131	2.635 ± 32 1310	.09963 ± 73 1617
D	d>4.6 HF	196.0	45.24	390.7	.25453	13.473	25.568	.2667 ± 14 1524	3.661 ± 20 1562	.09957 ± 11 1616
E	d>4.6 Ø>160 HF	186.7	44.00	960	.10251	11.373	19.851	.2724 ± 15 1552	3.740 ± 22 1579	.09957 ± 21 1616
F	4.2<d<4.6 Ø>160 HF	485.0	117.85	668.7	.14879	12.012	16.235	.2808 ± 15 1595	3.855 ± 24 1604	.09957 ± 28 1616
G	d>4.6	264.3	46.09	164.7	.60613	18.263	38.338	.2016 ± 12 1183	2.747 ± 25 1341	.09883 ± 62 1602
H	d>4.6 HF	229.7	47.55	118.5	.84354	21.552	46.971	.2392 ± 16 1382	3.262 ± 30 1472	.09890 ± 57 1603
I	4.2<d<4.6 70<Ø<160 abr	753.5	178.82	926	.10657	11.440	14.493	.2743 ± 17 1562	3.770 ± 28 1586	.09969 ± 34 1618
J	d>4.6; Ø>130 abr	196.1	46.15	413.9	.23702	13.217	24.394	.2720 ± 33 1550	3.728 ± 59 1577	.09942 ± 91 1613

For symbols, see Table 3.

clusters (see Fig. 39), the upper one consisting of fractions with $^{206}Pb/^{204}Pb > 390$ and the lower one of fractions with $^{206}Pb/^{204}Pb < 220$. The most concordant five data points include two air abraded fractions (I and J) and three fractions preleached in hydrofluoric acid (D, E and F). Air abrasion confirms that, in this case, selective lead loss did not occur during hydrofluoric acid treatment.

On geological criteria, the quartz porphyry of Hamina (A323) is the youngest member. It yields an age of 1617 ± 3 Ma with a ten-point best-fit chord (see Fig. 39). Thus, even the youngest quartz porphyry of the Wiborg area is older than the oldest members of the Åland rapakivi complex.

The Salmi rapakivi pluton

The Salmi pluton northeast of Lake Ladoga, Soviet Karelia, is composed of several intrusive phases, but its southern part is covered by the supracrustal Salmian series. Two of the three outcropping intrusive phases (Velikoslavinski 1978) were dated in the present study from samples supplied by the Geology Branch of the Soviet Academy of Science in Petrozavodsk after a joint excursion to the area. The first and more abundant

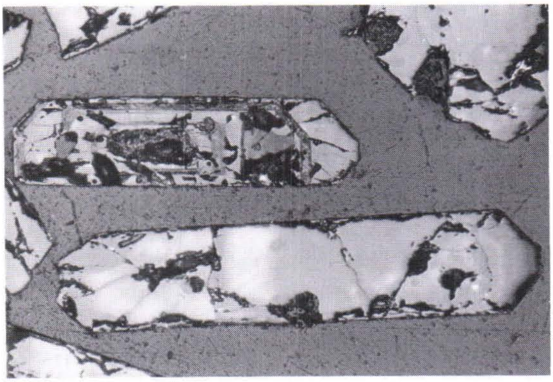

Fig. 40. Microphotographs of HF-etched zircon crystals from sample Salmi I. The largest zircon is 0.6 mm long. Note the growth nucleus and the metamict zone. Photo Veli Suominen.

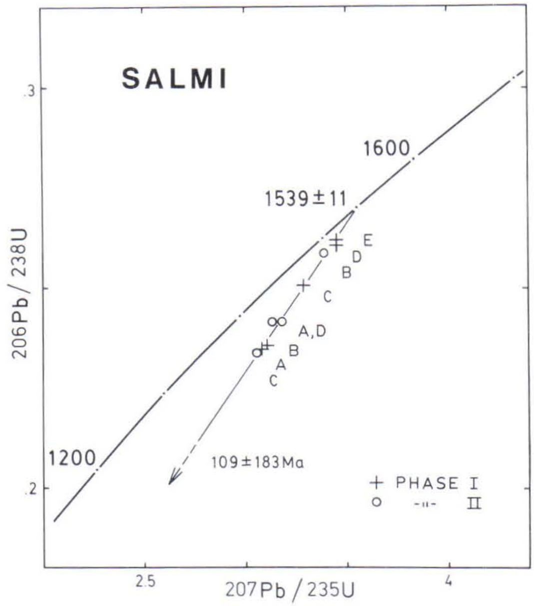

Fig. 41. Concordia plot for the nine zircon fractions analysed from the Salmi rapakivi area (USSR) in SE Fennoscandia.

is the pyterlitic textural type, in which oligoclase-mantled ovoids are not uncommon. The second intrusive phase consists of an even-grained rapakivi variety. According to Sahama (1945), who investigated the Salmi pluton in detail, the two types differ in dark mineral contents: the ovoidic rapakivi contains both biotite and hornblende, but the even-grained variety only biotite.

During the refining process it was found that the first phase (Salmi I) contains abundant zircon and some molybdenite. The second phase (Salmi II) is less rich in zircon, but some bastnaesite was found in the heavy magnetic fraction.

The zircons of phase I are acicular, simple tetragonal crystals with zonal growth (see Fig. 40). Pyramid faces are not well developed in all zircon crystals.

For analytical data, see Table 11. The age obtained from the upper intercept of the chord plotted on a concordia diagram is 1539 ± 11 Ma. The lower intercept is 109 ± 183 Ma (see Fig. 41). The two intrusive faces seem to be of roughly the same age. Neymark et al. (1991a and 1991b) report an U-Pb age of 1543 ± 8 Ma on zircon fractions from the first intrusive phase of the Salmi rapakivi. The Rb-Sr age of 1508 ± 6 Ma, even if too low as a result of albitization, and the K-Ar ages of 1500 ± 30 Ma and 1550 ± 30 Ma reported by Velikoslavinski (1978) for whole-rock samples of the ovoidic rapakivi, are not far from the zircon ages of the present study. The Salmi pluton is clearly younger than the Wiborg rapakivi complex, thus suggesting an age zonation from centre to periphery in the Baltic shield, contrary to the opinion of Kratz et al. (1968), who are among those who favour westward younging of ages.

Table 11. U–Pb isotopic data on the rapakivi granites of the Salmi pluton in the USSR.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration μg/g ^{238}U	^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
	Salmi, USSR: pyterlitic rapakivi granite, phase I									
A	d>4.3;	154.0	31.29	128.8	.77396	20.251	44.252	.2348	3.074	.09497
	Ø>70							± 14	± 27	± 52
								1359	1426	1527
B	d>4.3	145.8	29.75	185.3	.53691	16.998	36.050	.2359	3.103	.09542
	cr							± 21	± 32	± 44
								1365	1433	1536
C	d>4.3	138.9	30.10	145.9	.68256	18.980	41.543	.2505	3.280	.09496
	HF							± 18	± 33	± 60
								1441	1476	1527
D	d>4.3;	123.9	28.06	307.2	.31756	13.951	28.272	.2619	3.445	.09541
	Ø>70							± 14	± 31	± 59
	abr							1499	1514	1536
E	d>4.3;	136.8	30.86	332.6	.28994	13.611	27.775	.2608	3.447	.0959
	Ø>70							± 20	± 50	± 11
	abr							1493	1515	1545
	Salmi, USSR: even-grained rapakivi granite, phase II									
A	d>4.5	126.4	26.39	161.6	.61519	17.963	39.654	.2413	3.129	.09406
								± 15	± 30	± 64
								1393	1429	1509
B	4.3<d<4.5	199.4	44.63	384.3	.25618	13.049	25.451	.2587	3.385	.09489
	Ø<160							± 19	± 29	± 32
	abr							1483	1500	1526
C	4.2<d<4.3	434.8	87.88	955	.10317	10.917	18.356	.2336	3.054	.09484
	HF							± 14	± 28	± 58
								1353	1421	1524
D	4.0<d<4.2	732.6	153.24	1674	.05883	10.332	17.136	.2418	3.172	.09515
	HF							± 13	± 22	± 37
								1395	1450	1531

For symbols, see Table 3.

SVECOFENNIAN FORMATIONS

The Svecofennian formations, which comprise postorogenic granitoids, huge areas of late orogenic migmatite-forming granites and synorogenic granitoids and gabbros, have traditionally been divided into these groups in relation to the Svecofennian orogeny. Pyroxene granodiorites over a relatively large area proved to be of intraorogenic age. As the study proceeded it became increasingly clear that some of the Svecofennian intrusive formations in southwestern Finland, which are often in contact with the Subjotnian formations would have to be dated.

Owing to the lack of radiometric age determinations, similarities in composition and mode of occurrence caused problems with correlations. As the number of radiometric ages grew, it became obvious that even more would be needed before a chronostratigraphic correlation could be worked out.

The postorogenic granitoids of Åland: the Lemland and Åva intrusions

The granitoid complexes of Lemland, Mosshaga, Seglinge and Åva in the Åland islands represent the group III granitoids of Sederholm (1934). These granitoid plutons are close to the Åland rapakivi batholith, and those of Lemland and Mosshaga are known to be in direct contact with it (see Figs. 1 and 62). Contact relations and radiometric age determinations show that these granitoid plutons are older than the rapakivi intrusions of Åland.

The Lemland intrusion

Sample A440, previously dated by Vaasjoki (1977), is from Ytterklobb, an island in Lemland, south of Mariehamn.

The Lemland granite is a coarse-grained, porphyritic potassium granite with weak parallel orientation of the microcline megacrysts. The accessory minerals of interest in the present context are zircon and titanite. Titanite is a common characteristic accessory mineral of the Lemland granite in contrast to the rapakivi granites. Galena was found in the zircon fractions during the refining processes. The lead isotope ratios measured for this galena are $^{206}Pb/^{204}Pb = 15.78$, $^{207}Pb/^{204}Pb = 15.36$, $^{208}Pb/^{204}Pb = 35.32$. This lead isotopic composition corresponds to the group F »Leads from the svecofennian supracrustal rocks» of Vaasjoki (1981) and is nearest to lead G 48 from Hästö, Perniö.

The zircon from sample A440 occurs as faint pinkish, transparent or translucent, long (L/B ratio 4—8) prisms. The crystal faces are partly corroded and contain some unidentified impurities.

The U-Pb isotope ratios of four zircon fractions plotted on a concordia diagram (see Fig. 42) yielded an age of 1770±2 Ma. For analytical results, see Table 12. The former analysis of A440A is omitted from the calculations. Had it been included a slightly younger age would have been obtained.

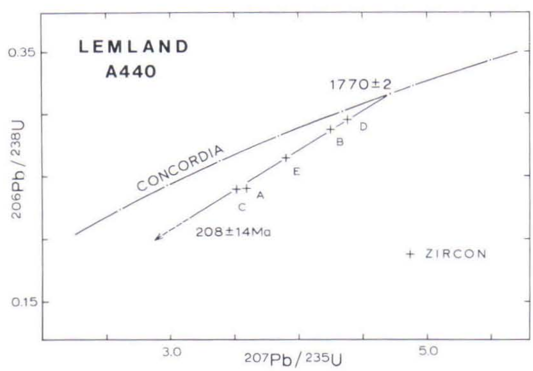

Fig. 42. Concordia plot for U-Pb isotope ratios of zircon fractions from the Lemland granite (A440).

The Åva intrusion

The Åva intrusion has been described by Sederholm (1924, 1934), Kaitaro (1953), Bergman (1973), Ehlers and Bergman (1984) and Bergman (1986), making it the best documented of the postorogenic granite intrusions in southwestern Finland. An age of about 1.8 Ga was previously reported for the intrusion by Neuvonen (1970), Vaasjoki (1977), Patchett et al. (1981) and Patchett and Kouvo (1986).

Zircon crystals from the Getören granodiorite (A334) are transparent and clear with a faint

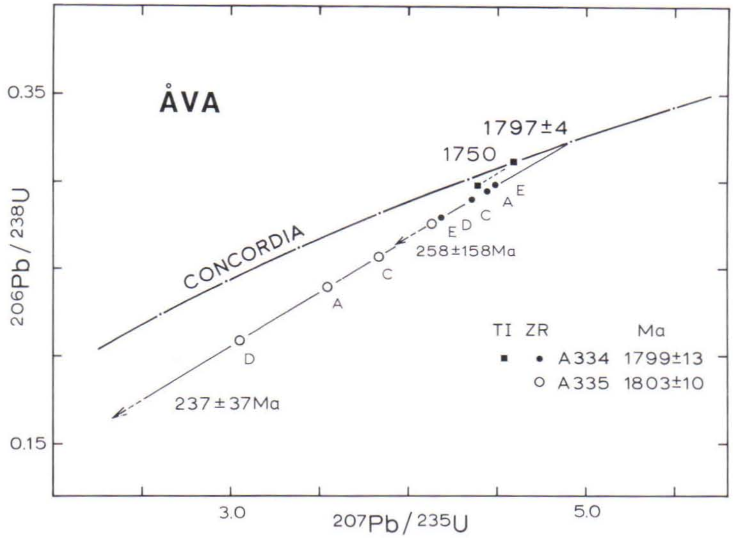

Fig. 43. Summary concordia diagram for zircons and titanites from »monzonite» sample A334-Getören, Brändö and granite sample A335—81-va, Brändö from the postorogenic Åva stock. The lower intercept for the summary chord is 237 ± 37 Ma.

brown-red tint or translucent and milky. The L/B ratio is 4—6. The pyramid faces often have an acute angle, and the crystal faces are glossy.

Zircon crystals from the Åva granite (A335) are transparent, pinkish or translucent, milky tetragonal prisms with L/B ratio 4—6. The crystal faces are glossy, and inclusions are few.

The isotope ratios for zircons from both samples yields a pooled age of 1797 ± 4 Ma, with a lower intercept of 217 ± 24 Ma (see Fig. 43). The age obtained for the A335-Åva granite is 1803 ± 10 Ma and for the A334-Getören granodiorite (earlier called monzonite) 1799 ± 13 Ma. For analytical results, see Table 12, also published by Patchett and Kouvo (1986). The titanite of the Åva area yields a younger, probably regional, metamorphic age (see Fig. 43 and Table 12). The common lead content of titanite in sample A335 is too high for the age to be determined.

Late-orogenic granites in southwestern Finland

Extensive areas in the Åland archipelago and southwestern Finland are covered with red and grey microcline granites (see Fig. 1). Except in the most homogeneous parts of the plutons, they tend to be migmatite building and migmatitic in habit (cf. Härme 1965). Inclusions of older supracrustal and infracrustal rocks are common and often granitized into nebulous remnants. The age relations between the older igneous and sedimentogenous rocks and these granites and the younger cutting postorogenic granitoids have been understood since the beginning of this century, but the time of this major event had to be established with radiometric age determinations.

The granite of Kumlinge

The grey, even-grained potassium granite, A901-Kumlinge, from the village of Kumlinge-by, Åland, represents a typical group II granite in Sederholm's classification of granitoids in southern Finland. It forms migmatites with the supracrustal rocks and with the group I granitoids. The granite pluton of Kumlinge is homo-

Table 12. U–Pb isotopic data on the postorogenic granites of Åland.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration $\mu g/g$ ^{238}U	Concentration $\mu g/g$ ^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, $^{206}Pb = 100$: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A440–Ytterklobb, Lemland: granite										
A440A[2]	d>3.8; Ø>110	557.2	115.78	319.4	.30137	14.958	24.731	.2402 ± 17 1387	3.592 ± 65 1547	.1085 ± 16 1774
B	4.3<d<4.6 HF	386.3	95.85	757.4	.13086	12.539	18.481	.2868 ± 21 1625	4.251 ± 37 1683	.10753 ± 42 1758
C	4.2<d<4.3	678.8	140.97	281.0	.35500	15.469	26.575	.2400 ± 36 1386	3.513 ± 56 1530	.10614 ± 56 1734
D	4.3<d<4.6 HF; cr	330.2	84.23	1469	.06684	11.689	16.341	.2948 ± 20 1665	4.380 ± 55 1708	.1078 ± 10 1762
E	d>4.6	328.2	75.17	294.2	.33491	15.265	26.449	.2647 ± 16 1513	3.901 ± 54 1613	.1069 ± 12 1747
A334–Getören, Brändö: granodiorite (earlier called monzonite)										
A334A[2]	total borax	216.7	55.31	390.9	.23631	14.158	21.911	.2949 ± 21 1666	4.448 ± 44 1721	.10939 ± 55 1789
B	titanite borax	104.6	26.99	173.3	.56170	18.364	65.463	.2981 ± 21 1681	4.393 ± 57 1710	.10689 ± 97 1747
B	titanite reanalysed dissolved in HF	103.0	27.75	210.8	.47198	17.149	64.537	.3114 ± 31 1747	4.595 ± 60 1748	.10701 ± 81 1749
C	d>4.6	177.2	44.47	1808	.04967	11.581	16.253	.2900 ± 15 1641	4.360 ± 28 1704	.10904 ± 35 1783
D	4.2<d<4.6	295.1	71.40	2141	.04181	11.437	13.231	.2796 ± 15 1589	4.189 ± 25 1671	.10867 ± 24 1777
E	d>4.6 HF	171.6	44.32	3473	.02531	11.254	15.645	.2986 ± 29 1684	4.491 ± 44 1729	.10909 ± 18 1784
A335–Åva, Brändö: granite										
A335A[2]	total borax	428.5	88.78	568.1	.16295	12.955	21.072	.2395 ± 18 1384	3.543 ± 35 1536	.10729 ± 61 1754

Table 12. (continued)

A335	B	titanite total borax	91.7	21.79	96.6	1.0203	24.693	103.22	.2748 ± 20 1564	4.08 ± 12 1649	.1076 ± 26 1759
	B	titanite total, reanalysed dissolved in HF	73.6	19.30	77.7	1.2793	28.270	126.78	.3029 ± 28 1705	4.52 ± 14 1734	.1082 ± 29 1768
	B	titanite 3.5<d<3.6 cr/HNO_3; dissolved in HF	72.9	20.07	70.2	1.4211	30.116	126.28	.3183 ± 33 1781	4.70 ± 13 1766	.1070 ± 24 1749
	B	titanite 3.5<d<3.6, reanalysed dissolved in HF, abr	72.5	17.92	75.0	1.3298	29.025	121.29	.2857 ± 49 1620	4.29 ± 17 1691	.1090 ± 35 1782
	C	d>4.6	323.7	71.94	1978	.04568	11.461	17.399	.2568 ± 14 1473	3.838 ± 22 1600	.10838 ± 14 1772
	D	4.2<d<4.6	880.7	159.41	1050	.09258	11.868	18.012	.2092 ± 11 1224	3.058 ± 19 1422	.10602 ± 30 1732
	E	d>4.6 HF	280.1	66.84	4093	.02216	11.178	16.554	.2758 ± 23 1570	4.136 ± 36 1661	.10876 ± 15 1778

For symbols, see Table 3.

geneous in its central parts, but becomes coarse-grained or often almost pegmatitic towards the margins, and occurs as veins or neosome in agmatitic migmatites (see Sederholm 1934 and Ehlers and Ehlers 1978, 1981 for details, chemical analyses and modes).

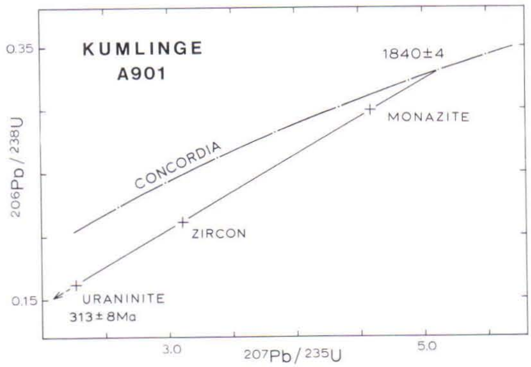

Fig. 44. Isotope ratios and radiometric age of zircon, monazite and uraninite from granite A901-Kumlingeby, Kumlinge, Åland islands.

The heavy accessory minerals include abundant monazite, some uraninite, molybdenite and very little zircon. The zircon occurs as small acicular crystals rich in uranium (see Table 13).

The U-Pb isotope ratios (see Table 13) of zircon, monazite and uraninite from sample A901 plotted on a concordia diagram (see Fig. 44) yield an age of 1840±4 Ma. The data points for zircon and uraninite are discordant, but with the more concordant monazite they yield a good chord.

The granite of Mattnäs, Nauvo

Mattnäs in Nauvo (Nagu) is a type locality of the coarse-grained, red, porphyritic microcline granite so common in the archipelago of south-

Table 13. U–Pb isotopic data on the late-orogenic granites of southwestern Finland.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration μg/g ^{238}U	Concentration μg/g ^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A901– Kumlingeby, Kumlinge: granite										
A901A	d>4.0; Ø<70	1204	220.35	882	.11193	12.190	47.085	.2115 ± 13 1236	3.109 ± 23 1434	.10660 ± 37 1742
B	monazite	3292	851.8	1983	.04958	11.805	522.33	.2990 ± 21 1686	4.589 ± 39 1747	.11131 ± 47 1821
C	uraninite	69.12%	9.69%	24753	.00379	10.192	1.749	.1620 ± 11 968	2.265 ± 16 1201	.10140 ± 17 1650
A322–Mattnäs, Nauvo: granite										
A322A	monazite	3927	1120	7602	.008612	11.290	479.5	.3295 ± 25 1835	5.075 ± 41 1831	.11173 ± 26 1827
B	d>4.2; Ø>45	1489	244.04	1047	.09290	12.177	9.113	.1894 ± 12 1118	2.849 ± 23 1368	.10911 ± 49 1784
C	d>4.2 long crystals	1632	263.78	711.4	.13396	12.648	9.798	.1868 ± 12 1104	2.787 ± 24 1352	.10820 ± 58 1769
D	4.0<d<4.2	1524	274.24	730.5	.13611	12.786	22.150	.2079 ± 15 1217	3.134 ± 24 1440	.10931 ± 26 1788
E	total long crystals	2556	295.41	640.7	.15342	12.339	9.737	.1336 ± 11 808	1.884 ± 22 1075	.10231 ± 80 1666
F	3.8<d<4.0 Ø<70	2521	310.80	322.0	.3094	14.410	15.651	.1425 ± 10 858	1.995 ± 28 1113	.1016 ± 11 1653
G	3.8<d<4.0 abr	2593	331.76	515.3	.19025	12.967	11.740	.1479 ± 9 889	2.112 ± 17 1152	.10357 ± 47 1689
H	3.6<d<3.8 Ø>130 cr	2085	325.96	760.6	.13001	12.376	11.862	.1807 ± 13 1070	2.641 ± 22 1312	.10598 ± 43 1731
I	3.6<d<3.8 Ø>130 abr	2069	343.63	670.7	.14756	12.658	9.527	.1919 ± 13 1131	2.816 ± 22 1359	.1064 ± 4 1738
J	large crystals HF; 0.56 mg	587.1	132.96	1050	.06837	12.409	9.801	.2617 ± 24 1498	4.144 ± 57 1663	.11485 ± 96 1877

Table 13. (continued)

A322K	3.6<d<3.8 70<Ø<130 abr	2028	333.17	521.7	.19008	13.235	11.700	.1899 ± 12 1120	2.785 ± 21 1351	.10636 ± 40 1738
A64a–Kakola, Turku: grey variety of granite										
A64aA	monazite abr cr	4916	1388.4	26011	.003369	11.210	290.42	.3264 ± 25 1821	5.025 ± 45 1823	.11165 ± 47 1826
B	d>4.3 Ø>160	614.9	149.07	2379	.04090	11.544	11.836	.2802 ± 16 1592	4.245 ± 26 1682	.10987 ± 16 1797
C	d>4.3 70<Ø<160 long crystals removed	589.4	151.04	3716	.02605	11.489	7.274	.2962 ± 19 1672	4.547 ± 30 1739	.11135 ± 18 1821
D	4.2<d<4.3 Ø>160	1258	258.50	954	.10368	12.301	11.739	.2375 ± 18 1373	3.566 ± 45 1541	.1089 ± 10 1780
E	4.0<d<4.2 Ø>160	1569	302.44	857	.11497	12.485	9.762	.2228 ± 17 1296	3.354 ± 32 1493	.10918 ± 57 1785
F	4.2<d<4.3 70<Ø<160 cr	1067	274.91	2961	.03284	11.612	4.281	.2977 ± 19 1680	4.583 ± 29 1746	.11165 ± 11 1826
G	d>4.2 70<Ø<160 long crystals	1106	264.50	2348	.04161	11.532	7.388	.2763 ± 16 1572	4.177 ± 26 1669	.10966 ± 12 1793
H	d>4.3 abr	627.2	158.63	3056	.03135	11.500	9.208	.2923 ± 19 1652	4.462 ± 31 1724	.11073 ± 22 1811
I	4.2<d<4.3 abr	1009	275.61	6471	.01442	11.446	3.237	.3158 ± 19 1769	4.898 ± 30 1801	.11251 ± 13 1840
J	4.0<d<4.2 Ø<160	1494	232.63	1581	.06248	11.795	5.180	.2504 ± 15 1440	3.777 ± 24 1587	.10944 ± 22 1790
A55- and A399–Kistola, Muurla: granite										
A055A	4.0<d<4.2	1266	210.05	259.4	.38505	16.120	24.912	.1917 ± 10 1130	2.873 ± 16 1374	.10869 ± 4 1777
B	3.8<d<4.0	1533	202.30	248.1	.40181	16.075	26.550	.1525 ± 8 915	2.225 ± 12 1188	.10577 ± 12 1727
A399A	monazite	2866	807.4	10563	.008955	11.319	689.16	.3256 ± 21 1816	5.026 ± 35 1823	.11197 ± 29 1831
B	d>4.2	1020	228.71	2697	.03620	11.475	18.528	.2593 ± 22 1485	3.926 ± 34 1618	.10982 ± 17 1796

Table 13. (continued)

A399C	4.0<d<4.2 HF	1323	249.71	2000	.04884	11.546	7.306	.2181 ± 13 1271	3.271 ± 21 1474	.10880 ± 19 1779
A389–Haarla, Perniö: granite										
A389A	monazite	6718	1909	12652	.007592	11.264	289.36	.3285 ± 31 1830	5.054 ± 55 1828	.11161 ± 58 1825
B	d>4.2	868.7	167.42	340.2	.29169	14.486	45.200	.2228 ± 13 1296	3.222 ± 49 1462	.1049 ± 13 1713
C	3.8<d<4.0 abr	1520	350.97	418.4	.23626	13.910	15.700	.2669 ± 15 1525	3.931 ± 35 1620	.10681 ± 66 1745
A390–Pungböle, Kemiö: granite										
A390A	4.0<d<4.2 Ø>160	1641	292.92	2894	.03315	11.207	12.585	.2063 ± 12 1208	3.058 ± 18 1422	.10755 ± 14 1758
B	4.0<d<4.2 70<Ø<160	1707	295.86	1530	.06408	11.572	17.766	.2004 ± 13 1177	2.955 ± 25 1396	.10697 ± 51 1748
C	monazite	4996	1425	28440	.00296	11.264	370.89	.3296 ± 23 1836	5.100 ± 38 1836	.11224 ± 21 1836
D	4.2<d<4.6 Ø>160	994.7	198.21	2823	.03262	11.373	23.538	.2303 ± 20 1336	3.470 ± 33 1520	.10929 ± 35 1787
E	4.2<d<4.6 Ø<160	944.8	200.92	2878	.03230	11.444	30.961	.2458 ± 22 1416	3.729 ± 35 1577	.11004 ± 21 1800
F	4.0<d<4.2 70<Ø<160	1748	352.82	603.4	.16405	13.137	56.528	.2332 ± 21 1351	3.505 ± 35 1528	.10901 ± 37 1783
G	4.0<d<4.2 70<Ø<160 cr	1528	298.37	3627	.02611	11.237	8.958	.2257 ± 13 1311	3.385 ± 20 1500	.10881 ± 18 1779
H	4.2<d<4.6 HF	434.3	126.22	8943	.00744	11.354	40.464	.3359 ± 18 1866	5.211 ± 30 1854	.11253 ± 17 1840
I	3.8<d<4.0 abr	2236	392.60	2191	.04465	11.321	6.613	.2029 ± 13 1191	2.997 ± 19 1406	.10711 ± 13 1750
J	galena	–	–	5380 ± 70	.01859	10.837	2.264	–	–	.10583 ± 16 1729
A997–Tammo, Parainen: granite										
A997A	3.8<d<4.0 Ø>160	1373	352.73	3923	.02503	11.427	4.404	.2969 ± 15 1676	4.538 ± 24 1738	.11086 ± 10 1813

Table 13. (continued)

A997B	3.8<d<4.0	1413	355.30	5057	.01918	11.347	4.919	.2906	4.441	.11086
	Ø<160							± 16	± 24	± 8
								1644	1720	1813
C	3.6<d<3.8	2094	375.91	2362	.04086	11.255	5.013	.2075	3.060	.10697
								± 11	± 19	± 29
								1215	1422	1748
D	monazite	1675	478.02	3931	.01994	11.456	1375	.3299	5.088	.11185
								± 49	± 78	± 32
								1837	1834	1829
A875-Märaskär, Hanko: Hanko granite (recalculated from Huhma 1986)										
A875A	d>4.0	1064	220.16	1584	.06031	11.830	35.616	.2392	3.631	.11009
								± 20	± 30	± 10
								1382	1556	1801
B	3.8<d<4.0	1786	238.12	1152	.08359	11.811	10.544	.1541	2.266	.10668
								± 9	± 13	± 10
								923	1201	1743
C	monazite	2229	619.14	4918	.01644	11.405	567.06	.3210	4.949	.11182
								± 18	± 36	± 44
								1794	1810	1829
A876-Tulludden, Hanko: Hanko granite										
A876A	3.8<d<4.0	1796	357.61	1071	.09215	11.879	11.661	.2301	3.369	.10619
	Ø>160							± 14	± 25	± 37
	HF							1334	1497	1735
B	4.0<d<4.2	1332	266.16	1204	.08053	11.947	11.531	.2310	3.455	.10849
								± 18	± 31	± 38
								1339	1517	1774
C	3.8<d<4.0	1990	344.88	959	.10022	12.174	13.958	.2003	2.984	.10807
	Ø>160							± 12	± 18	± 16
								1176	1403	1767
D	3.8<d<4.0	2243	366.53	666.0	.14633	12.409	15.648	.1888	2.709	.10403
	Ø<160							± 10	± 17	± 28
								1115	1330	1697
E	monazite	2618	735.65	8268	.009516	11.268	537.10	.3248	4.988	.11138
	abr							± 22	± 36	± 24
								1813	1817	1822
F	3.8<d<4.0	1939	390.75	1296	.07612	11.761	10.492	.2329	3.443	.10722
	Ø<160							± 13	± 24	± 44
	abr							1349	1514	1752
G	4.0<d<4.2	1859	357.24	1381	.07159	11.792	9.935	.2222	3.313	.10815
	abr							± 14	± 24	± 35
								1293	1484	1768
H	4.0<d<4.2	1753	418.51	2171	.04510	11.637	8.088	.2759	4.193	.11023
	abr							± 17	± 28	± 27
	cr							1570	1672	1803

For symbols, see Table 3.

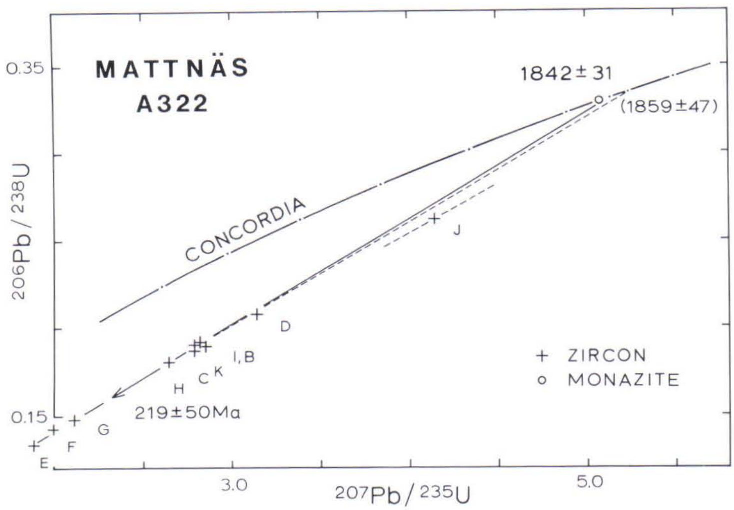

Fig. 45. Concordia diagram for U-Pb isotope ratios of zircon and monazite fractions from granite A322-Mattnäs, Nauvo. The age of monazite is 1828 ± 6 Ma.

western Finland. It has been described by Hausen (1944a, 1944b) and Edelman (1972, 1973, 1985). Nebulous inclusions of older supracrustal and infracrustal rocks at different granitization stages are common in the granite. Sample A322-Mattnäs is from a homogeneous part (building stone quarry) where the palaeosome is nebulous, if visible at all.

The accessory minerals of interest in the present context are monazite, zircon, rutile and apatite. The zircon fraction can be divided into three types: large euhedral crystals or fragments of crystals, long euhedral acicular crystals with L/B ratio 3—4; and rounded, glassy, drop like crystals with clear interfaces due to recrystallization. Even the milky apatite crystals have glassy faces and a rounded form.

The U-Pb ratios of the zircon fractions and monazite on a concordia plot yield an upper intercept age of 1842 ± 31 Ma and a lower intercept of 219 ± 50 Ma (see Fig. 45). Fraction J, which consists of 0.56 mg of large zircon crystals preleached in hydrofluoric acid, was omitted from the calculations. For the nine remaining zircon fractions the intersections give 1859 ± 47 Ma and 244 ± 68 Ma, respectively. If fraction J is included, the ten zircon fractions, without monazite, yield a synorogenic age of 1877 ± 47 Ma and with monazite (all fractions analysed) 1853 ± 35 Ma and 235 ± 56 Ma. For analytical results, see Table 13.

The Mattnäs granite was formed through ultrametamorphic processes (Edelman 1985). The ages determined from the zircon fractions are too discordant to be used for establishing the age of the leucosome at the time of migmatization; this age is most probably indicated by monazite. Archaean zircons have not been found in the country rocks of the Svecofennian granitoids except as detrital material (Huhma et al. 1991). Thus, even the slightest impact of Archaean material on zircon isotopic systematics might be significant. In this case, the excluded high age of the large zircon crystals (fraction J) may have been the synorogenic age mentioned above. The diffusion model age for fraction J is 1932 Ma.

The granite of Kakola, Turku

One of the migmatite-building granites in southwestern Finland, the Kakola granite (sample A64), represents the garnet-cordierite-bearing type that occurs together with strongly migmatized metapelites over large areas of southwestern Finland.

The Kakola granite has been described by Hietanen (1943, 1947), Metzger (1945) and Härme (1960).

Sample A64a represents the most common type, the grey Kakola granite. A medium to coarse-grained variety, it has microcline, quartz, plagioclase, biotite, garnet and cordierite as main constituents. The accessory minerals of interest are monazite, zircon, rutile and apatite.

A reddish, medium-grained type of Kakola granite with the same main constituents and accessory minerals as the grey type is also common. There is even a reddish, coarse-grained, almost pegmatitic type of Kakola granite that is frequently encountered. The colour and grain size of the different types vary without clear contacts between them. The texture of all of them is granoblastic.

The heavy accessory minerals of the Kakola granite have been studied by A. Laitakari (1934), who, starting from 500 kg of rock powder, identified almandine, ilmenite, sillimanite, anatase, monazite, zircon and spinel. Apatite is abundant but only a few crystals of dumortierite, tourmaline and andalusite have been found. Ilmenite is altered to anatase.

The zircon crystals (see Figs. 46 and 47a) from sample A64a (d = 4.2—4.3 g/cm^3) can be divided into four main morphological types:

1. a short, transparent variety with L/B ratio 1—1.5 and numerous crystal faces. The crys-

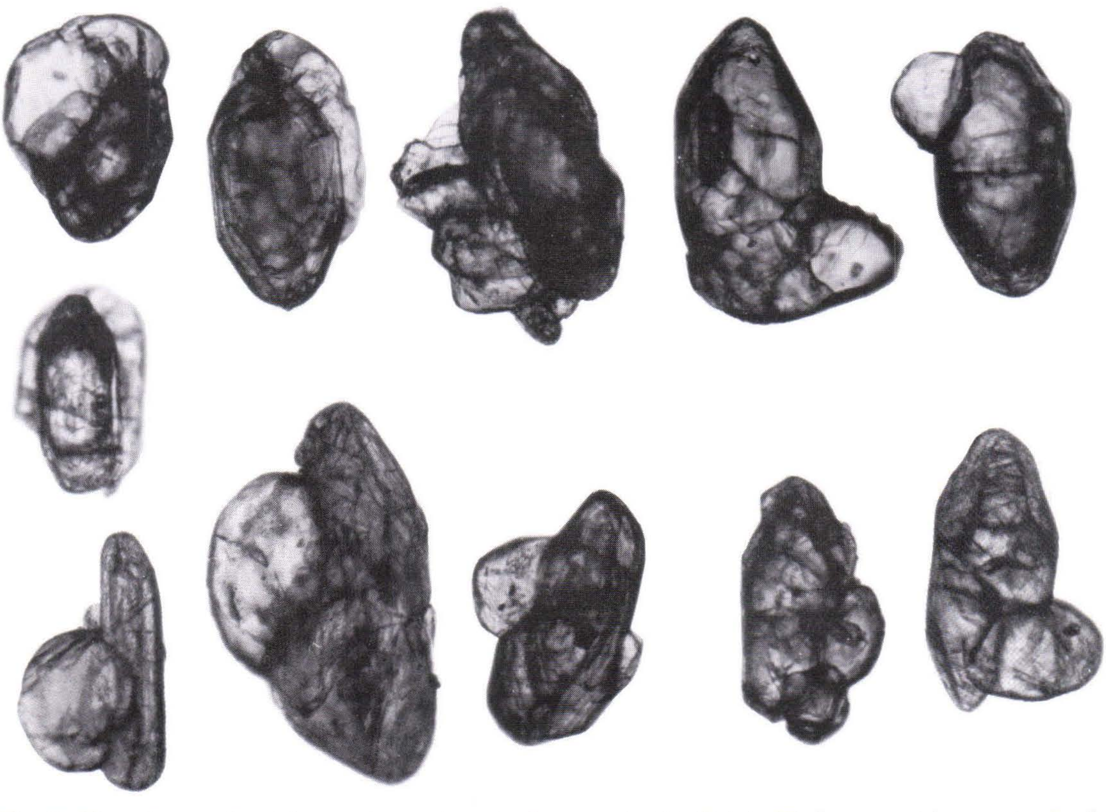

Fig. 46. Microphotographs of zircon and monazite grains from sample A64a-Kakola. The lowest crystal aggregates showing zircons growing on monazite. Largest grain is 0.6 mm long. For details and discussion, see text. Photo Veli Suominen.

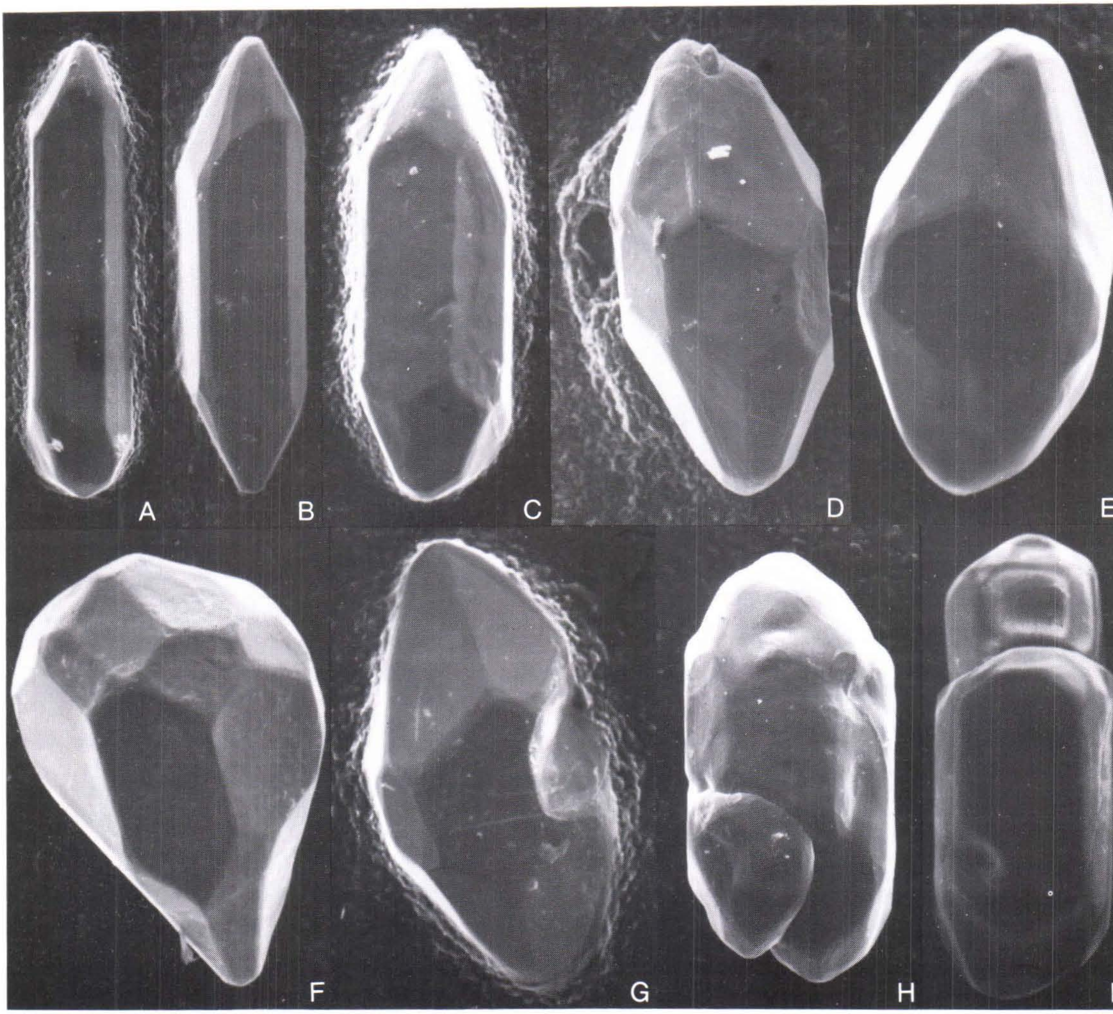

Fig. 47a. SEM microphotographs of zircon crystals from A64a-Kakola. Lengths of zircons are: A. 750 μm, B. 415 μm, C. 690 μm, D. 540 μm, E. 310 μm, F. 390 μm, G. 460 μm, H. 375 μm, and I. 405 μm. Photo Ragnar Törnroos.

1. tals exhibit growth shells, the innermost of which are often rounded, some of them even showing crystal faces;
2. unusually large prisms with L/B ratio 2—4. They are transparent but have a brownish tint,
3. long acicular transparent prisms with L/B ratio 8—12. A core is visible. Most of the crystals have rounded ends although some have sharp-edged pyramids;
4. rounded, drop like transparent crystals with a distinct core. Much of this fraction is composed of fragments of larger zircons. A thin brown zircon shell is visible in some of the tetragonal pyramid fragments. Some of the grains have joined up into crystal aggregates.

In fraction $d > 4.3$ g/cm^3, most of the zircon crystals are transparent, short (L/B ratio is 1—2), microgem-like and rich in crystal faces. A core is often visible. A second common type is a short (L/B ratio 2—4), transparent prism with a narrow, transparent, acicular core. Some of the zir-

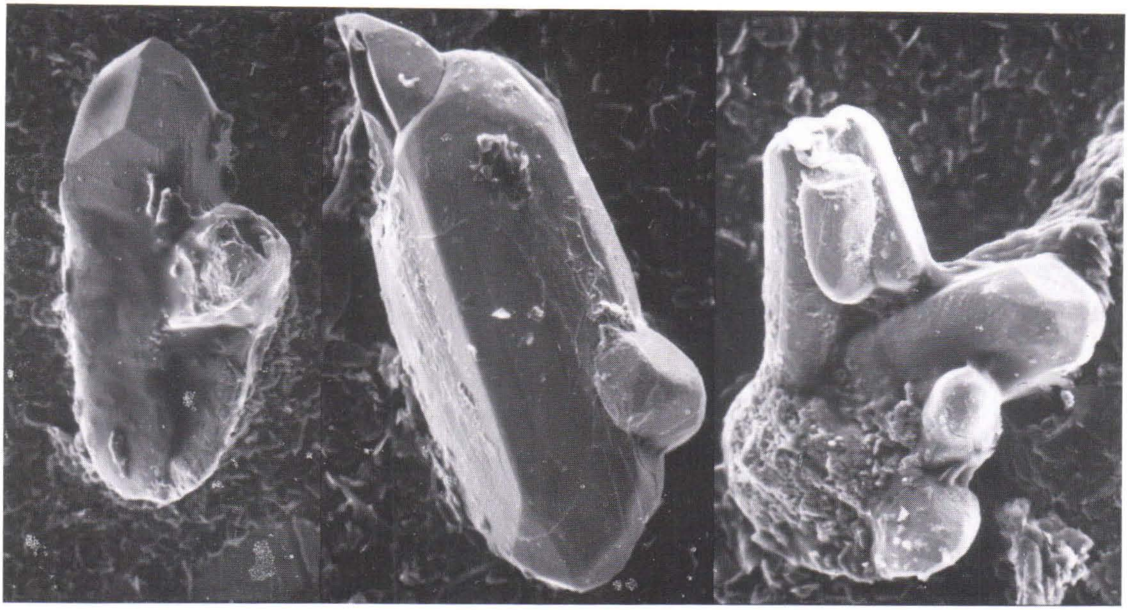

Fig. 47b. SEM microphotographs of crystal aggregates of sample A399-Kistola showing zircons and monazites. For discussion, see text.
Photo Bo Johansson.

cons have a reddish tint. Only a few of the prisms have an L/B ratio exceeding 4.

Intergrowths of the heavy accessory minerals — zircon in monazite, and monazite in zircon — show that these minerals crystallized simultaneously (see Fig. 46). The indentification of the intergrown minerals in Fig. 46 was verified with microsonde analyses made by Mr L. Pakkanen. Though the monazite-zircon aggregates in Figs. 46 and 47a demonstrate that monazite was the first to crystallize, in one case zircon was found as inclusion in monazite. Intergrowths of zircon and monazite are also common in other late-orogenic granites in southwestern Finland, as seen in Fig. 47b of sample A399 Kistola. The multi-faced zircon crystals are morphologically similar to the zircon crystals of granulites in Finland (Dr O. Kouvo, pers. communication) and elsewhere in shield areas (Bibikova 1984). All the details visible in the zircon morphology show that the Kakola granite crystallized in several phases and has a complex history.

The U-Pb isotope ratios plotted on a concordia diagram (see Fig. 48) yield an age of 1832 ± 11 Ma for the Kakola granite. For analytical data, see Table 13. Note that the zircon crystals of different habit seem to have the same age within the limits of error (e.g. fractions C and G). Long needles are absent from fraction C whereas fraction G is composed of them alone. All the zircon fractions are rich in uranium. The coarse fraction, Ø > 160 μm, indicates that the zircon crystals had time to grow. Fraction E contains almost 1600 μg/g of uranium, and the $^{206}Pb/^{204}Pb$ ratio is the lowest. If this fraction were omitted, the upper intercept of the best-fit line for the eight zircon fractions would be 1840 ± 14 Ma, but the lower intercept would be as high as 319 ± 114 Ma. The age 1832 ± 11 Ma obtained is, within the limits of error, the same as that of the other late-orogenic granites in southwestern Finland.

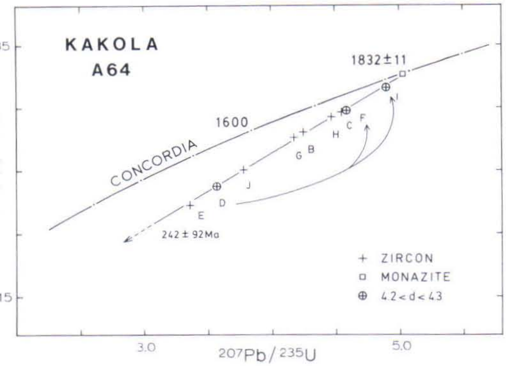

Fig. 48. Concordia plot for zircon and monazite fractions from Kakola granite (A64a), Turku. Fraction D is the original, F crushed and washed in HNO_3, I air abraded.

The Perniö granite: Kistola, Haarla and Pungböle

The Perniö microcline granite has been described by Eskola (1914), Lehijärvi (1955, 1957), Salli (1955) and Seitsaari (1955). The Perniö granite cuts the surrounding infracrustal and supracrustal rocks and forms migmatites with them. In its most homogeneous parts, the pluton is a coarse-grained, homogeneous, red microcline granite with weak parallel orientation of the microcline megacrysts. It is represented by samples A55 and A399 from Kistola, A389 from Haarla and A390 from Pungböle. Inclusions of supracrustal rocks are common and different types of migmatite within the pluton are the rule. Over large areas the Perniö granite is nebulitic and garnetiferous.

The first age of the Perniö granite, 1800 ± 80 Ma, was determined by Gast (1960) with the Rb-Sr whole-rock method. A Rb-Sr age of 1780 Ma for biotite fractions from the same sample was reported by Wetherill et al. (1962). If calculated with new decay constants (Steiger and Jäger 1977), the corresponding ages are 1762 ± 80 Ma and 1742 Ma.

The accessory minerals of samples A55 and A399 are monazite, zircon and rutile. Monazite and zircon grew simultaneously as shown by the intergrown crystal aggregates (see Fig. 47b). The zircon crystals are reddish brown and the L/B ratio is up to 10. The crystals are rich in faces and have sharp edges. There are many exceptionally large zircon crystals. The bulk of density fraction $3.6 < d < 3.8$ g/cm^3 is composed of grey rutile.

Plotted on a concordia diagram, the U-Pb isotope ratios of the zircon fractions from the Kistola samples (A55 and A399) yield an age of 1829 ± 14 Ma and 1830 ± 10 Ma, if fractions from only one sample (A399) were used (see Fig. 49). The data point of the monazite analysis fits the chord. For analytical results, see Table 13.

The zircon grains of A389-Haarla, Perniö are red and reddish-brown translucent fragments of larger zircon crystals with corroded surfaces.

The U-Pb data points of the zircon fractions of sample A389-Haarla (see Fig. 50) do not fit the same chord as the data points of sample A390-Pungböle, Kemiö. For analytical data, see Table 13. The monazites from the three samples of Perniö granite (Kistola,, Haarla, Pungböle) yield the same age (about 1830—1840 Ma) within the limits of error.

The zircon crystals of sample A390-Pungböle are transparent, small, pinkish, tetragonal needles (L/B ratio 4—6) or, more frequently, fragments of red or yellow transparent or translucent crystals with many, often corroded, crystal faces.

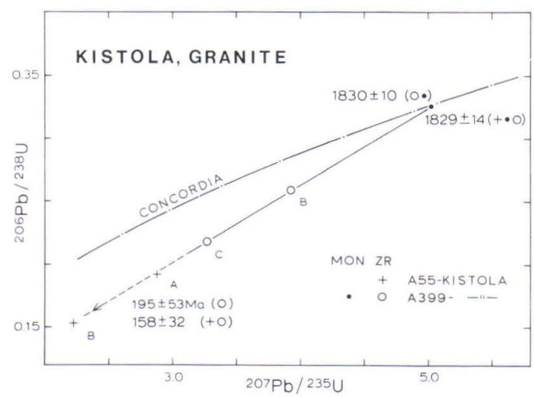

Fig. 49. Concordia plot for zircon and monazite fractions from samples A55 and A399, Kistola granite, Muurla.

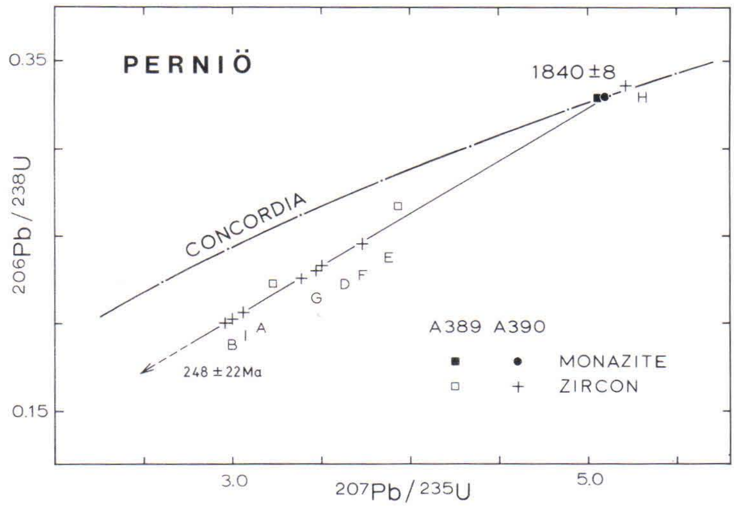

Fig. 50. Concordia diagram for U-Pb isotope ratios of zircon and monazite fractions from the Perniö granite (A390-Pungböle and A389-Haarla).

The U-Pb isotope ratios of the eight zircon fractions from sample A390-Pungböle, in the western part of the pluton, do not fall on the best-fit line of Kistola, but give a chord of their own (see Fig. 50). The chord yields an upper intercept age of 1840 ± 8 Ma and a lower intercept of 248 ± 22 Ma (data point H above the concordia line was omitted from the calculations). The zircons are highly radioactive and hence heavily damaged. All the data points except H (preleached in hydrofluoric acid) are discordant. The common-lead content is high. For analytical data, see Table 13.

The lead in the Pungböle galena is highly radiogenic ($^{206}Pb/^{204}Pb = 5380 \pm 70$; see Table 13) and corresponds to an age of 1729 Ma if corrected for common lead with a model age of about 1.8 Ga. This lead is distinquished by the conspicuously low $^{208}Pb/^{206}Pb$ radiogenic ratio of 0.0161, which points to a source with a high U/Th ratio.

The granite of Tammo, Parainen

The small round granite stock of Tammo is composed of a coarse-grained microcline granite showing sharp-cutting contacts with adjacent rocks (see Edelman 1973). The microcline grains are surrounded by orthoclase, and both euhedral and anhedral quartz are present (Edelman 1949). There are inclusions of country rock, and granite veins intrude the country rock. These features clearly distinguish the Tammo granite from the other granites of the region, as pointed out by Edelman (1960), who postulated a postorogenic age for the Tammo granite.

Sample A997 is from the southern part of the intrusion, on the northern shore of the island of Bockholm.

The heavy accessory minerals of interest in the present context are monazite and zircon. The zircon crystals are large and transparent with glossy faces, L/B ratio 4—6, but even short reddish crystals occur in fraction d>4.0 g/cm^3 (L/B ratio 2). The monazite is reddish-brown and dull.

The data points for the three zircon fractions and one monazite fraction plotted on a concordia diagram yield an age of 1829 ± 3 Ma, the lower intercept being 251 ± 14 Ma (see Fig. 51). The data point of the monazite analysis falls slightly above the concordia curve. If monazite were omitted, the age would be 1829 ± 4 Ma, and the lower intercept 252 ± 21 Ma. For analytical results, see Table 13. The age is typical of late-orogenic intrusions in Finland.

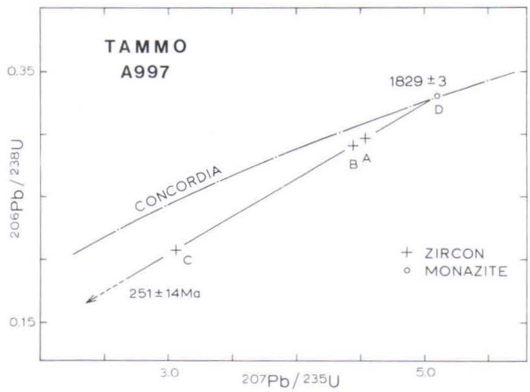

Fig. 51. Concordia plot showing U-Pb isotope ratios of zircon and monazite fractions from A997-Tammo granite, Parainen.

The granite of Tulludden and Märaskär, Hanko

The Hanko granite is similar to that of Perniö in many respects. A red, medium to coarse-grained porphyritic microcline granite, it cuts the older infracrustal and supracrustal rocks, building with them migmatites of different textural types near its contacts. On the islands south of the town of Hanko the granite is homogeneous, porphyritic and pinkish, with only sparse remnants and inclusions of older supracrustal rocks (see Laitala 1970).

The Hanko granite has been dated with the U-Pb method. Sample A875-Märaskär yielded an age of 1830 ± 10 Ma on both zircons and monazite (published by Huhma 1986). An aplogranite has been dated from Trekobb, immediately east of Hanko (Hopgood et al. 1983). The zircon and monazite fractions yielded an age of 1790 ± 3 Ma. Another aplogranite from Innerskär gives a zircon chord of 1841 ± 5 Ma and a single monazite yields an age of 1807 Ma. The Innerskär aplogranite is cut by thin pegmatite veins in places (Hopgood et al. 1983). The initial Nd isotope ratio of the Märaskär sample of Hanko granite has been studied by Huhma (1986).

The Hanko granite contains abundant honey yellow monazite, some zircon and some garnet as accessory minerals. Bastnaesite was also identified.

The zircon crystals in the Märaskär sample, fraction $3.8 < d < 4.0$ g/cm^3, can be divided into three groups by habit: a) acicular, clear, transparent prisms with L/B ratio 8—10 and sharp-angled pyramid faces; b) brownish-grey, transparent prisms with L/B ratio 4—5, and less sharply angled pyramid faces than the crystals of group a; a growth nucleus is often visible; c) short, brownish multifaceted or droplike crystals with L/B ratio 1—3. In fraction $4.0 < d < 4.2$ g/cm^3, pinkish crystals with an L/B ratio of 3—5 are clear. They are rich in crystal faces, and the pyramid faces have an obtuse angle.

In the Tulludden sample the zircon crystals in fraction $3.8 < d < 4.0$ g/cm^3, finer than 100 mesh, are reddish, transparent or translucent simple prisms. The L/B ratio is 3—5 and the pyramid faces have an obtuse angle. In some of the short crystals a zircon crystal forms the nucleus. In the same density fractions, crystals coarser than 100 mesh often have L/B ratios of up to 10, mostly 6—8. The pyramid faces have an obtuse angle. The colour of the transparent crystals is greyish brown, and a zircon crystal is often encountered as an inclusion. In fraction $4.0 < d < 4.2$ g/cm^3 the zircon crystals are clear, pinkish prisms with L/B ratio 4—5. Some of the grains have a growth nucleus.

The seven zircon fractions analysed and monazite can be compared (see Fig. 52) with the fractions from Märaskär. The ages of the highly concordant monazite fractions are:

A875-Märaskär	1829 ± 9 Ma
A876-Tulludden	1822 ± 6 Ma.

The zircon fractions combined with the monazite fractions yield the following upper and lower intercepts:

A876-Tulludden	1824 ± 38 Ma (263 ± 112 Ma)
A875-Märaskär	1830 ± 10 Ma (142 ± 20 Ma).

Within the limits of error the results are the same, but the role of the monazites is dominant.

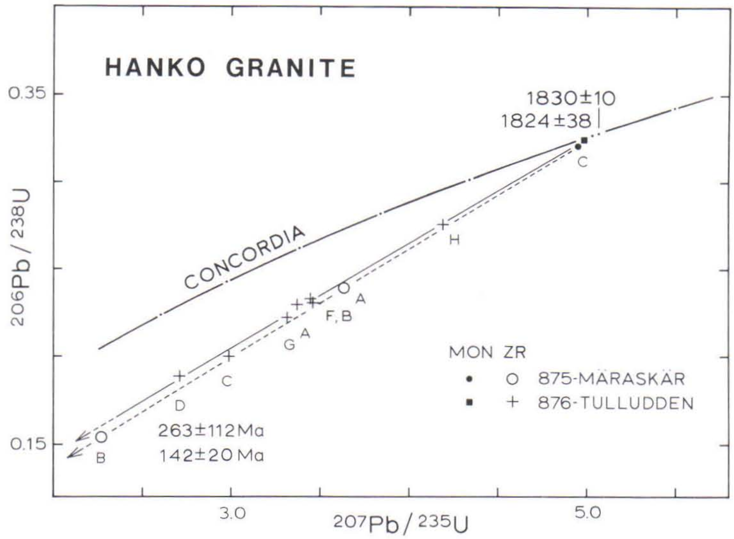

Fig. 52. Concordia plot for isotope ratios of zircon and monazite fractions from the Hanko granite (A875-Märaskär and A876-Tulludden). If the large anomalous zircons, fractions A876A and C, are omitted, the age of sample A876 is 1832 ± 21 Ma (303 ± 65 Ma).

The age of the zircon of the Tulludden sample is 1826 ± 61 Ma (266 ± 162 Ma).

Within the zircon population of the Tulludden sample fractions A and C, consisting of large crystals (> 160 µm) may be anomalous. If they are omitted from calculations, the age of the five zircon fractions and monazite is 1832 ± 21 Ma (303 ± 65 Ma) and that of the five zircon fractions alone 1842 ± 34 Ma (328 ± 87 Ma).

For analytical results, see Table 13. The ages are typical of late-orogenic rocks in southern Finland and, within the limits of error, are the same as the age of the above monazite-bearing granites. The scatter shows that the zircon population must be mixed.

Intraorogenic intrusions in southwestern Finland

In the Turku district, pyroxene granodiorites occur as large plutons (see Hackman 1923, Hietanen 1947) among migmatites composed of garnet-cordierite-sillimanite-bearing metapelites and granites of the Kakola and Mattnäs types. Garnet-bearing tonalite dykes of the same age occur in the northernmost part of the Brändö archipelago in the Gulf of Bothnia.

The pyroxene granodiorite of Kakskerta, Turku

The pyroxene granodiorite of Kakskerta has been described by Hackman (1923) and Hietanen (1947). The various textural types are

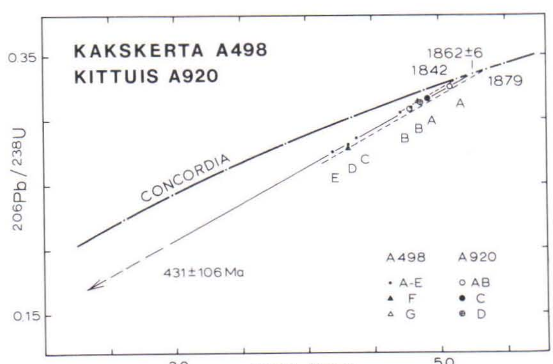

Fig. 53. Concordia diagram and radiometric age of zircon fractions from pyroxene granodiorite A498-Kakskerta, Turku and A920-Kittuis, Houtskär. The upper intercept age (1862 ± 6 Ma) is for the Kittuis sample.

Table 14. U–Pb isotopic data on the intraorogenic intrusions in southwestern Finland.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, μm	Concentration μg/g ^{238}U	Concentration μg/g ^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A498–Naula-ahde, Kakskerta, Turku: pyroxene granodiorite										
A498A	d>4.1;	930.9	248.80	1986	.03099	11.667	5.239	.3089	4.790	.11247
	Ø>130							± 19	± 44	± 58
								1735	1783	1839
B	d>4.1;	984.9	259.39	3245	.02258	11.521	10.312	.3044	4.706	.11215
	Ø<130							± 18	± 31	± 23
								1713	1768	1834
C	3.3<d<3.5	1266	312.96	1502	.05313	11.824	11.899	.2858	4.375	.11102
								± 17	± 34	± 43
								1620	1707	1816
D	3.5<d<3.6	1304	317.52	1440	.05631	11.876	16.202	.2814	4.310	.11110
								± 17	± 35	± 47
								1598	1695	1817
E	3.6<d<4.1	1458	347.39	1507	.05348	11.771	6.605	.2755	4.194	.11044
								± 17	± 33	± 41
								1568	1672	1806
A920–Kittuis, Houtskär: pyroxene granodiorite										
A920A	4.3<d<4.6	474.6	133.40	10191	.00869	11.463	6.600	.3248	5.081	.11345
								± 21	± 36	± 29
								1813	1832	1855
B	4.2<d<4.3	655.5	174.50	6433	.01480	11.457	6.349	.3077	4.775	.11256
								± 17	± 27	± 10
								1729	1780	1841
A822–Västerhamnen, Brändö: garnet-bearing tonalite dyke										
A822A	d>4.3	434.4	123.00	2250	.02507	11.687	8.003	.3273	5.120	.11347
	abr							± 26	± 52	± 53
								1825	1839	1855
B	4.2<d<4.3	902.9	257.66	7900	.01161	11.542	10.051	.3298	5.177	.11385
	abr							± 20	± 32	± 11
								1837	1848	1861
C	4.0<d<4.2	1352	374.57	6071	.01512	11.550	10.884	.3203	5.009	.11345
	Ø>70							± 19	± 31	± 7
	abr							1790	1820	1855
D	4.0<d<4.2	1419	396.12	4922	.01947	11.580	12.097	.3226	5.033	.11316
	Ø<70							± 17	± 27	± 7
	abr							1802	1824	1850
E	4.0<d<4.2	1520	427.34	4960	.01907	11.587	12.386	.3250	5.076	.11328
	Ø<70							± 17	± 27	± 5
	abr							1814	1832	1852
F	3.8<d<4.0	1645	396.71	2887	.03320	11.539	12.130	.2788	4.262	.11088
	Ø>70; abr							± 15	± 23	± 7
	long crystals							1585	1685	1814

For symbols, see Table 3.

Additional data for samples A498 and A920, see Appendix 5.

represented in the present study by sample A498-Naula-ahde, Kakskerta, Turku.

The pyroxene granodiorites are interpreted as having crystallized from a dry magma under PT conditions close to those of the granulite facies. Garnet-cordierite thermometry demonstrates that such conditions did in fact prevail over large areas of southwestern Finland (Schellekens 1980, Hölttä 1986). The presence of rutile in the monazite granites refers to granulite facies conditions (Bohlen et al. 1983).

Plotted on a concordia diagram, the seven data points for different zircon fractions of sample A498-Kakskerta yield an age interval of 1842—1879 Ma (see Fig. 53). For analytical data, see Table 14.

The pyroxe granodiorite of Kittuis, Houtskär

The pyroxene granodiorite (sample A920) of Kittuis, Houtskär was found recently in the course of regional mapping for map sheet 1034 Korpo (Suominen 1987b). The granodiorite is coarse-grained, and in places porphyritic with microcline megacrysts. The hypersthene granodiorite is surrounded by porphyritic microcline granite of the same type as the Mattnäs granite.

The accessory minerals in the Houtskär pyroxene granodiorite include zircon, monazite, appreciable apatite of two different generations and some titanite (no rutile). Molybdenite was found in the heavy mineral fractions.

The four zircon fractions analysed fit the chord of 1862 ± 6 Ma (see Fig. 53). For analytical data, see Table 14.

The garnet-bearing tonalite dyke of Västerhamnen, Brändö

In the northeasternmost part of the Åland archipelago, some 4—5 km east of the Åland rapakivi batholith (Suominen, in prep.) and some 17—18 km west of the Vehmaa rapakivi pluton, a complex brecciated, banded, gabbro-anorthosite-diorite to tonalite intrusion is cut by a set of garnet-bearing dykes on the island of Västerhamnen. The dykes are plagioclase and hornblende porphyritic, quartz dioritic and tonalitic in composition. Similar dykes are met with on nearby islands and skerries. To test whether the gabbro with its anorthositic portions could be related to

Fig. 54. Garnet-bearing tonalite dyke cross cutting the diorite and a more mafic dyke on Västerhamnen, Brändö, Åland. Photo Markus Torssonen.

Fig. 55. Concordia diagram showing the isotope ratios of zircon fractions from the garnet-bearing tonalite dyke, Västerhamnen.

the Subjotnian formations in age a sample of the garnet-bearing tonalitic dyke was dated. A cross-cutting dyke would give a minimum age.

The tonalite dyke is 30—60 cm wide. It is medium to fine-grained with garnet aggregates 1—2 cm in diameter. The contacts with the adjacent rocks are intrusive but not linear (see Fig. 54). The garnet-bearing dykes of different types cross-cut each other, thus rendering their mutual age relations obscure. They seem to have intruded an existing joint system almost contemporaneously.

The heavy accessory mineral fraction contains zircon, abundant apatite, some anatase and a few dark coloured titanite grains. In the homogeneous zircon fractions with $d > 4.0$, the zircons crystals are acicular and clear. The lighter fractions ($3.8 < d < 4.0$ g/cm^3) contain abundant crystals with corroded prisms, and crystal aggregates with parallel overgrowth. Some drop-like crystals were observed and some grains were without crystal faces. The anatase was encountered in this weight fraction.

For analytical results, see Table 14. Note the usual variation in uranium content. Despite the differences in uranium content, the data points of fractions A — E are very concordant; only fraction F with the above anomalous and long grains is more discordant (see Fig. 55). The age obtained for fractions A—E is 1864 ± 16 Ma, with a lower intercept of 474 ± 482 Ma. The corresponding intercepts for all fractions are 1862 ± 3 Ma and 425 ± 58 Ma. The lower intercept is slightly higher than normal, suggesting later disturbance.

The age is very close to that of the pyroxene granodiorites dated in this study and to those dated by J. van Duin in Amsterdam, The Netherlands (pers. communication).

Synorogenic plutonic rocks in the Åland islands

Some of the granitoid intrusions in different parts of the Åland archipelago, are very alike in composition and mode of occurrence. Some are older than the post- and late-orogenic granites dated in this study, but the temporal comparison was made (Hausen 1960) with the postorogenic granites because of the similarities in field relations, compositions and textures. A few of the gabbros close to the rapakivi plutons had to be dated to reveal the age relations between these rocks. Samples of some of these intrusions were included in the Hf and Nd isotope studies reported by Patchett et al. (1981), and Patchett and Kouvo (1986).

The granite of Håkonsnäs, Kökar

The Kökar granite sample, A879-Håkonsnäs, was taken from a granite quarry in the southern part of the island of Karlby, Kökar. The rock is a coarse, porphyritic, red microcline granite with weak parallel orientation. At the contacts the pluton cuts the surrounding infracrustal and supracrustal rocks. Hausen (1960) included this granite in the Lemland, Mosshaga, Åva and Fjälskär group of granites. The Kökarsfjärden rapakivi pluton starts from the western contact of the Kökar granite.

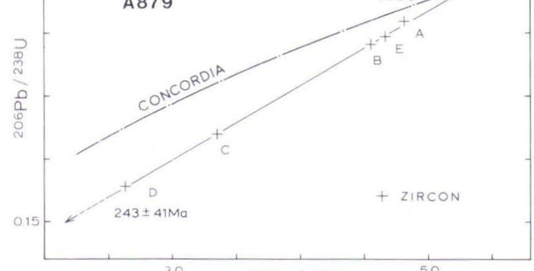

Fig. 56. Concordia plot of isotope ratios of zircon fractions from granite A879-Håkonsnäs, Karlby, Kökar. If fraction A is omitted, the age is 1883 ± 9 Ma (253 ± 26 Ma), see text.

The zircon crystals are euhedral, sharp-edged, transparent and short in habit with L/B ratio 2—4, although longer needles also occur.

The U-Pb isotope ratios plotted on a concordia diagram yield an age of 1878 ± 13 Ma for the five zircon fractions (see Fig. 56). Data point A does not fit the chord, and the common lead content is exceptionally high. If this fraction is omitted, the age from the upper intercept is 1883 ± 9 Ma and from the lower intercept 253 ± 26 Ma.

For analytical results, see Table 15.

The age obtained assigns the rock to the synorogenic age group.

The granite of Mörskär, Kökar

The granite pluton of Mörskär, in the outermost archipelago of Kökar, is a homogeneous, coarse, porphyritic microcline granite. The foliation along the regional trend is due to parallel orientation of microcline megacrysts (see Suominen 1983). The pluton contains only a few, albeit quite large, angular or subangular fragments of the same type of granodiorite as that surrounding it. The pluton is cut by amphibolite and uralite-plagioclase porphyrite dykes.

Sample A880 is from Käringen, a skerry lying south of Mörskär.

The U-Pb isotopic ratios of the three zircon fractions plotted on a concordia diagram yield a synorogenic age of 1881 ± 8 Ma (see Fig. 57). The titanite fraction gives a younger age, 1804 Ma, probably indicating a metamorphic event during that time or marking the end of a metamorphic event.

For analytical data, see Table 15.

The Hf and Nd isotopic compositions of the Mörskär zircon and whole-rock sample have been reported by Patchett et al. (1981) and Patchett and Kouvo (1986).

The gabbro of Alvik, Karlby, Kökar

The gabbro pegmatoid, A998-Alvik, Kökar, is part of a gabbro lens (100x300 m^2) in granodiorite on the western shore of the island of Karlby. Alvik lies some 3.5 km north of Håkonsnäs and 2.5 km northeast of the island of Söderharun (rapakivi granite sample A441, see Suominen 1981 and Fig. 14).

The zircon crystals of fraction d > 4.2 g/cm^3 are mostly transparent, euhedral, sharp- edged prisms with L/B ratio 3—4. Some of the crystals are round and rich in crystal faces. The crystallization history seems to be complicated. Some zircon crystals have a dull core in a transparent shell. Fraction d = 4.0—4.2 g/cm^3 contains

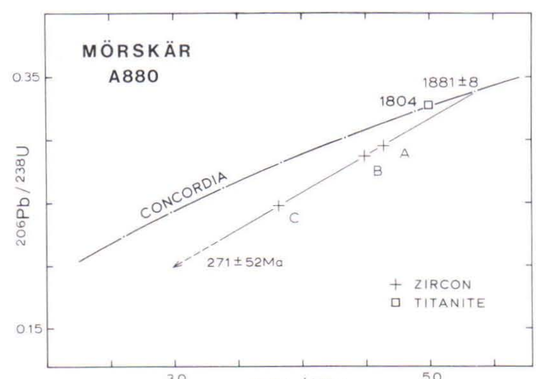

Fig. 57. Concordia diagram for U-Pb isotope ratios of zircon and titanite fractions from granite A880-Käringen, Mörskär, Kökar.

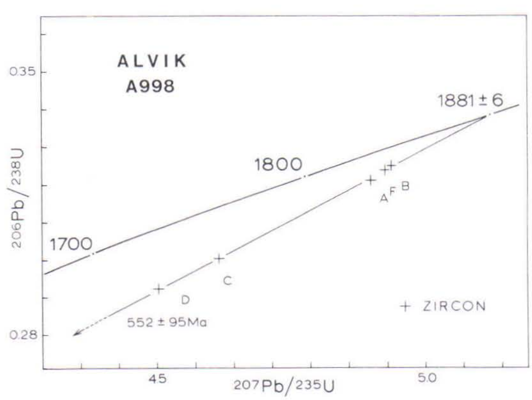

Fig. 58. U-Pb isotope ratios of zircon fractions from gabbro pegmatoid A998-Alvik, Karlby, Kökar.

Table 15. U–Pb isotopic data on the synorogenic granites, granodiorites and gabbro pegmatoids of Åland.

Sample No.	Fraction[1] d=density, g/cm^3 Ø=grain size, µm	Concentration µg/g ^{238}U	Concentration µg/g ^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A879–Håkonsnäs, Karlby, Kökar: granite										
A879A	d>4.6	281.0	75.18	698.1	.13833	13.175	13.961	.3092	4.817	.1130
								± 20	± 61	± 11
								1736	1787	1848
B	4.2<d<4.6	535.5	134.74	1369	.07250	12.339	10.251	.2908	4.554	.11358
								± 16	± 29	± 33
								1645	1740	1857
C	4.0<d<4.2	1169	221.57	2346	.04216	11.657	8.937	.2191	3.349	.11084
	Ø>70							± 12	± 19	± 10
								1277	1492	1813
D	3.8<d<4.0	1943	299.46	1522	.06516	11.616	9.665	.1781	2.635	.10728
	Ø>70							± 11	± 18	± 27
								1056	1310	1753
E	4.2<d<4.6	377.1	96.89	2080	.04667	12.037	9.278	.2970	4.670	.11406
	cr							± 19	± 31	± 20
								1676	1761	1865
A880–Mörskär, Kökar: granite										
A880A	d>4.6	497.0	127.55	4605	.01739	11.623	8.158	.2966	4.656	.11387
								± 17	± 28	± 15
								1674	1759	1862
B	4.2<d<4.6	593.8	148.05	3534	.02476	11.666	7.956	.2882	4.501	.11331
								± 21	± 33	± 10
								1632	1731	1853
C	4.0<d<4.2	1182	254.73	3149	.02971	11.582	8.324	.2491	3.839	.11179
								± 14	± 22	± 8
								1433	1600	1828
D	titanite	193.2	54.69	452.9	.21954	14.060	37.804	.3271	4.994	.1107
	3.4<d<3.5							± 24	± 78	± 14
								1824	1818	1811
A998–Alvik, Karlby, Kökar: gabbro pegmatoid										
A998A	d>4.6	362.5	100.71	2371	.03528	11.906	7.142	.3210	5.059	.11428
								± 17	± 30	± 20
								1794	1829	1868
B	4.2<d<4.6	573.1	161.19	2911	.03147	11.830	7.533	.3251	5.112	.11405
								± 17	± 28	± 12
								1814	1838	1865
C	4.0<d<4.2	869.6	226.01	2584	.03819	11.774	8.767	.3004	4.662	.11257
	Ø<160							± 18	± 31	± 32
								1693	1760	1841
D	4.0<d<4.2	960.7	242.95	2044	.04832	11.836	9.251	.2923	4.506	.11180
	Ø>160							± 16	± 25	± 16
								1652	1731	1829

Table 15. (continued)

A998F	4.2<d<4.6	565.1	158.46	6263	.01544	11.617	6.934	.3241	5.097	.11408
								± 17	± 27	± 5
								1809	1835	1865
A877–Svartgrund, Föglö: gabbro pegmatoid										
A877A	d>4.2; Ø>160	567.5	157.34	4142	.02162	11.735	10.764	.3204	5.055	.11442
								± 19	± 31	± 9
								1791	1828	1871
B	4.0<d<4.2	846.9	221.66	3130	.02958	11.666	11.904	.3025	4.698	.11265
								± 17	± 27	± 14
								1703	1766	1842
C	titanite	144.5	39.25	597.6	.16104	13.562	7.940	.3139	4.926	.11382
								± 17	± 30	± 20
								1759	1806	1861
D	3.8<d<4.0	1510	342.53	2605	.03682	11.219	10.634	.2622	3.875	.10717
								± 19	± 28	± 11
								1501	1608	1751
E	3.6<d<3.8	2549	441.40	1429	.06833	10.743	11.114	.2002	2.705	.09801
								± 10	± 15	± 18
								1176	1329	1586
F	3.6<d<3.8	2408	416.62	1642	.05825	10.636	10.526	.2000	2.711	.09834
								± 10	± 15	± 10
								1175	1331	1593
G	3.8<d<4.0	1531	342.32	2045	.04664	11.377	10.869	.2585	3.828	.10741
								± 16	± 24	± 7
								1481	1598	1756
A560–Bockholm, Kumlinge: granodiorite										
A560A	3.8<d<4.1	1151	267.37	3326	.02909	11.490	10.417	.2686	4.108	.11095
	Ø<110							± 16	± 26	± 15
								1533	1655	1815
B	4.1<d<4.2	840.5	203.67	3107	.02753	11.609	10.062	.2801	4.339	.11236
								± 14	± 24	± 13
								1591	1700	1838
C	3.6<d<3.8	1832	386.27	1708	.05687	11.723	14.132	.2437	3.679	.10949
								± 13	± 20	± 8
								1405	1566	1791
D	3.8<d<4.1	990.4	264.27	8396	.01093	11.508	9.847	.3084	4.830	.11360
	abr							± 18	± 30	± 12
								1732	1790	1858
A563–Algersö, Föglö: granodiorite										
A563A	d>4.1; Ø>70	316.1	86.11	3282	.02850	11.910	11.021	.3148	5.002	.11525
								± 18	± 31	± 16
								1764	1819	1883
B	d>4.6	249.2	70.11	3128	.02760	11.900	11.246	.3251	5.167	.11527
								± 17	± 28	± 12
								1814	1847	1884
C	4.2<d<4.6	337.2	92.47	2780	.03267	11.943	11.266	.3169	5.026	.11502
								± 16	± 27	± 9
								1774	1823	1880

Table 15. (continued)

A563 D	4.1<d<4.2	715.2	173.08	1180	.08209	12.401	13.198	.2797 ± 15 1589	4.353 ± 24 1703	.11288 ± 16 1846
E	titanite	55.0	15.89	329.3	.29007	15.324	18.141	.3338 ± 29 1856	5.247 ± 62 1860	.11402 ± 76 1864

For symbols, see Table 3.

more brownish crystals, some with a transparent shell; the L/B ratio is 4. Fraction d = 3.8—4.0 g/cm³ is different, most of the zircons being dark brown, round and corroded. The zircon morphology shows that the gabbro has recrystallized to some degree.

The isotope ratios from the U-Pb analyses of five zircon fractions plotted on a concordia diagram yield an age of 1881 ± 6 Ma (Fig. 58). The lower intercept, 552 ± 95 Ma, is high compared with the 177 ± 141 Ma for the Hyvinkää gabbro of the same age (Suominen 1988).

The age is typically synorogenic, and shows that the gabbro is not a Subjotnian formation.

For analytical data, see Table 15. Increasing uranium content causes increasing discordance (see concordia diagram Fig. 58).

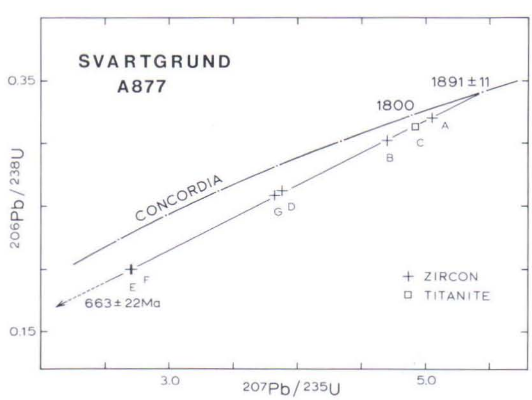

Fig. 59. Concordia plot for zircon and titanite fractions from gabbro pegmatoid A877-Svartgrund, Föglö, Åland.

Fig. 60. Microphotographs of zircon crystals from granodiorite A563-Algersö. Zonal growth on a growth nucleus is present in all crystals, although the habit varies markedly. Some zircon crystals are rounded. Photo Erkki Halme.

The gabbro of Svartgrund, Föglö

The gabbro island of Svartgrund lies about 4 km south of the Åland rapakivi batholith, close to its known southwesternmost contact (see Suominen 1978). The gabbro penetrates a granodiorite with cutting amphibolite dykes. The normal type is a medium-grained hornblende gabbro. Ophitic pegmatoidic varieties constitute small, unevenly distributed patches in the rock.

Initial Hf isotopic ratios of zircons have been reported by Patchett et al. (1981) and initial Nd isotopic data on whole-rock by Patchett and Kouvo (1986).

The zircons of A877 are euhedral, long, acicular and sharp-edged crystals. They are reddish brown in colour due to pigment. The crystals also contain lath-shaped inclusions, often parallel to the c-axis. The L/B ratio is up to 6.

The U-Pb isotope ratios of the six zircon fractions and one titanite (see Table 15) plotted on a concordia diagram yield an age of 1891 ± 11 Ma (see Fig. 59). The density fractions, 3.8—4.0 and 3.6—3.8 g/cm^3, were analysed twice (data points G, D and E, F). The age obtained is almost as high as that for Algersö, see later in this study. The age on the zircon fractions is equal to that on titanite. There are no signs of later recrystallization. However, as the high lower intercept (663 Ma) indicates later disturbance, the Svartgrund gabbro is not genetically related to the anorthosite and rapakivi of Åland.

The granodiorites of Algersö, Föglö and of Bockholm, Kumlinge

The granodiorites of Algersö, Föglö (see Fig. 14) and of Bockholm, Kumlinge (see Fig 1 and 62) were dated at the same time as the diabases

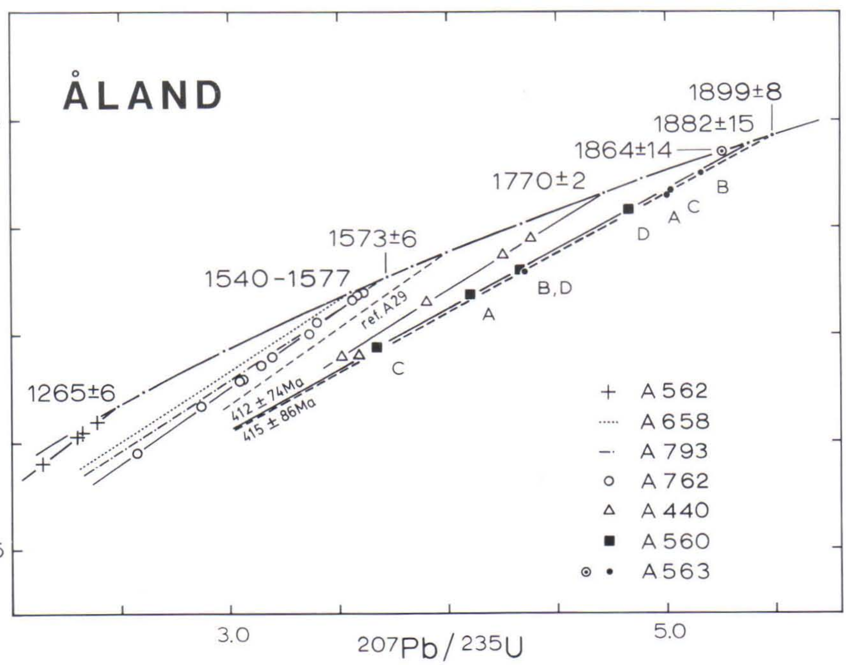

Fig. 61. Summary plot for U-Pb isotope ratios of zircon and titanite fractions from granodiorites A560-Bockholm and A563-Algersö (dot in circle titanite), granite A440-Lemland, rapakivi A762-Godby and diabases A658- and A793-Föglö and A562-Märket Åland islands. For details see the corresponding diagrams. N.B. A29 is from the Wiborg rapakivi area.

Table 16. Rb–Sr isotope data.
Analyst: Otto van Breemen

Sample No.	Phase	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$ atomic r.	$^{87}Sr/^{86}Sr$ atomic r.	Age $(^{87}Sr/^{86}Sr)i$ M.S.W.D.
Diabases in southern Finland						
1212	Sorkka, olivine diabase					
	w.r.	17	449	0.1075	0.70578	
		17	447	0.1086	0.70582	1430±46Ma
	3F	17	709	0.0681	0.70518	0.7037±2
	8F	59	544	0.3128	0.70982	0.7
	9F	94	494	0.5525	0.71481	
	10F	99	495	0.5780	0.71535	
	pyroxene	1.9	47	0.1155	0.70518	
	biotite	307	42	21.94	1.0921	1263±18 MA
1215	Sorkka, hybrid					
	4F	61	101	1.761	0.74559	
	5F	99	125	2.317	0.75419	1184±26 Ma
	6F	150	116	3.773	0.77886	0.7162±11
	8F	209	87	7.056	0.83217	2.2
	9F	174	87	5.848	0.81431	
1217	Kiperinoja, olivine diabase					
	biotite	408	43	28.73	1.2074	1251±18 Ma
1231	Vaasa, olivine diabase					
	biotite	290	61	14.21	0.95310	1253±18 Ma
		283	69	12.04	0.91447	1249±18 Ma
1208	Föglö, pyroxene diabase					
	w.r.	12.8	419	0.0886	0.70563	
	4F	25.6	562	0.1317	0.70616	
	8F	6.5	520	0.0362	0.70428	1556±34 Ma
	10F	38.1	240	0.4591	0.71365	0.7035±2
		38.2	240	0.4613	0.71371	1.2
	11F	69.4	300	0.6708	0.71814	
	13F	99.4	307	0.9367	0.72396	
1198	Kumlinge, hornblende diabase					
	w.r.	10	297	0.0981	0.70575	
	6F	13	439	0.0837	0.70524	1599±26 Ma
	7F	70	363	0.5577	0.71633	0.7036±3
	8F	216	393	1.597	0.73995	
	9F	318	373	2.485	0.75890	
	10F	374	340	3.208	0.77502	
1222	Ansio, olivine diabase					
	w.r.	33	433	0.2195	0.70870	
	6F	23	685	0.0952	0.70590	
	9F	100	559	0.5180	0.71583	1661±26 Ma
	12F	270	482	1.628	0.74127	0.7036±3
		270	482	1.625	0.74117	2.5
	13F	329	498	1.917	0.74870	
		298	447	1.935	0.74800	
	14F	302	420	2.088	0.75345	
	biotite	493	36	43.29	1.7115	1656±24 Ma
		463	63	22.23	1.2173	1643±24 Ma

Table 16. (continued)

1221	Tuomasvuori, rheomorphic dyke.					
	4F	48	156	0.8881	0.72554	
	8F	30	145	0.6026	0.72002	1580±62 Ma
	9F	19	111	0.4873	0.71700	0.7063±7
	10F	31	157	0.5724	0.71930	4.5
	11F	143	153	2.709	0.76672	
		143	154	2.702	0.76671	
1228	Heinola, olivine diabase					
	biotite	392	104	11.14	0.95879	1630±24 Ma
1229	Lovasjärvi, olivine diabase					
	biotite	272	8.12	123.7	3.524	1622±24 Ma
	Rapakivi granites of the Åland islands					
						I.R. 0.706±3
						DC ^{87}Rb=1,42 x 10^{-11} a^{-1}
2	Högbergen, Hammarland: even-grained rapakivi					
	w.r.	254	586	12.85	0.98711	1524±26 Ma
5	Böle, Eckerö: pyterlite					
	w.r.	183	111	4.822	0.81048	1509±48 Ma
12	Prästö I, Sund: wiborgite					
	w.r.	188	125	4.375	0.80227	1533±52 Ma
	w.r.	187	125	4.363	0.80149	1524±52 Ma
17	Långnäs, Lumparland: biotite rich, porphyritic rapakivi					
	w.r.	357	45.3	23.98	1.2287	1518±23 Ma
	biotite	954	15.8	276.4	6.7042	1511±21 Ma
	biotite	1014	15.7	309.1	7.3672	1502±21 Ma

and their country rocks in the Åland area.

The granodiorite A563-Algersö is coarse-grained and partly gneissose in texture. The main minerals are plagioclase, quartz, K-feldspar, hornblende and biotite. In the present context the accessory minerals zircon and titanite are of interest. The rock is rich in zircon.

The zircons in sample A563 are small, euhedral, tetragonal acicular crystals with L/B ratio 1—3. They are clear and transparent but small. Small cores can be found in the zonally grown zircons (see Fig. 60 for microphotographs).

The Bockholm granodiorite, sample A560 (see Sederholm 1934, p. 32 and Ehlers 1979), has been referred to as a gneissose granite. The sample was taken from a site 30 m east of the »Bockholm conglomerate».

The composition is much the same as that of sample A563-Algersö but the rock is less coarse-grained. The Bockholm granodiorite, too, is rich in zircon. The habit of the translucent zircon crystals is the same as that of the Algersö zircon crystals, but the size varies and the crystals are smaller than those of the Algersö granodiorite. The L/B ratio is 1—4. The crystals are slightly rounded and not always clear. A growth nucleus and zoning are characteristic features.

A concordia plot yields an age of 1899 ± 8 Ma for the Algersö zircon fractions. The more discordant zircon fractions from the Bockholm granodiorite yield a chord of 1882 ± 15 Ma age (see Fig. 61). Titanite from A563-Algersö is concordant with an age of 1864 ± 14 Ma. These are slightly higher than the typical ages of synorogenic granitoids in southern Finland (cf. Simonen 1980b, Kähkönen et al. 1989). For isotope data, see Table 15.

Rb-Sr DATING OF DIABASES AND ÅLAND RAPAKIVI

Samples of postmetamorphic diabase dykes were collected by Dr Otto van Breemen for dating with the Rb-Sr method at the Scottish Universities Reactor and Research Centre. Some of the samples were from the same localities as the samples dated with U-Pb on zircons for this study. Patchett (1978) has referred to these Rb-Sr results with van Breemen and Halliday (in prep.).

Later, some of the rapakivi granites of Åland were sampled and dated by Dr O. van Breemen to be used as a reference for the Subjotnian diabases. The Rb-Sr isotopic data are listed in Table 16, and the sampling sites are given in Appendix 4.

The biotite ages of diabase dykes fit those dated with the U-Pb method on zircon fractions and also most of the whole-rock determinations (see Table 16). The Rb-Sr ages on biotite of the Åland rapakivi are lower than the U-Pb ages on zircon fractions. The same feature was noticed by Kouvo (1958) for biotite from sample A29 (rapakivi) and for biotite from the Bodom granite dated with Rb-Sr and K-Ar methods. The whole-rock Rb-Sr ages for rapakivi are the same as those for biotite fractions from the same samples. This might be due to later disturbances or later chemical processes, as thoroughly discussed by Welin et al. (1983) with reference to the Mosshaga granite stock in the Åland islands and by Kähkönen et al. (1989) to the Hämeenkyrö batholith near Tampere.

ISOTOPE GEOCHEMICAL STUDIES IN SOUTHWESTERN FINLAND

To unravel the genetic aspects, Hf and Nd isotope geochemical studies were made on zircon and whole-rocks from some of the samples from southwestern Finland dated during this study. The Hf initial ratios measured lie slightly above the CHUR curve and the Nd initial ratios are close to the CHUR curve, thus precluding the likelihood of a significant amount of Archaean material in southwestern Finland (Patchett et al. 1981, Patchett and Kouvo 1986 and Huhma 1986). Haapala and Rämö (1990) and Rämö (1990, 1991) studied the petrogenesis of the rapakivi granites in southern Finland by means of Nd isotopic analyses and verified that the magmas were derived from the lower crust of probably a Svecofennian granodiorite in composition, but the Salmi rapakivi magma, however, has a mixture of more or less equal amounts of juvenile (1.9 Ga) and Archaean lower crustal materials.

The high ^{208}Pb (Bibikova 1984) content shown by the zircon from the Postjotnian diabase dykes and from the Föglö diabase was not seen in the granitoids of this study. The high $^{208}Pb/^{206}Pb$ ratio was also observed in the Ansio and Lovasjärvi dykes (Siivola 1987).

DISCUSSION

The rock formations dated from southwestern Finland are listed in Table 17. The bulk of the crust cropping out in southwesternmost Finland was created during the Subjotnian, Jotnian and Postjotnian sub-eras (see Fig. 62). The radiometric ages of the samples dated in this study are summarized in Fig. 63. The samples are divided into distinct age groups representing synorogenic and late- and postorogenic Svecofennian intrusions, and Subjotnian and Postjotnian magmatic events. The Subjotnian, with its intrusions, constitutes a coherent time span (see Fig. 63) and the Postjotnian diabases are the youngest intrusive rocks in southwestern Finland. The synorogenic intrusions form a coherent age group within the limits of error. The age relations of the intrusions will have to be established through field observations on the contact relations.

The pyroxene granodiorites of Naula-ahde, Kakskerta and of Kittuis, Houtskär seem to be intraorogenic as postulated by Simonen (1980b). The other pyroxene granodiorites in southwestern Finland are of the same age (J. van Duin, pers. communication). The intraorogenic event is also shown by the garnet-bearing tonalite dykes of Västerhamnen in Brändö, Åland. Titanite of A563-Algersö, Föglö of this age is one more marker of the event. Mafic dyke swarms cutting the synorogenic intrusions in the southernmost Åland archipelago might be of this age.

The late-orogenic intrusions in southwestern Finland constitute a very distinctive age group with a high uranium content in zircons. They are time markers for a thermal pulse at the peak of the regional metamorphism imprinted in their accessory minerals: monazite and rutile. Monazites of the nine late-orogenic granite samples give an age of 1826—1836 Ma. The same, or a slightly older, thermal pulse is also evidenced by the existence of the younger titanites and monazites (1837 ± 6—1845 ± 10 Ma) of the trondhjemites of the Uusikaupunki area (Patchett and Kouvo 1986). The same peak of metamorphism has been reported from southern Finland by Korsman (1977) and Hölttä (1986) and from southern central Sweden by Stålhös and Björk (1984). However, the ages on monazites from the Tammisaari area are synorogenic around 1.88 Ga or, in the case of the Dynerskär aplogranite, still lower at 1807 Ma (Hopgood et al. 1983).

The ages on monazite and titanite may be younger than those on zircons and may indicate the time of metamorphism, as discussed by Aho (1979) and other workers. In the Kakola granite, monazite and zircon grew simultaneously. This mineral association is common to all S-type granites (Sawka et al. 1986). The U-Pb ages of monazite, zircon and titanite can be the same, as demonstrated by the A877-Svartgrund sample (Fig. 59), by the Hämeenkyrö (Patchett and Kouvo 1986), Vaaraslahti (Salli 1983) and other batholiths, and even by those within the Archaean in Ilomantsi (Tilton and Grünenfelder 1968). Mattinson (1982) reports blocking temperatures of over 600°C for zircon, 450—500°C for titanite and ca. 400°C for apatite.

The inherited zircon in S-type granites can be reset isotopically during the formation of a granite as a result of high temperatures during the generation of the granitic magma (Wielens 1979, cf. Halliday 1983). Moreover, two zircon generations of different ages and different habit can exist side by side within the same rock as reported by Meriläinen (1976) from a quartz dioritic orthogneiss in the granulite belt of Lapland. The late- orogenic (1.83 Ga) Mattnäs and Hanko granites bear evidence of inherited zircon, showing that the silicate melt of granitic composition was not completely homogenized, whereas granites from Tammo, Kistola and Kakola do not show isotopic ratios indicating inherited zircons.

A regional metamorphic event is marked by the postorogenic granites of Lemland, Mosshaga and Åva, and by the younger titanite age of the Mör-

Table 17. Ages of events and rock formations in Åland and adjacent areas in southwestern Finland.

Age, Ma	Method	GSF No.	Formations and processes	Ref.
PALAEOZOIC				
480	Palaeont.		Ordovician limestone, Lumparn	(2)
550	Palaeont.		Cambrian sandstone dykes	(2)
POSTJOTNIAN				
1265±6	U-Pb z	A562	Olivine diabase, Märket	(1,7)
1264±12	U-Pb z, bd	A784	Olivine diabase, Säppi	(1)
		A785		
		A786		
1258±13	U-Pb z, bd	A975	Olivine diabase, Hankkila	(1)
JOTNIAN				
>1260			Jotnian sandstone, Satakunta	(1)
SUBJOTNIAN (anorogenic)				
1523±34	Rb-Sr wr		Pyroxene diabase, Vidskär, Föglö	(6)
1550±35	Rb-Sr b		Quartz porphyry dyke, Källholm, Åva	(6)
1565±26	Rb-Sr wr		Hornblende diabase, Börsskär, Kumlinge	(6)
1540±12	U-Pb z, bd	A658	Pyroxene diabase, Bergskär, Föglö	(1)
1577±12	U-Pb z, bd	A793	Pyroxene diabase, Källsholm, Föglö	(1)
1560	U-Pb z, bd	A792	Anorthosite, Västersten, Hammarland	(1)
1562±14	U-Pb z	A373	Rapakivi, Siipyy	(13)
1571±9	U-Pb z	A716	Quartz porphyry, Hammarudda, Hammarland	(1)
1574±6	U-Pb z	A715	Quartz porphyry, Blåklobb, Eckerö	(1,4)
1571±20	U-Pb z	A717	Quartz porphyry dyke, Jyddö, Föglö	(1)
1576±13	U-Pb z	A714	Quartz porphyry dyke, Källholm, Åva	(1)
1568±10	U-Pb z	A468	Rapakivi, Långnäs, Lumparland	(1,4)
1573±20	U-Pb z	A129	Rapakivi granite, Peipohja	
(1,4,5)				
1573±8	U-Pb z		Rapakivi, Eurajoki and Laitila, pooled isochron of A255,A606,A608,A689,A690	(4)
1575±6	U-Pb z	A762	Rapakivi, Godby, Finström	(1)
1574±14	U-Pb z	A441	Rapakivi, Söderharun, Kökarsfjärden	(1,4)
1584±9	U-Pb z	A1020	Rapakivi, Reposaari, Pori	(12)
1560±14	U-Pb z	A467	Rapakivi, Böle, Eckerö	(1,4)
1575±11	U-Pb z	A295	Rapakivi, Vabbängarna, Eckerö	(1)
1576±9	U-Pb z	A764	Rapakivi, Getabergen, Geta	(1,4)
1579±13	U-Pb z	A287	Rapakivi, Fjärdskär, Houtskär	(1)
1590±15	U-Pb z	A710	Rapakivi, Kustavi-Vehmaa	(4)
1600±30	Rb-Sr wr		Pyroxene diabase, Korsö, Brändö	(6)
POSTOROGENIC				
1730	Rb-Sr b	A095	Trondhjemite, Heinänen, Uusikaupunki	(5,9)
1742±34	Rb-Sr wr		Granite, Mosshaga, Högskär, Sottunga	(10)
1750	U-Pb t	A334	Granodiorite ("Monzonite"), Åva	(1,9)
1770±2	U-Pb z	A440	Granite, Ytterklobb, Lemland,	(1,4)
1788±11	U-Pb z	A442	Granite, Mosshaga, Sälskär, Sottunga	(10)
1799±13	U-Pb z	A334	Granodiorite ("Monzonite") of Åva	(1,9)
1803±10	U-Pb z	A335	Granite, Åva, Brändö	(1,9)
1804	U-Pb t	A880	Granite, Käringen, Mörskär, Kökar	(1)
1810	U-Pb t	A174	Pyroxene trondhjemite, Putsaari	(9)
1815	U-Pb z	A508	Granite, Seglinge, Kummelskär	(4)
1815±12	U-Pb z, t	A568a	Gabbro pegmatite, Tynki, Kalanti	(9)

Table 17. (continued)

LATE-OROGENIC				
1824±38	U-Pb z, m	A876	Granite, Tulludden, Hanko	(1)
1829±3	U-Pb z, m	A997	Granite, Tammo, Parainen	(1)
1830±10	U-Pb z, m	A875	Granite, Märaskär, Hanko	(1,11)
1830±10	U-Pb z, m	A399	Granite, Kistola, Muurla	(1,5)
1830	U-Pb m	A389	Granite, Haarla, Perniö	(1)
1832±11	U-Pb z, m	A64	Granite, Kakola, Turku	(1)
1840±8	U-Pb z, m	A390	Granite, Pungböle, Kemiö	(1)
1840±4	U-Pb m, z, u	A901	Granite, Kumlingeby, Kumlinge	(1)
1842±31	U-Pb z, m	A322	Granite, Mattnäs, Nauvo	(1)
INTRAOROGENIC				
1842–1879	U-Pb z	A498	Pyroxene granodiorite, Kakskerta, Turku	(1)
1862±6	U-Pb z	A920	Pyroxene granodiorite, Kittuis, Houtskär	(1)
1862±3	U-Pb z	A822	Garnet tonalite dyke, Västerhamnen, Brändö	(1)
SYNOROGENIC				
1864±14	U-Pb t	A563	Granodiorite, Algersö, Föglö	(1)
1872±11	U-Pb z	A554	Diorite/tonalite, Ruokola, Uusikaupunki	(9)
1874±2	U-Pb z	A552	Diorite/tonalite, Kaleva, Kalanti	(9)
1878±13	U-Pb z	A879	Granite, Håkonsnäs, Kökar	(1)
1878	U-Pb z	A568b	Gabbro, Tynki, Kalanti	(9)
1881±6	U-Pb z	A998	Gabbro pegmatoid, Alvik, Kökar	(1)
1881±8	U-Pb z	A880	Granite, Käringen, Mörskär, Kökar	(1,9)
1882±15	U-Pb z	A560	Granodiorite, Bockholm, Kumlinge	(1)
1891±10	U-Pb z	A832	Granodiorite, V. Rödgrund, Sottunga	(10)
1891±11	U-Pb z, t	A877	Gabbro pegmatoid, Svartgrund, Föglö	
(1,8,9)				
1892±5	U-Pb z	A174	Pyroxene trondhjemite, Putsaari	(9)
1899±8	U-Pb z	A563	Granodiorite, Algersö, Föglö	(1)

1. This study
2. Tynni 1982
3. Simonen 1980
4. Vaasjoki 1977
5. Kouvo 1958
6. Otto van Breemen, pers. comm.
7. Patchett 1978
8. Patchett et al. 1981
9. Patchett & Kouvo 1986
10. Welin et al. 1983
11. Huhma 1986
12. Vaasjoki et al. 1988
13. Idman 1989

z zircon
t titanite
m monazite
u uraninite
b biotite
wr whole rock
bd baddeleyite

skär granite. In the Mörskär area the younger titanite may be associated with the formation of the mafic dykes of at least two generations that cut the granite. In Tynki (Uusikaupunki trondhjemite area) the formation of a coarse-grained gabbro pegmatite with zircon and titanite of 1815 ± 12 Ma age (Patchett and Kouvo 1986) in a gabbro with a synorogenic age of 1878 Ma is evidence of mobilization at that time.

There seems to be a spatial and, to some extent, temporal connection between rapakivi and quartz porphyry dykes, and anorthosites and pyroxene diabases. This is the case in the Åland area, in Satakunta and in the Wiborg rapakivi

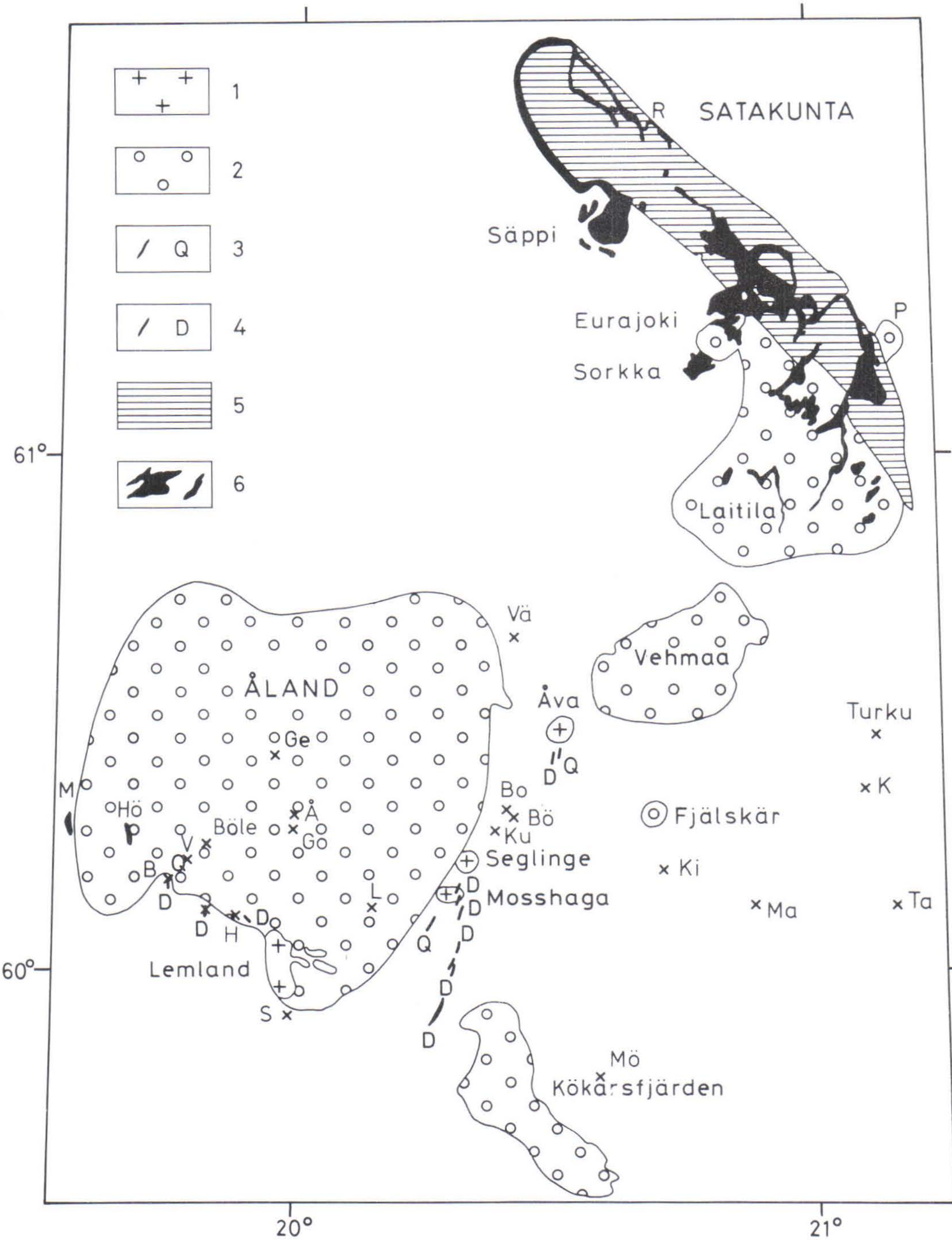

Fig. 62. (1) Post-orogenic granites in southwestern Finland, (2) rapakivi granites, (3) Subjotnian quartz porphyry dykes, (4) Subjotnian pyroxene diabase dykes, (5) Jotnian sandstone, (6) Postjotnian olivine diabases. Because of the scale, the narrow but numerous Subjotnian hornblende diabase dykes parallel to the pyroxene diabases in the area between the Åland, Kökarsfjärden and Vehmaa rapakivi plutons (more than 300 known dykes) are omitted. Sampling sites marked with letters refer to: R = Reposaari, P = Peipohja, Vä = Västerhamnen, K = Kakskerta, Ta = Tammo, Ma = Mattnäs, Ki = Kittuis, Bo = Bockholm, Bö = Börsskär, Ku = Kumlinge, Mö = Mörskär, S = Svartgrund, H = Hammarudda, M = Märket, Hö = Höggrund, B = Blåklobb, V = Vabbängarna, Ge = Geta, Å = Åsbacka, Go = Godby, L = Långnäs. The map is simplified after Simonen (1980a), and the Jotnian in Satakunta is drawn after Hämäläinen (1985).

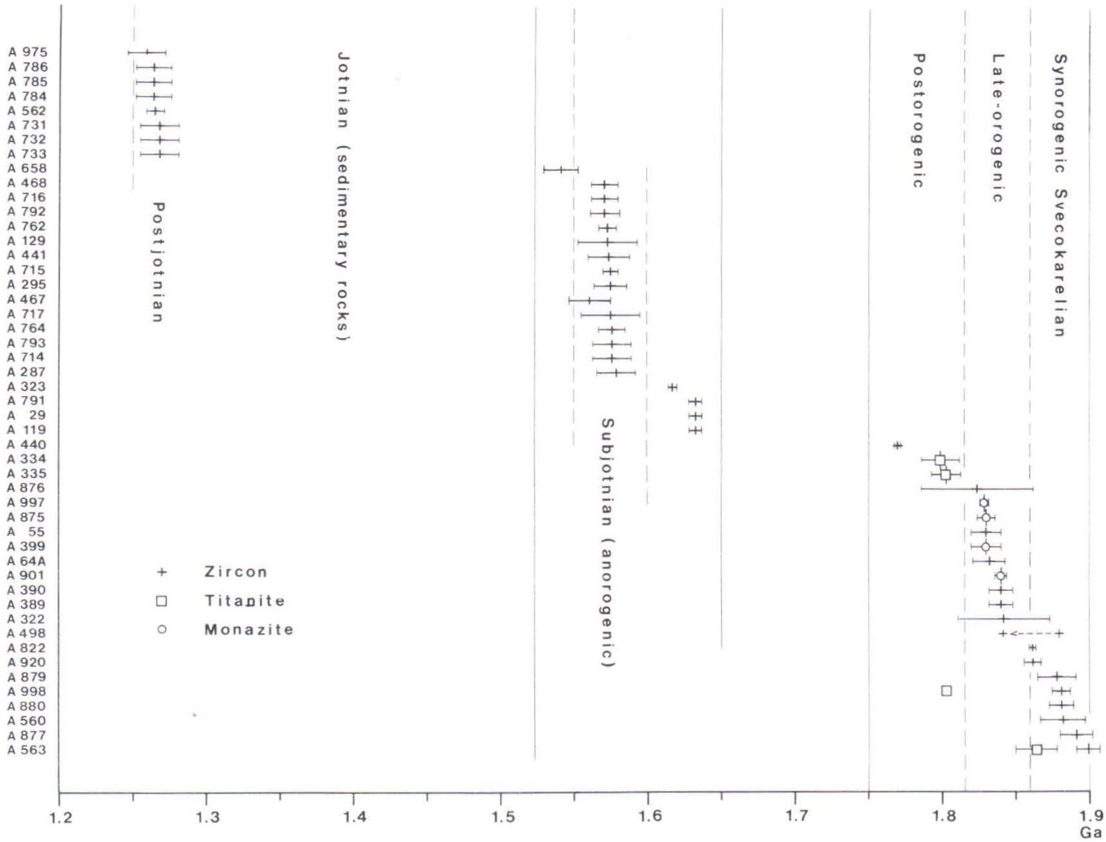

Fig. 63. Chronogram for the rock formations in southwestern Finland dated in this study.

area. The same rock type association is found in the Nordingrå and Rödö areas in Sweden. As suggested by observations on erratic blocks, there is a rapakivi area on the bottom of the Bothnian Sea near Vaasa (Eskola 1928, 1934, von Eckerman 1937, Veltheim 1962, Flodén and Winterhalter 1981). A similar rock association and rifting have been reported from North America by Geijer (1922) and Emslie (1978). Jotnian sandstone and Postjotnian diabases are often found close to rapakivi, implying that sedimentation from cratonized areas to grabens and continuous rifting continued until the basaltic intrusions associated with the movements were emplaced.

The Jotnian sediments form a series of sediments covering a long time span and large areas of Fennoscandia (see von Eckermann 1937). In Soviet Karelia the red sandstone on the western shore of Lake Onega is older because it is cut by diabase dykes of 1670 Ma (K-Ar) age (Kratz and Mitrofanov 1980). Back in 1938, Väyrynen suggested that, »it would thus seem more natural to consider the sandstone series, too, older than the Rapakivi granite, ...» Younger formations are those of the Salmian series of Lake Ladoga, which transgressively overlie rapakivi granite in Karelia, and the sandstones of the Tersky coast of the White Sea with 1450—1000 Ma ages (Kratz et al. 1968). K-Ar ages of 1280—1318 Ma for argillaceous Jotnian facies (Muhos siltstone formation) and of between 1130 Ma (Leistilänjärvi, Nakkila) and 1300 Ma (Lammastenkoski, Harjavalta) for Satakunta sandstones have been reported by Simonen (1960) and by Polkanov and

Gerling (1961a). The Leistilänjärvi specimen, taken from close to a Postjotnian diabase dyke, gives too low an age (Simonen 1960).

The lithological association rapakivi granite, quartz porphyry, labrador porphyrite — gabbro anorthosite (and pyroxene diabase) occurs in the Åland and Wiborg rapakivi areas. Kranck (1929, 1968) pointed out the cratonic origin of this rock association, in which the anorthositic members are older than the granitic ones. According to Borgström (1947), the diabase dykes must be older than the rapakivi batholith. But there are some younger diabase dykes, e.g. the Kungsholm dyke, that cut the rapakivi within the Åland rapakivi area. The similarities in the contact zones are obvious, as pointed out by Wahl (1936, 1938) with reference to the island of Someri (Sommarö) in the Gulf of Finland, at the southern margin of the Wiborg rapakivi area, where two different generations of quartz porphyry occur. This may be true in the Åland area as well, even though the quartz porphyry dykes dated in the present study are of the same age within the limits of error. However, not all quartz porphyry dykes in southwestern Finland are of Subjotnian age, as demonstrated by the Sara, Karvia dyke dated to 1883 ± 3 Ma (Suominen et al. in prep.).

The Salmian series in Soviet Karelia is subdivided into a lower and an upper subseries. The lower series, which is 37.2 m thick, deposited on the erosional surface of the rapakivi granites, with an angular unconformity on the rocks of the Ladogian series. It is composed of conglomerates, gravellites, arkose and quartz-feldspathic sandstones, subgreywackes, tuff sandstones, tuffites and clay slates. The upper Salmian subseries, which is up to 137.5 m thick, is composed of alternating diabasic, basaltic andesite-basaltic porphyrites and their tuffs. The lower Salmian subseries is correlated with coarse-clastic Jotnian rocks of the Satakunta region, but on the whole the Salmian series is correlated with the lower sedimentary-volcanogenic cycle of the Nordingrå region, Sweden. According to preliminary information, the porphyrites of the Salmian series are 1100—1300 Ma old (Kairyak and Khazov 1967). Thus formations of this series are dated as Jotnian. Popov et al. (1977), however, report a Pb-Pb isochron age of 1400 Ma for the basalt on Mantsinsaari of the Salmian series and refer to the K-Ar age of 1350—1450 Ma obtained by Rozanov et al. 1975.

The rapakivi magma was generated in the lower crust (Vorma 1976, Emslie 1978, Andersson 1983, Nurmi and Haapala 1986, Haapala and Rämö 1990 and Rämö 1991). The zircons started to crystallize during the residence of the magma in the crust and, owing to oscillating PT conditions (Grigorev 1965), their growth was often zonal, as demonstrated by photographs of etched zircon crystals from the Wiborg and Åland areas. The final emplacement was associated with a distensional phase of movements contemporaneous with the intrusion of basaltic dykes (Vorma 1976, Vaasjoki 1977, Laitakari and Leino 1989, Rämö 1991) in the cratonic crust. Caused by isostatic uplift, these events resulted in faults and grabens in the Riphean crust (Kahma 1978).

In the Föglö diabase the autolithic portions started to crystallize while the magma was still mobile. This resulted in the rounded and corroded corners shown by some of the labradorite laths. The same happened to the anorthositic variety of pyroxene diabase in Västersten and Höggrund.

The Subjotnian Föglö dyke set, the anorthositic variety of pyroxene diabase on Västersten, the quartz porphyry dykes of Blåklobb, Hammarudda, Jyddö and Källholm, and the rapakivi of Kökarsfjärden and the Åland area are all very close in age to the Laitila — Eurajoki rapakivi stock dated to 1573 ± 11 Ma (Vaasjoki 1977), the Kustavi—Vehmaa rapakivi stock dated to 1590 ± 15 Ma (Vaasjoki 1977), the Reposaari satellite body of the Laitila stock dated to 1584 ± 9 Ma (Vaasjoki et al. 1988) and the Peipohja rapakivi stock dated to 1573 ± 20 Ma. The Siipyy rapakivi granite in northern Satakunta was dated to 1562 ± 14 (Idman 1989). The Nordingrå rapakivi granite and anorthosite in northern central Sweden are 1578 ± 19 Ma in age (Welin and Lundqvist 1984). The Ragunda rapakivi in Sweden has been dated with the Rb/Sr method to 1320 ± 30 Ma (Kornfält 1976), but this age is not unambiguous (Lundqvist 1990). The Berdiaush rapakivi pluton in the Soviet Union is 1340—1350 Ma old (Rb-Sr isochron) (Keller and Krasnobaev 1983). The Wolf River rapakivi batholith in the U.S.A. has been dated with the U/Pb method on zircons to 1485 ± 15 Ma (Van Schmus et al. 1975). Anderson (1983) reports anorogenic granite intrusions in North America with age intervals of 1.41—1.49 Ga, 1.34—1.41 Ga and 1.03—1.08 Ga.

The Subjotnian formations in southwestern Finland (see Fig. 61) are, within the limits of error, very close to each other in age (see Fig. 63). It would seem that the diabase and rapakivi magmas existed contemporaneously and that these rocks were emplaced concomitantly within the limits of dating error. As in the Wiborg rapakivi area, the age relations between rapakivi, gabbro-anorthosite and diabases (Siivola 1987, I. Laitakari 1987) will ultimately have to be based on field observations. The mafic members of the rock association were the first to intrude and the quartz porphyry dykes the last. All the ages given are interpreted as crystallization ages.

The Breven and Hällefors dykes in Sweden correspond to the Föglö dyke set in age (Patchett 1978) but their east-west trend is subparallel to the Subjotnian Häme olivine diabase dyke swarm in southern Finland described by I. Laitakari (1969). Zircons from the Lovasjärvi diabase, cut by the Wiborg and Suomenniemi rapakivis, have been dated to 1643 ± 5 Ma (Siivola 1987). The Rb-Sr age on biotite from the Lovasjärvi diabase is 1622 ± 24 Ma (Table 16). The Ansio and Heinola dykes of the Häme swarm have been dated with the U-Pb method on zircons to 1646 ± 6 Ma (I. Laitakari 1987). For the Ansio dyke the Rb-Sr biotite ages are 1656 ± 24 Ma and 1643 ± 24 Ma, and for the Heinola diabase dyke the Rb-Sr biotite age is 1630 ± 24 Ma (Table 16).

The pulse of the Post- and Subjotnian diabases demonstrates a major widening of the stable cratonic crust due to rifting or parting under tension caused by a shearing couple. The Föglö diabase dyke set probably intruded tension fractures opened by a shearing couple, when the eastern block moved south relative to the western block. This movement was similar to those that opened the tension joints filled with quartz porphyry on Jyddö. The same feature is also seen in the many hornblende diabases in the eastern Åland archipelago.

The five olivine diabases — Märket, Säppi, Hankkila, Ämmänpelto and Moikipää — are regarded as Postjotnian from field observations and on petrographic criteria. They are some 300 Ma younger than the Subjotnian diabases of Åland. The results of palaeomagnetic measurements by Neuvonen (1965, 1966) and by Neuvonen and Grundström (1969) support the above concept.

Despite the obvious petrographic similarities between the olivine diabases studied, there are also some differences. For instance the mega-ophitic pegmatoidic varieties on Säppi and Moikipää have no counterparts in the Märket diabase.

The presence of baddeleyite does not prove the subsilicic character of these diabases, as is demonstrated by the free quartz in the Föglö diabase occurring together with baddeleyite.

The olivine diabases were emplaced at the same time as the similar olivine basalts in Sweden (CSDG = Central Scandinavian Dolerite Group) (Gorbatschev et al. 1979, 1985, 1987), in the Nordingrå area (Welin and Lundqvist 1975, 1984) and in other areas in northern central Sweden (Patchett 1978). The openings that extended to the mantle during this world-wide thermal pulse also resulted in the formation of the Gardar dykes in Greenland, and the Mackenzie and Sudbury dyke swarms in Canada (Van Schmus 1975, Patchett et al. 1978, LeCheminant and Heaman 1989).

The various diabase dyke swarms in the Åland area have a subparallel trend of N 20—40° E.

The Fennoscandian shield had dilated repeatedly in the directions in which the diabases of different ages now trend. The dilation in this direction was also active at the time the feeding channels of the granitic intrusions opened, as interpreted by Hausen (1964), at the eastern contact of the Åland rapakivi. In the course of gravimetric studies, Laurén (1970) was able to establish the same direction for the feeding channels of the Åland rapakivi. Edelman (1960) had already pointed out that the almost straight line on which the postorogenic granites lie is subparallel to the eastern contact of the Åland rapakivi area. Further to the north-northeast the two rapakivi granites of Vehmaa and Laitila lie close to this line. The hornblende diabase dykes in the eastern archipelago of Åland and the pyroxene diabase dykes of Föglö and Korsö trend in the same direction (see Fig. 62).

The Siipyy rapakivi granite intrusion lies close to the junction of the extensions of the NNE-trending Åland and WNW-trending Häme diabase swarms. Although there seems to be spatial tectonic control, there is a temporal difference of about 100 Ma between Häme and Åland diabase swarms.

The aeromagnetic map of Finland reveals a clear magnetic anomaly line trending in the same direction as the dykes discussed here. It can be followed southwestwards for 250 km as a smoothly curving line from west of the city of Tampere to east of the Fjälskär rapakivi stock and to the Kökarsfjärden rapakivi pluton. The Subjotnian intrusions are bounded by a major deep crustal fracture, and the anomaly line lies parallel to the strike of most of the Subjotnian diabase dykes in southwestern Finland. The rapakivi intrusions of Kökarsfjärden, Fjälskär, Peipohja, Kustavi-Vehmaa and Laitila-Eurajoki lie on a line parallel to the same aeromagnetic anomaly. The postorogenic granite intrusions in the Åland islands lie close to it, too. Parkkinen and Huomo (1978) verified deep early or syntectonic fractures trending in this same direction in the Wiborg rapakivi area.

The repeated dilation caused by tension or a shearing couple in the cratonic crust took place pulsewise over a long period, activating the same zone, as demonstrated by the diabase intrusions of different ages. However, according to the results of palaeomagnetic measurements, the Subjotnian poles from Finland and Sweden lie close to each other, indicating that there has been no major lateral displacement between these blocks since Subjotnian time (Neuvonen 1986). The contemporaneous intrusions of diabase, quartz porphyry and other rocks are now more readily attributed to repeated dilations in the same directions and zones. The magmas could have developed, and probably did so, at different depths.

Some of the fracture lines are known to continue through the Fennoscandian shield (e.g. Strömberg 1978). The repeated crushing and solidification of fault gouge in crushed zones of bedrock in the walls of the Päijänne tunnel in southern Finland is one more manifestation of movements in the same directions and zones (Suominen 1985). Ploegsma (1989) reports a 1533 ± 23 Ma biotite age for the Suomusjärvi ultramylonite. E. Jäger and F. Pipping (in prep.) have compiled a Rb-Sr mineral isochron of 1318 ± 54 Ma for a hydrothermally altered rock (biotite, zeolite and authigenic K-feldspar) from one of these fracture lines north of Helsinki.

The lower intercept ages listed in Table 18 are divided into groups. Whether by accident or not, the gabbros show high lower intercept ages corresponding to the Eocambrian; the coherent age group for the synorogenic granodiorites would be Silurian and the »normal» 250 Ma for the granites would be Permian. The coherent Cretaceous group for the rocks of the Wiborg rapakivi area is worthy of note. The lower intercept ages listed by Vaasjoki et al. (1989) from the Wiborg rapakivi show that the most mafic rapakivi variety, tirilite, has the highest lower intercept; two of the listed rapakivis have values similar to the normal ones in the western Finnish rapakivis, but most of the values are close to zero.

Table 18. Upper and lower intercept ages (Ma), number of mineral fractions analysed (N), and reference to the Figure No. of rock formations in this study.

Sample	Location	Rock type	N	Fig.	Upper	Lower
A562	Märket, Eckerö	diabase	4	4	1265±6	324±87
A784	Säppi I, Luvia	diabase	3	10	1264±12	317±193
A785	Säppi II, Luvia	diabase	3	10	1264±12	317±193
A786	Säppi III, Luvia	diabase	3	10	1264±12	317±193
A975	Hankkila, Eurajoki	diabase	5	11	1258±13	384±307
A974	Ämmänpelto, Kauttua	diabase	1	11	-	-
A731	Svall, Korsnäs	diabase	2	13	-	-
A732	Norrgrynnan I, Korsnäs	diabase	7	13	1268±13	190±118
A733	Norrgrynnan II, Korsnäs	diabase	1	13	-	-
A658	Bergskär, Föglö	diabase	11	17	1540±12	436±47
A793	Källsholm, Föglö	diabase	8	17	1577±12	384±85
A371	Vidskär, Föglö	diabase	1	17	-	-
A792	Västersten, Hammarland	anorthosite	1	17	-	-
A796	Höggrund, Eckerö	anorthosite	1	17	-	-
A714	Källholm, Åva, Brändö	quartz porphyry	7	23	1576±13	291±155
A715	Blåklobb, Eckerö	quartz porphyry	11	20	1574±6	106±81
A716	Hammarudda, Hammarland	quartz porphyry	6	21	1571±9	186±150
A717	Jyddö, Föglö	quartz porphyry	7	22	1571±20	-
A467	Böle, Eckerö	rapakivi	11	25	1560±14	23±74
A295	Vabbängarna, Eckerö	rapakivi	5	25	1575±11	198±113
A762	Godby, Finström	rapakivi	11	27	1575±6	121±53
A764	Getabergen, Geta	rapakivi	7	29	1576±9	203±101
A763	Åsbacka, Saltvik	rapakivi	2	27	-	-
A468	Långnäs, Lumparland	rapakivi	9	31	1568±10	253±111
A441	Söderharun, Kökar	rapakivi	6	32	1574±14	156±44
A287	Fjärdskär, Houtskär	rapakivi	6	34	1579±13	229±83
A129	Peipohja, Kokemäki	rapakivi	7	35	1573±20	119±104
A029	Muurikkala, Miehikkälä	rapakivi	7	38	1633±5	75±56
A791	Ylijärvi, Ylämaa	rapakivi	2	38	-	-
A119	Ylijärvi, Ylämaa	anorthosite	3	38	-	-
A323	Hamina	quartz porphyry	10	39	1617±3	51±35
-	Salmi I, USSR	rapakivi	5	41	1539±11	109±183
-	Salmi II, USSR	rapakivi	4	41	1539±11	109±183
A440	Ytterklobb, Lemland	granite	5	42	1770±2	208±14
A334	Getören, Brändö	granodiorite	6	43	1799±13	258±158
A335	Åva, Brändö	granite	5	43	1803±10	237±37
A901	Kumlingeby, Kumlinge	granite	3	44	1840±4	313±8
A322	Mattnäs, Nauvo	granite	11	45	1842±31	219±50
A064a	Kakola, Turku	granite	10	48	1832±11	242±92
A055	Kistola, Muurla	granite	2	49	1829±14	158±32
A399	Kistola, Muurla	granite	3	49	1829±14	158±32
A389	Haarla, Perniö	granite	3	50	1840±8	248±22
A390	Pungböle, Kemiö	granite	9	50	1840±8	248±22
A997	Tammo, Parainen	granite	4	51	1829±3	251±14
A875	Märaskär, Hanko	granite	3	52	1830±10	142±20
A876	Tulludden, Hanko	granite	8	52	1824±38	263±112
A498	Kakskerta, Turku	granodiorite	7	53	-	-
A920	Kittuis, Houtskär	granodiorite	4	53	1862±6	431±106
A822	Västerhamnen, Brändö	tonalite	6	55	1862±3	425±58
A879	Håkonsnäs, Kökar	granite	5	56	1878±13	243±41
A880	Mörskär, Kökar	granite	4	57	1881±8	271±52
A998	Alvik, Karlby, Kökar	gabbro	5	58	1881±6	552±95
A877	Svartgrund, Föglö	gabbro	7	59	1891±11	663±22
A560	Bockholm, Kumlinge	granodiorite	4	61	1882±15	412±74
A563	Algersö, Föglö	granodiorite	5	61	1899±8	415±86

One explanation for these ages might be that given by the interpretation model of Wielens (1979) for the lower intercept ages of Proterozoic formations in southwestern Norway, which were affected by a moderate increase in temperature due to the Caledonian orogenesis. The uplift dilation model of Goldich and Mudrey (1975), however appears to offer an even better explanation, namely, that the episodic loss of lead from zircons is due to movements in the cratonic crust, in this case, at the times shown by the lower intercept ages. Pidgeon (1990) points out that if the lower intercept is significantly greater than zero (in this study all but Böle) it could indicate an isotopic disturbance at that time. In one case, he could verify with fission track dating that the lower intercept age had a corresponding geological event. Alternatively the positive lower intercepts could be due to a number of small disturbances in the zircon U-Pb isotopic systems at different times and thus have no geological significance (Pidgeon 1990). Gebauer and Grünenfelder (1976) could verify with the Rb-Sr whole rock method of low-grade metamorphic rocks that metamict zircons anneal at temperatures as low as 300°C, or even lower. They discuss the phenomena even for old shield areas where discordant lower intercepts might date a geological event, ending the discussion with »in any case, strongly metamict zircons seem to be able to respond to events wich cannot be detected by other standard minerals used in geochronology».

Although only tentative, the lower intercept ages in Table 18 could support the assumption of Hausen (1948) and Edelman (1949) that the long, continuous fracture lines in the Finnish archipelago mark the boundaries of blocks tilted and lifted to different levels during several episodes from the Eocambrian to the Quaternary. Ordovician limestone on the bottom of the bay of Lumparn has been preserved in a graben postdating sedimentation. Dating these events would give us a more detailed picture of the evolution of the crust in southwestern Finland.

CONCLUSIONS

The results of this study can be summarized as follows:

1. During Middle Proterozoic time the crust in southwestern Finland was under tension in repeated pulses as shown by the Subjotnian and Postjotnian intrusions and opening of the graben for Jotnian sediments. The age difference between the Postjotnian and Subjotnian diabases is ca. 300 Ma.

2. The olivine diabases in western Finland are all of the same Postjotnian age (1260 ± 10 Ma) within the limits of error.

3. The Subjotnian formations in the Åland area are close to each other in age (1575 ± 10 Ma). The pyroxene diabases and anorthosite seem to be contemporaneous with the rapakivi and quartz porphyry dykes of Åland.

4. Sample A295-Vabbängarna represents the hornblende-bearing, oldest phase and the A468-Långnäs the biotite-rich porphyritic youngest phase of the Åland rapakivi complex (cf. Vaasjoki 1977, Bergman 1986). The corresponding radiometric ages given in this study are 1576 ± 9 Ma (A295) and 1568 ± 10Ma (A468).

5. The western Finnish rapakivi intrusions are of the same age and coeval with the Swedish Nordingrå rapakivi. They are younger than the Wiborg rapakivi (1640 ± 10 Ma). The Salmi rapakivi (1540 ± 10 Ma) is younger than the western Finnish rapakivi intrusions, but the Ragunda rapakivi (1320 ± 30 Ma) is the youngest of all the Fennoscandian rapakivis.

6. No inherited Archaean zircons have been found in the rapakivi granites studied.

7. The postorogenic granite intrusions in the Åland islands clearly differ from the rapakivi granites in age, but the minor rapakivi granites of Bodom, Onas and Obbnäs are of the same age as the Wiborg rapakivi intrusions.

8. The late-orogenic granites in southwestern Finland are characterized by their monazite content and lack of titanite. They form a coherent age group of 1830 ± 10 Ma.

9. Pyroxene granodiorites are time markers (1862 ± 6 Ma) of the intraorogenic intrusions of the study area.

10. The synorogenic intrusions in southwestern Finland form an age group of 1880 ± 20 Ma within the limits of error.

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Appendix 1. Location of samples. The grid coordinates refer to the Finnish national grid.

No.	Location	Rock type	Map Sheet	Grid Coordinates
A029	Falin, Muurikkala, Miehikkälä	rapakivi	3044 02	6725.40-3547.60
A055	Kistola, Muurla	granite	2021 11	6693.30-2458.55
A064a	Kakola, Turku	granite	1043 09	6704.28-1568.74
A119	Ylijärvi, Ylämaa	anorthosite	3133 01	6740.20-3546.50
A129	Peipohja, Kokemäki	rapakivi	1134 12	6793.82-1570.04
A287	Fjärdskär, Houtskär	rapakivi	1041 07	6689.80-1520.86
A295	Vabbängarna, Eckerö	rapakivi	1012 03	6677.97-1420.86
A322	Mattnäs, Nauvo	granite	1034 03	6670.34-1544.20
A323	Hamina	quartz porphyry	3042 04	6719.10-3509.80
A334	Getören, Brändö	granodiorite	1041 03	6758.00-1502.70
A335	Åva, Brändö	granite	1041 03	6706.40-1503.30
A371	Vidskär, Föglö	diabase	1013 06	6646.55-1474.09
A389	Haarla, Perniö	granite	2012 12	6677.40-2450.96
A390	Pungböle, Kemiö	granite	2012 03	6679.74-2424.34
A399	Kistola, Muurla	granite	2021 11	6693.30-2458.55
A440	Ytterklobb, Lemland	granite	1012 07	6655.52-1446.81
A441	Söderharun, Kökar	rapakivi	1013 12	6645.12-1490.00
A467	Böle, Eckerö	rapakivi	1021 01	6670.30-1421.96
A468	Långnäs, Lumparland	rapakivi	1014 02	6667.34-1461.21
A498	Naula-ahde, Kakskerta, Turku	granodiorite	1043 08	6694.37-1565.12
A560	Bockholm, Kumlinge	granodiorite	1023 07	6689.96-1488.38
A562	Märket, Eckerö	diabase	0043 07	6688.20-0562.80
A563	Algersö, Föglö	granodiorite	1014 04	6657.35-1479.52
A658	Bergskär, Föglö	diabase	1014 04	6657.31-1478.85
A714	Källholm, Åva, Brändö	quartz porphyry	1041 03	6702.65-1500.30
A715	Blåklobb, Eckerö	quartz porphyry	1012 15	6672.98-1418.46
A716	Hammarudda, Hammarland	quartz porphyry	1012 05	6665.07-1431.68
A717	Jyddö, Föglö	quartz porphyry	1014 05	6665.00-1473.29
A731	Svall, Korsnäs	diabase	1242 03	6978.07-1500.26
A732	Norrgrynnan I, Korsnäs	diabase	1242 03	6978.47-1500.72
A733	Norrgrynnan II, Korsnäs	diabase	1242 03	6978.50-1500.74
A762	Godby, Finström	rapakivi	1021 07	6681.00-1443.58
A763	Åsbacka, Saltvik	rapakivi	1021 07	6686.73-1442.18
A764	Getabergen, Geta	rapakivi	1021 05	6697.65-1436.55
A784	Säppi I, Luvia	diabase	1141 05	6818.84-1518.10
A785	Säppi II, Luvia	diabase	1141 05	6818.85-1518.14
A786	Säppi III, Luvia	diabase	1141 05	6818.87-1518.18
A791	Ylijärvi, Ylämaa	rapakivi	3133 01	6740.15-3546.60
A792	Västersten, Hammarland	anorthosite	1012 02	6668.91-1424.87
A793	Källsholm, Föglö	diabase	1014 04	6659.50-1479.37
A796	Höggrund, Eckerö	anorthosite	0043 10	6683.05-0574.80
A822	Västerhamnen, Brändö	tonalite	1024 11	6722.65-1492.28
A875	Märaskär, Hanko	granite	2011 08	6634.27-2442.50
A876	Tulludden, Hanko	granite	2011 05	6633.44-2439.10
A877	Svartgrund, Föglö	gabbro	1011 09	6645.02-1446.41
A879	Håkonsnäs, Kökar	granite	1013 12	6643.43-1494.83
A880	Käringen, Mörskär, Kökar	granite	1031 01	6628.67-1508.61
A901	Kumlingeby, Kumlinge	granite	1023 07	6685.04-1486.94
A920	Kittuis, Houtskär	granodiorite	1032 09	6676.08-1523.45
A974	Ämmänpelto, Kauttua	diabase	1134 07	6776.73-1562.19
A975	Hankkila, Eurajoki	diabase	1132 11	6787.78-1532.28
A997	Bockholm, Tammo, Parainen	granite	1034 11	6669.20-1573.70
A998	Alvik, Karlby, Kökar	gabbro	1013 12	6646.44-1492.38

Appendix 2. Main minerals of the samples studied.

Pl = plagioclase, Kf = K-feldspar, Qu = quartz, Ol = olivine, cp = clinopyroxene, op = orthopyroxene, Bi = biotite, Hb = hornblende, Ma = magnetite, G = garnet, I = ilmenite, Co = cordierite.
M major, m minor, s secondary, + accessory, - not present, tr traces.

No	Location	Rock type	Pl	Kf	Qu	Ol	cp	op	Bi	Hb	Ma	G	I	Co
A562	Märket	diabase	M	-	+	m	M	-	+	s	m	-	m	-
A784	Säppi I	diabase	M	-	+	-	M	-	+	s	m	-	m	-
A785	Säppi II	diabase	M	-	+	-	M	-	+	s	m	-	m	-
A786	Säppi III	diabase	M	-	+	-	M	-	+	s	m	-	m	-
A975	Hankkila	diabase	M	-	+	m	M	-	+	s	m	-	m	-
A974	Ämmänpelto	diabase	M	-	+	+	M	-	+	s	m	-	m	-
A731	Svall	diabase	M	-	+	-	M	m	+	s	m	-	m	-
A732	Norrgrynnan I	diabase	M	-	+	-	M	m	+	s	m	-	m	-
A733	Norrgrynnan II	diabase	M	-	+	-	M	m	+	s	m	-	m	-
A658	Bergskär	diabase	M	-	+	tr	M	-	+	s	m	-	m	-
A793	Källsholm	diabase	M	tr	+	tr	M	-	+	s	m	-	m	-
A371	Vidskär	diabase	M	-	+	tr	M	+	+	s	m	-	m	-
A792	Västersten	anorthosite	M	-	+	-	M	-	+	m	m	-	m	-
A796	Höggrund	anorthosite	M	-	+	-	M	-	+	m	m	-	m	-
A714	Källholm, Åva	quartz porphyry	m	M	M	-	-	-	m	-	+	-	-	-
A715	Blåklobb	quartz porphyry	m	M	M	-	-	-	m	-	+	-	-	-
A716	Hammarudda	quartz porphyry	m	M	M	-	-	-	m	-	+	-	-	-
A717	Jyddö	quartz porphyry	m	M	M	-	-	-	m	-	+	-	-	-
A467	Böle	rapakivi	m	M	M	-	-	-	M	m	+	-	-	-
A295	Vabbängarna	rapakivi	m	M	M	-	-	-	+	+	+	-	-	-
A762	Godby	rapakivi	m	M	M	-	-	-	+	+	+	-	-	-
A763	Åsbacka	rapakivi	m	M	M	-	-	-	m	+	+	-	-	-
A764	Getabergen	rapakivi	m	M	M	-	-	-	+	+	+	-	-	-
A468	Långnäs	rapakivi	M	M	M	-	-	-	M	m	+	-	-	-
A441	Söderharun	rapakivi	M	M	M	-	-	-	M	m	+	-	-	-
A287	Fjärdskär	rapakivi	m	M	M	-	-	-	+	-	+	-	-	-
A129	Peipohja	rapakivi	m	M	M	-	-	-	+	+	+	-	-	-
A029	Falin	rapakivi	m	M	M	-	-	-	+	+	+	-	-	-
A791	Ylijärvi	rapakivi	m	M	M	-	-	-	+	+	+	-	-	-
A119	Ylijärvi	anorthosite	M	-	+	-	-	-	+	+	+	-	-	-
A323	Hamina	quart porphyry	m	M	M	-	-	-	+	+	+	-	-	-
-	Salmi I	rapakivi	m	M	M	-	-	-	+	+	+	-	-	-
-	Salmi II	rapakivi	m	M	M	-	-	-	m	+	+	-	-	-
A440	Lemland	granite	M	M	M	-	-	-	M	-	+	-	-	-
A334	Getören, Åva	granodiorite	M	M	m	-	-	-	M	M	+	-	-	-
A335	Åva	granite	M	M	M	-	-	-	M	m	+	-	-	-
A901	Kumlingeby	granite	m	M	M	-	-	-	m	-	+	+	-	-
A322	Mattnäs	granite	m	M	M	-	-	-	m	-	+	+	-	-
A64a	Kakola	granite	M	M	M	-	-	-	m	-	+	m	+	m
A55	Kistola	granite	M	M	M	-	-	-	m	-	+	+	-	-
A399	Kistola	granite	M	M	M	-	-	-	m	-	+	+	-	-
A389	Haarla	granite	M	M	M	-	-	-	m	-	+	+	-	-
A390	Pungböle	granite	M	M	M	-	-	-	m	-	+	+	-	-
A997	Tammo	granite	M	M	M	-	-	-	+	+	+	+	-	-
A875	Märaskär	granite	M	M	M	-	-	-	+	+	+	+	-	-
A876	Tulludden	granite	M	M	M	-	-	-	+	+	+	+	-	-
A498	Kakskerta	granodiorite	M	M	M	-	+	m	m	+	+	-	-	-
A920	Kittuis	granodiorite	M	M	m	-	+	m	+	+	+	-	-	-
A822	Västerhamnen	tonalite	M	+	M	-	+	-	m	M	+	M	-	-
A879	Håkonsnäs	granite	M	M	M	-	-	-	+	+	+	-	-	-
A880	Mörskär	granite	M	M	M	-	-	-	m	+	+	-	-	-
A998	Alvik	gabbro	M	-	+	-	tr	-	+	m	+	-	-	-
A877	Svartgrund	gabbro	M	-	+	-	tr	-	m	M	+	-	-	-
A560	Bockholm	granodiorite	M	M	M	-	-	-	+	m	+	-	-	-
A563	Algersö	granodiorite	M	M	M	-	-	-	+	m	+	-	-	-

Appendix 3. Characteristic accessory minerals of the samples studied.

Z = zircon, B = baddeleyite, T = titanite, A = anatase, R = rutile, Mo = monazite, F = fluorite, Ml = molybdenite, G = galena, Fl = fluocerite, Ba = bastnaesite, C = columbite, Ap = apatite, To = topaz, U = uraninite,
M major, m minor, + traces, - not present.

No.	Location	Rock type	Z	B	T	A	R	Mo	F	Ml	G	FL	Ba	C	Ap	To	U
A562	Märket	diabase	M	m	+	-	-	-	-	-	-	-	-	-	M	-	-
A784	Säppi I	diabase	M	m	-	-	-	-	-	-	-	-	-	-	M	-	-
A785	Säppi II	diabase	M	m	-	-	-	-	-	-	-	-	-	-	M	-	-
A786	Säppi III	diabase	M	m	-	-	-	-	-	-	-	-	-	-	M	-	-
A975	Hankkila	diabase	M	m	-	-	-	-	-	-	-	-	-	-	M	-	-
A974	Ämmänpelto	diabase	m	M	-	-	-	-	-	-	-	-	-	-	M	-	-
A731	Svall	diabase	m	M	-	-	-	-	-	-	-	-	-	-	M	-	-
A732	Norrgrynnan I	diabase	M	m	-	-	-	-	-	-	-	-	-	-	M	-	-
A733	Norrgrynnan II	diabase	m	M	-	-	-	-	-	-	-	-	-	-	M	-	-
A658	Bergskär	diabase	M	m	-	-	-	-	-	-	-	-	-	-	M	-	-
A793	Källsholm	diabase	M	m	-	-	-	-	-	-	-	-	-	-	M	-	-
A371	Vidskär	diabase	+		-	-	-	-	-	-	-	-	-	-	M	-	-
A792	Västersten	anorthosite	m	m	-	-	-	-	-	-	-	-	-	-	M	-	-
A796	Höggrund	anorthosite	+		-	-	-	-	-	-	-	-	-	-	m	-	-
A714	Källholm, Åva	quartz porphyry	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A715	Blåklobb	quartz porphyry	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A716	Hammarudda	quartz porphyry	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A717	Jyddö	quartz porphyry	M	-	-	-	-	-	-	+	-	-	-	-	-	-	-
A467	Böle	rapakivi	M	-	-	+	-	-	M	-	-	-	-	-	+	-	-
A295	Vabbängarna	rapakivi	M	-	-	-	-	-	M	+	+	-	-	-	M	-	-
A762	Godby	rapakivi	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A763	Åsbacka	rapakivi	M	-	-	+	-	-	M	m	-	+	+	-	+	-	-
A764	Getabergen	rapakivi	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A468	Långnäs	rapakivi	M	-	-	-	-	-	+	-	-	-	-	-	-	-	-
A441	Söderharun	rapakivi	M	-	-	-	-	-	m	+	+	-	-	-	+	-	-
A287	Fjärdskär	rapakivi	M	-	-	-	-	-	M	+	+	+	+	+	+	M	-
A129	Peipohja	rapakivi	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A029	Falin	rapakivi	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A791	Ylijärvi	rapakivi	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A119	Ylijärvi	anorthosite	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A323	Hamina	quartz porphyry	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	Salmi I	rapakivi	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	Salmi II	rapakivi	M	-	-	-	-	-	-	-	-	-	+	-	-	-	-
A440	Lemland	granite	M	-	M	-	-	-	-	-	+	-	-	-	+	-	-
A334	Getören, Åva	granodiorite	M	-	m	-	-	-	+	-	-	-	-	-	+	-	-
A335	Åva	granite	M	-	m	-	-	-	+	-	-	-	-	-	+	-	-
A901	Kumlingeby	granite	m	-	-	-	-	m	-	+	-	-	-	-	-	-	m
A322	Mattnäs	granite	M	-	-	-	m	m	-	-	-	-	-	-	m	-	-
A64a	Kakola	granite	M	-	-	+	m	M	-	-	-	-	-	-	m	-	-
A55	Kistola	granite	M	-	-	-	m	m	-	-	-	-	-	-	-	-	-
A399	Kistola	granite	M	-	-	+	+	m	-	-	-	-	-	-	-	-	-
A389	Haarla	granite	M	-	-	-	-	m	-	-	-	-	-	-	-	-	-
A390	Pungböle	granite	M	-	-	-	-	m	-	-	m	-	-	-	+	-	-
A997	Tammo	granite	M	-	-	-	-	m	-	-	-	-	-	-	-	-	-
A875	Märaskär	granite	M	-	-	-	-	m	-	-	-	-	-	-	-	-	-
A876	Tulludden	granite	M	-	-	-	-	m	-	-	+	-	-	-	-	-	-
A498	Kakskerta	granodiorite	M	-	-	-	-	-	-	-	-	-	-	-	+	-	-
A920	Kittuis	granodiorite	M	-	+	-	-	m	-	+	-	-	-	-	M	-	-
A822	Västerhamnen	tonalite	M	-	+	+	-	-	-	-	-	-	-	-	M	-	-
A879	Håkonsnäs	granite	M	-	m	-	-	-	-	-	-	-	-	-	-	-	-
A880	Mörskär	granite	M	-	m	-	-	+	-	-	-	-	-	-	+	-	-
A998	Alvik	gabbro	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A877	Svartgrund	gabbro	M	-	m	-	-	-	-	-	-	-	-	-	+	-	-
A560	Bockholm	granodiorite	M	-	m	-	-	-	-	-	-	-	-	-	-	-	-
A563	Algersö	granodiorite	M	-	m	-	-	-	-	-	-	-	-	-	-	-	-

Appendix 4. Locations of the Rb–Sr samples. The coordinates refer to the Finnish national grid.

Sample	Rock type	Location	Map sheet	Grid coordinates
	Diabase			
1212	olivine diabase	Sorkka, Eurajoki	1132 11	6787.8-1532.3
1215	diabase hybrid	Sorkka, Eurajoki	1132 11	6787.8-1532.3
1217	olivine diabase	Kiperinoja, Eura	1134 07	6774.6-1562.3
1231	olivine diabase	Vaasa archipelago	1313 10 - 1242 03*	
1208	pyroxene diabase	Tvigoskär, Föglö	1014 04	6654.6-1477.6
1198	hornblende diabase	Börsskär, Kumlinge	1023 10	6686.4-1490.7
1222	olivine diabase	Ansio, Padasjoki	2143 02	6815.0-1549.2
1221	olivine diabase	Tuomasvuori, Padasjoki	2143 07	6806.7-2569.3
1228	olivine diabase	Heinola	3112 12	6794.4-3450.5
1229	olivine diabase	Lovasjärvi, Hakosaari (A574)	3132.02	6783.0-3507.9
	Rapakivi of Åland			
2	even-grained	Högbergen, Hammarland	1012 06	6673.50-1432.90
5	pyterlite	Böle, Eckerö (A467)	1021 01	6680.81-1421.86
12	wiborgite	Prästö I, Sund	1021 12	6677.81-1459.82
17	porphyritic	Långnäs (A468)	1014 02	6667.34-1461.21

* The Vaasa archipelago sample is composed of drill core samples, for sites see Neuvonen (1966).

Appendix 5. Additional data for samples A 489 and A920.

Table 14. (continued)

Sample No.	Fraction[1] d=density, g/cm³ Ø=grain size, μm	Concentration μg/g ^{238}U	^{206}Pb radiog.	$^{206}Pb/^{204}Pb$ measured	Isotopic composition of lead, ^{206}Pb = 100: 204	207	208	Atomic ratios and radiometric ages, Ma: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A498-Naula-ahde, Kakskerta, Turku: pyroxene granodiorite										
A498F	4.2<d<4.6	613.3	147.38	1837	.05088	11.963	7.646	.2777	4.316	.11273
	abr							± 15	± 24	± 10
	clear, stubby							1579	1696	1843
G	4.2<d<4.6; abr	1051	284.51	3625	.02651	11.579	5.461	.3130	4.841	.11219
	long, light brown							± 16	± 26	± 6
								1755	1792	1835
H	d>4.2; abr	985.7	265.71	2914	.03309	11.670	5.681	.3116	4.820	.11221
	long							± 17	± 26	± 11
								1748	1788	1835
I	d>4.2; abr	796.0	185.00	1594	.05442	11.981	7.259	.2686	4.163	.11242
	clear, stubby							± 14	± 25	± 23
								1533	1666	1839
A920-Kittuis, Houtskär: pyroxene granodiorite										
A920E	4.3<d<4.6	472.8	132.89	9074	.007934	11.442	6.520	.3249	5.076	.11334
								± 18	± 28	± 9
								1813	1832	1853

For symbols, see Table 3.

Appendix 5. (continued)

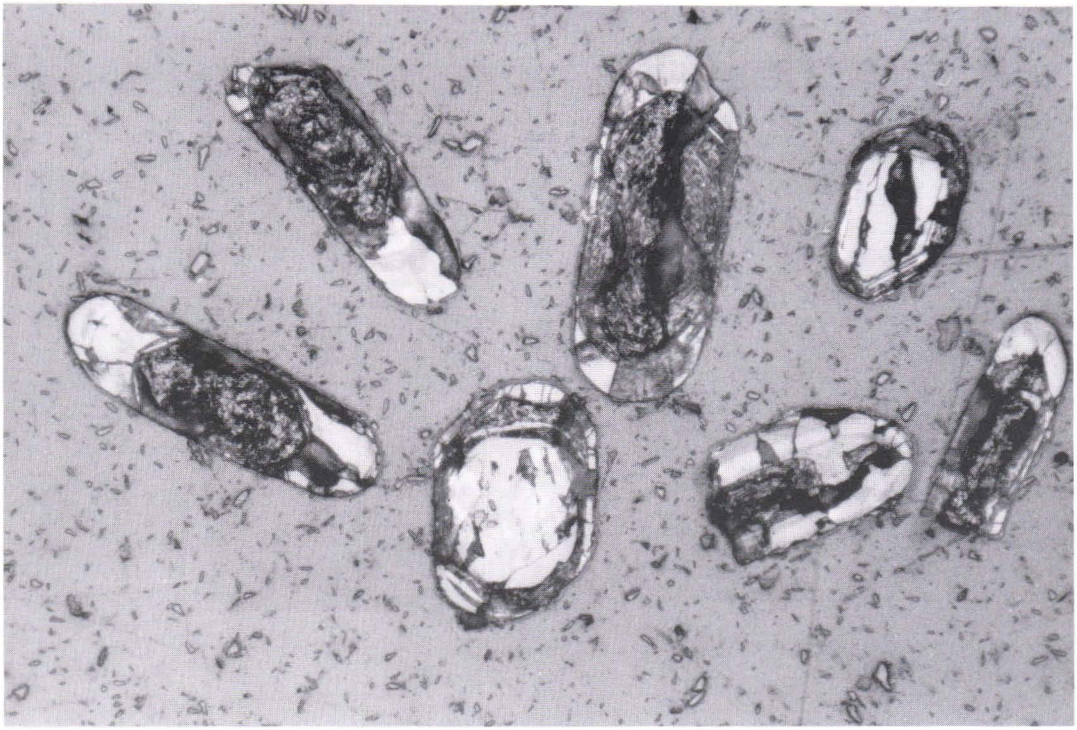

Fig. 1. Microphotograph of polished mounts of zircons from the Kakskerta pyroxene granodiorite (Sample A498). Zircons have been etched in HF vapour to highlight zoning. The longest zircons are about 200 µm. Reflected light. — Most zircons from this sample are light brown, clear, euhedral, elongate crystals. Several grains consist of metamict zircon cores surrounded by a owergrowth of clear zircon (fractions G and H on the concordia diagram (see Fig. 2 in Appendix 5). A minority of grains are colourless and stubby with somewhat rounded ends and show a high-U rim (fractions F and I on the concordia diagram). Some crystal are irregularly shaped.

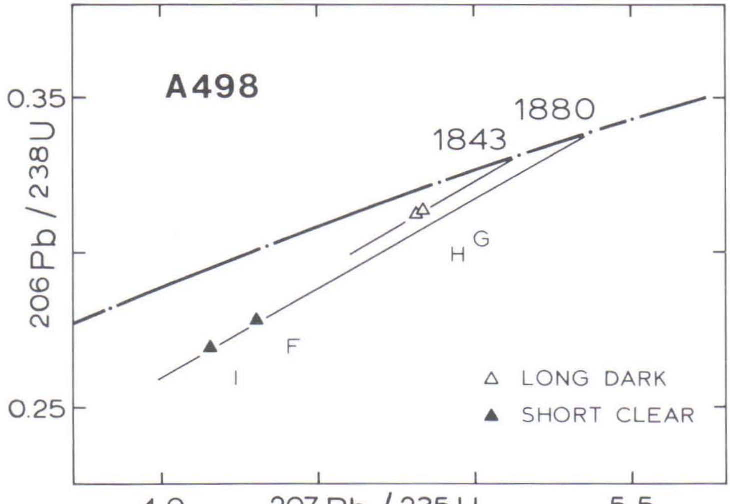

Fig. 2. Simplified enlargement of U-Pb concordia diagram given in Fig. 53 (p. 71) with two additional points H and I. The discordance paths are diffusion trajectories (Wasserburg 1963) and give the same age results as parallels with chord along the fractions A-E (Fig. 53). Open symbols refer to long, brown zircons; closed symbols to stubby colourless zircons. A critical question is whether the zircons analysed were formed during primary igneous crystallization or were formed during recrystalization. The simplest interpretation of the approximate chord through the stubby, transparent zircon points is that it records the age of primary crystallization ca. 1880 Ma ago. In making this interpretation it is necessary to conclude that the rock underwent high-grade metamorphism at 1843 Ma, indicated by abundance of long brown zircon.

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