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K-Ar AGES OF HORNBLENDE AND BIOTITE FROM LATE ARCHAEAN ROCKS OF EASTERN FINLAND — INTERPRETATION AND DISCUSSION OF TECTONIC IMPLICATIONS

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The K-Ar method of isotopic dating of biotite and hornblende was applied to ninety Late Archaean and four Palaeoproterozoic rock samples from eastern Finland. The aim was to establish a regionally significant data base of K-Ar dates for evaluating the Svecokarelidic tectonothermal impact on the Late Archaean basement of the foreland of the Svecokarelidic orogeny. The main findings to emerge from the data are: 1) The K-Ar ages of the biotites and hornblendes of the basement have been widely reset to 1795 ± 21 Ma and 1851 ± 41 Ma, respectively. 2) With a few exceptions, only rocks from granulite facies domains have retained, partially or completely, their Late Archaean K-Ar age signature; the rigidity and dryness of the granulitic rocks obviously prevented them from being easily reset (recrystallized). 3) The K-Ar data combined with our present understanding of Svecokarelidic tectonics indicate that mineral rejuvenation in the basement was caused by its deep burial under overthrust Svecokarelidic nappe units about 1900 Ma ago accompanied by heating of the basement sufficent to reset (recrystallize) biotite and, over extensive areas, hornblende, too. 4) The subsequent cooling of the basement through the diffusion-controlled closure temperatures of hornblende (500 °C) and biotite (300 °C) was integrated with the general, shield-wide postorogenic crustal cooling and uplift.

Key words (GeoRef Thesaurus, AGI): absolute age, K/Ar, hornblende, biotite, tectonics, metamorphism, isotherms, igneous rocks, metamorphic rocks, Archean, eastern Finland

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INTRODUCTION

The Archaean terrain of eastern Finland is bordered in the west by a major Palaeoproterozoic orogenic domain, the Svecokarelides (Simonen, 1980; Gaál & Gorbatschev, 1987). The magnitude of the tectonothermal effect of the 1900—1800 Ma Svecokarelidic orogeny on its Archaean foreland has long been a subject of controversy (e.g. Lavikainen, 1977; Pekkarinen, 1979, p. 16; Simonen, 1980, p. 19; Park & Bowes, 1983; Luukkonen, 1985, 1990; Papunen & Vorma, 1985, p. 129; Tuisku, 1988). As K-Ar mineral dates have been usefully applied to similar problems elsewhere (e.g. Hart, 1964; Harper, 1967; Stockwell, 1982; Ermanovics & Wanless, 1983; Harrison & McDougall, 1980; Anderson, 1988), a study group of the Petrological Department of the Geological Survey of Finland (GSF) in the Mid-Finland regional office set up a K-Ar project in 1985 with a view establishing an areally comprehensive K-Ar mineral age (hornblende, biotite) data base for the whole Archaean terrain of eastern Finland. It was hoped that with such a data base we would be able to delineate the dimensions and tectonic cause of the Svecokarelidic thermal impact on the Archaean basement.

Before this study only a few biotites from the Archaean rocks of eastern Finland had been dated with the K-Ar method. All these dates pointed to resetting at 1800—1700 Ma caused by the Svecokarelidic orogeny (Wetherill et al., 1962; Kouvo & Tilton, 1966). Only two K-Ar amphibole dates were available, both from rocks of the 2600 Ma old (zircon, U-Pb, Patchett et al., 1981) Siilinjärvi carbonatite complex. One on richterite yielding an age of 2530 Ma, and the other, on actinolite, an age of 2260 Ma (Puustinen, 1972).

Our preliminary results (Kallio et al., 1986; Kallio et al. 1987) indicated that not only Archaean biotites but also amphiboles were affected by the Proterozoic resetting of K-Ar systems, and that resetting was a regional feature covering essentially the entire Archaean terrain of eastern Finland. The biotites and hornblendes that have retained their Archaean Ar heritage partly or totally were observed mainly from granulite facies rocks indicating that metamorphic grade and from that dependent fluid content of rock clearly played an important role in determining the »blocking/opening temperature» for Ar loss from amphibole and biotite. This report summarizes the analytical results of the K-Ar project and looks briefly at the controlling factors and tectonic significance of the K-Ar ages obtained.

Throughout this paper we are speaking of biotite/hornblende K-Ar ages. Naturally the K-Ar mineral dates do not record igneous or metamorphic crystallization of rocks/minerals but rather their subsequent, sometimes much later cooling through certain temperatures at which the minerals became the last time closed to diffusion of the radiogenic Ar (see e.g. Faure, 1986; Mezger, 1990). The opening/blocking temperature for biotite is widely assigned to about 300 °C (e.g. Jäger, 1979; Mattinson, 1978; Harrison et al., 1985) and that of hornblende to 500 °C (e.g. Jäger, 1979; Harrison, 1981; Mattinson, 1982; Cliff, 1985).

The term »reset» is used thoroughout this paper without any genetic reference to the mechanism that caused the apparent rejuvenation of a given rock /mineral in terms of K-Ar age.

REGIONAL GEOLOGY

Southern Finland (Fig. 1) is composed of two major geological units 1) the Palaeoproterozoic Svecofennides in the west and 2) the Late Archaean greenstone — granite-gneiss terrain of the Karelia Province in the east. The western part of the Karelia Province, or Archaean/Karelian/Jatulian craton, with its metamorphosed and deformed Palaeoproterozoic, Jatulian and Kalevian, mainly metasedimentary cover rocks is often distinguished as the Karelides. The Svecofennides and Karelides together constitute that is known as the Svecokarelides (Simonen, 1980; Gaál & Gorbatschev, 1987; Gaál, 1990).

The Svecofennidic belt formed for most part between 1960 and 1880 Ma ago, most probably by accretion of, and subsequent rapid recycling at, volcanic-plutonic arcs from mantle derived materials (Patchett et al., 1981; Huhma, 1986; Gaál & Gorbatschev, 1987; Gaál, 1990). A general tectonic scenario very similar to that for the Svecofennides appears to apply to the Late Archaean terrain of eastern Finland, the bulk of which formed 2800—2700 Ma ago (Bibikova, 1984; Piirainen, 1988; Gaál & Gorbatschev, 1987), but which also contains older rocks (>3.1 Ga), at least in its western part (Paavola, 1986). The Archaean basement is thought to have been fully stabilized and cratonized before 2500 Ma (Gaál & Gorbatschev, 1987).

The domain of the Karelidic belt is considered to have been a site of continental break-up at 2100 Ma and subsequent passive margin deposition (Gaál, 1982; Gaál & Gorbatschev, 1987; Kontinen, 1987). The belt shows evidence of Svecokarelidic crustal shortening and related thrusting from the west as a consequence of docking of the early Svecofennian arcs to the passive margin about 1900 Ma ago (Park, 1985; Gaál, 1990). The large scale of the thrusting is revealed by the presence of ophiolitic material and rocks from the lower crust within the belt (Koistinen, 1981; Kontinen, 1987; Paavola, 1988). The tectonic impact of the 1900 Ma compression on the basement further to the east is not well known, although upright folding and faulting of locally preserved Palaeoproterozoic cover rocks in Soviet Karelia (e.g. Sokolov et al., 1970) indicate shortening to some extend by mechanisms like crustal-scale block faulting.

It is not only Svecokarelidic tectonism that has mauled the Karelia Province since its Late Archaean cratonization; the Belomorian orogenic movements in the east, and the Lapland granulite belt with the Belomorian belt of reworked Archaean gneisses as its main expressions, probably had a pronounced effect, too. The Belomorian orogeny, which in essence was collision of Archaean blocks of the Kola-White Sea area, probably occurred about 100—50 Ma before the Svecokarelidic orogeny (Barbey et al., 1984).

The time between 2500 and 2100 Ma was characterized by relative tectonic stability although even then the Karelia Province was periodically a site of continental rifting with intracratonic sedimentation and volcanism, manifested in the Sumi-Sariola deposits (Sokolov and Heiskanen, 1985; Strand, 1988; Luukkonen, 1990). We believe, however, that these events were associated with only locally increased heat flow and were thus unable to reset the K-Ar clocks of Archaean biotite and hornblende on a regional scale.

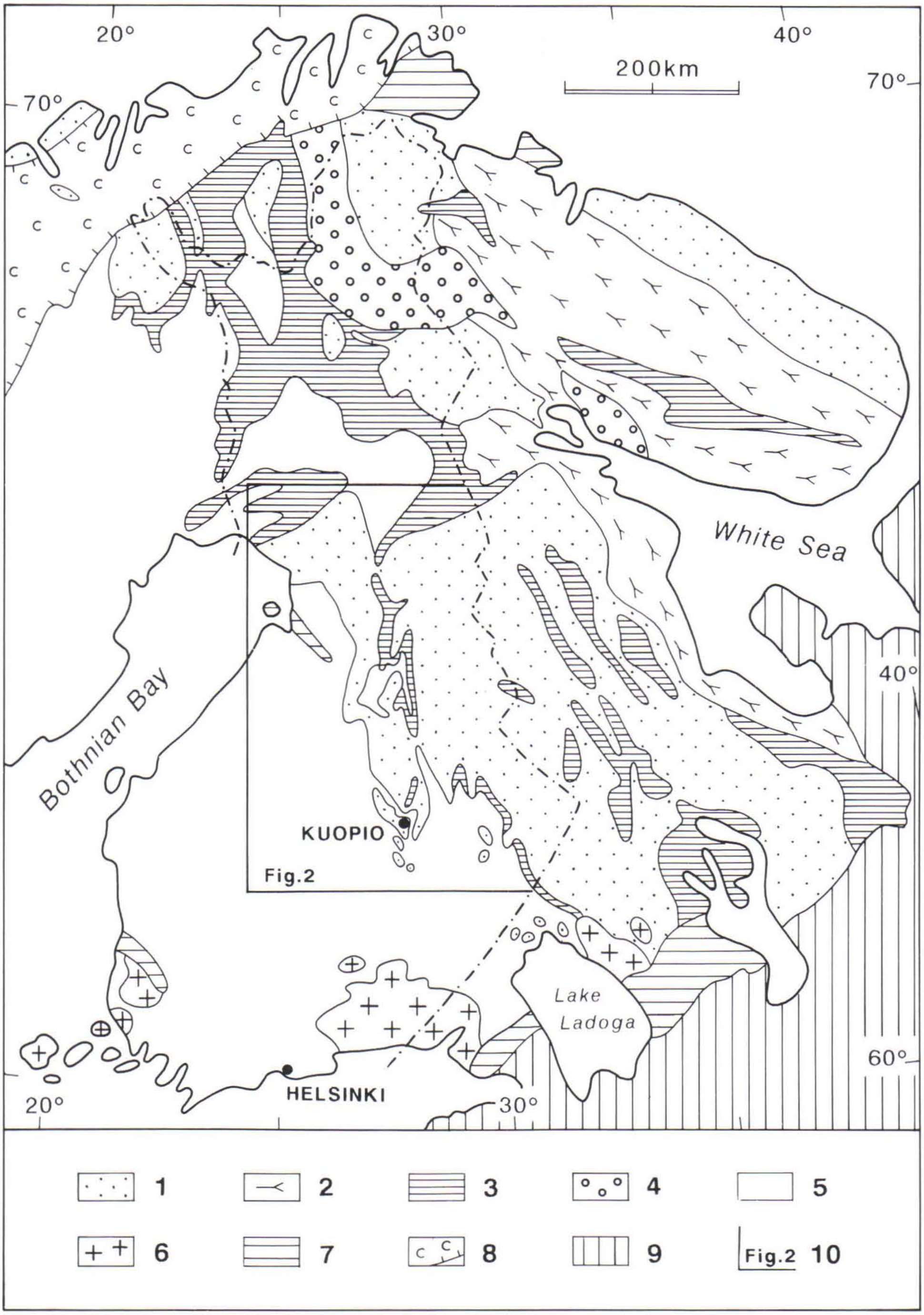

Fig. 1. Main geological units of the Baltic Shield. Modified after Gaál & Gorbatschev (1987), Gorbunov & Papunen (1985) and the Geological Map, Northern Fennoscandia (1987). Symbols: 1) Archaean gneiss-greenstone belts, 2) Belomorian gneisses, 3) Palaeoproterozoic cover of the Archaean basement: Sumi-Sariolan, Lapponian, Jatulian and Suisarian volcanic and sedimentary rocks (2.4—2.0 Ga), 4) Granulite belt of Lapland (2.0—1.9 Ga), Svecofennian supracrustal and plutonic rocks (1.93—1.78 Ga), 6) Rapakivi granites (1.7—1.54 Ga), 7) Meso/Neoproterozoic sedimentary rocks 8) Caledonides, 9) Phanerozoic sedimentary cover, 10) Area covered by Figs. 2—4.

SAMPLING

During this work samples were collected from 94 localities in various parts of eastern Finland (Fig. 2). Data on the sample locations and lithologies are given in Appendix 1. Homogeneous, quartz dioritic-tonalitic granitoids or homogenized, nebulous migmatites were preferred, although the large, geologically varied area of sampling forced us also to collect granodiorites, granites and amphibolites. For reference, some Proterozoic rocks were also sampled and analysed.

The map of the sampling localities (Fig. 2) shows that they did not uniformly cover the whole Archaean terrain of eastern Finland. This was mainly because the sampling was initially concentrated within two traverses across eastern Finland. A denser and more regular sampling network might have added some details, but it would obviously not have altered the main outcome.

Sampling of weathered rocks was studiously avoided. Thus most of the samples were taken from the outcrops by blasting or by hammer from blasted road cuttings. All the samples collected were studied in thin section under the microscope to asses their suitability for the separation of pure biotite and hornblende fractions.

The fractions were separated in the mineralogical laboratory of the GSF Mid-Finland Regional Office. Conventional methods, including crushing, sieving, density separation with heavy liquids and magnetic separation, were applied. The grade of the sieve fractions selected for biotite/hornblende concentration was typically between 0.125 and 0.250 mm. Hand picking was used as the final step to ensure pure monomineralic samples. XRD spectra for the separates indicated that a purity better than 98% was reached for nearly all the mineral concentrates analysed.

The analytical work was done under contract at Leeds University, England, under the supervision of Dr. D.C. Rex. The analytical methods are described by Rex & Dobson (1970) and Briden et al. (1979). All ages were calculated using the following constants: λ_β: 4.962 x $10^{-10}a^{-1}$, λ_e: 0.581 x $10^{-10}a^{-1}$, ^{40}K: 0.01167 atom. %.

RESULTS

The K-Ar analytical results are given in Table 1, and the respective sample localities in Fig. 2 and Appendix. Figs. 3 and 4 illustrate with pie diagrams the geographical distribution of the age data. Fig. 5 gives histograms of the age data, and shows that the majority of biotite ages obtained fall between 1850 and 1750 Ma. Forty-eight of the 68 biotite ages are within this range, the average being 1795 ± 21 Ma (1 σ). The distribution of the hornblende dates is more variable but is clearly concentrated between 1950 and 1750 Ma. Thirty of the 61 dates fall in this range, with an average of 1851 ± 41 Ma (1 σ).

Biotites with Archaean K-Ar ages (>2500 Ma) are rare and were found only in the Taivalkoski area, where four biotites had ages between 2496 and 2596 Ma. Hornblende ages of over 2500 Ma are from the Varpaisjärvi (2510—2776 Ma, n = 8) and Taivalkoski areas (2700—2705 Ma, n = 3) and the southeastern part of the Ilomantsi area (2612—2649 Ma, n = 2). Both the Varpaisjärvi (Paavola, 1984) and Taivalkoski areas (this work) are characterized by granulite facies metamorphism and subsequent exhuming of relatively deep, dry crust. The hornblende K-Ar ages suggest a Late Archaean age for the granulite facies metamorphism.

Both the Taivalkoski and Varpaisjärvi areas feature fault-bounded blocks of high-grade metamorphic rocks. These blocks are easily distin-

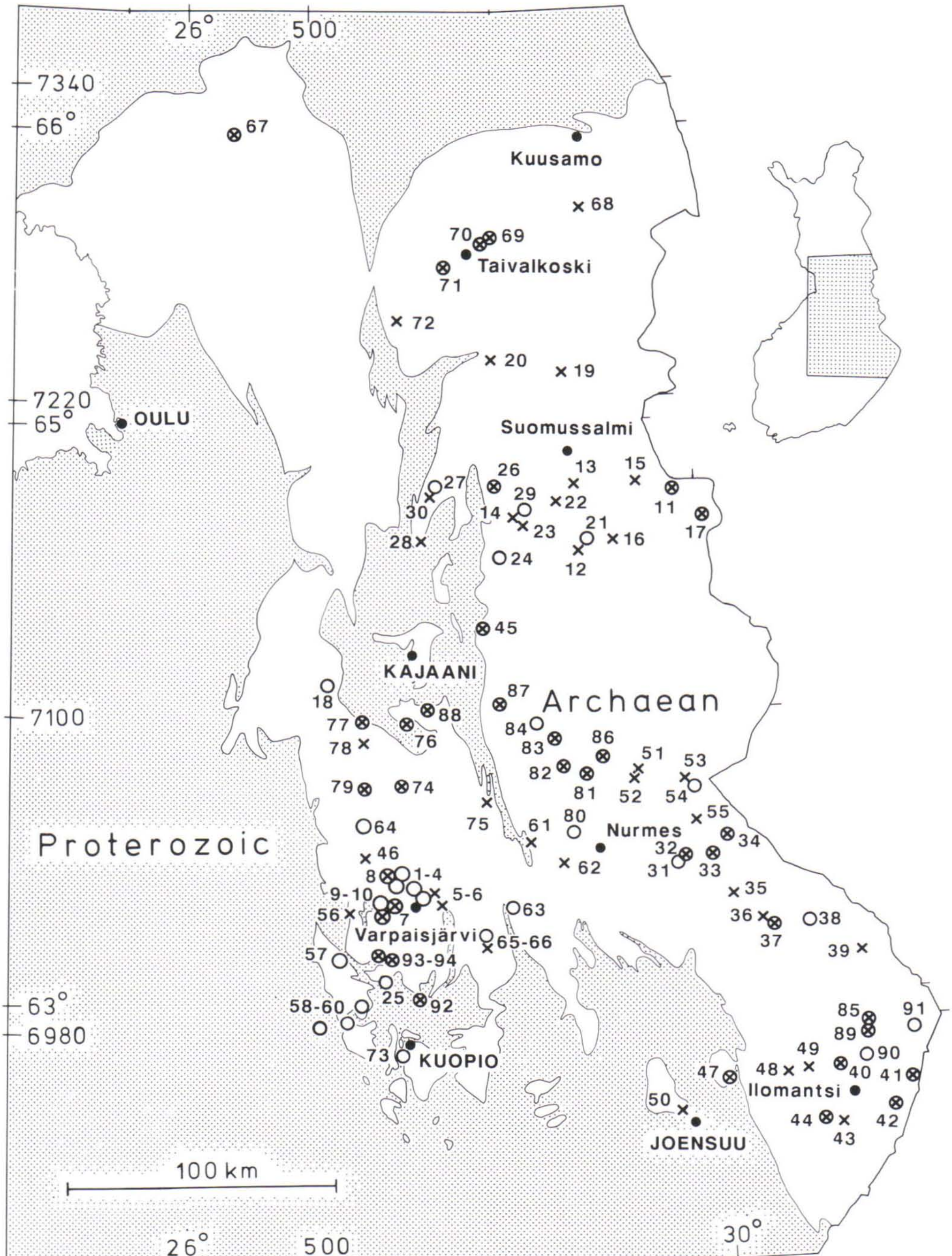

Fig. 2. Locations of the K-Ar dated samples. Sample numbers refer to table 1 and Appendix. Symbols: cross = biotite, circle = hornblende, crossed circle = biotite and hornblende. The Archaean-Proterozoic boundary after Luukkonen and Lukkarinen (1985) and Simonen (1980).

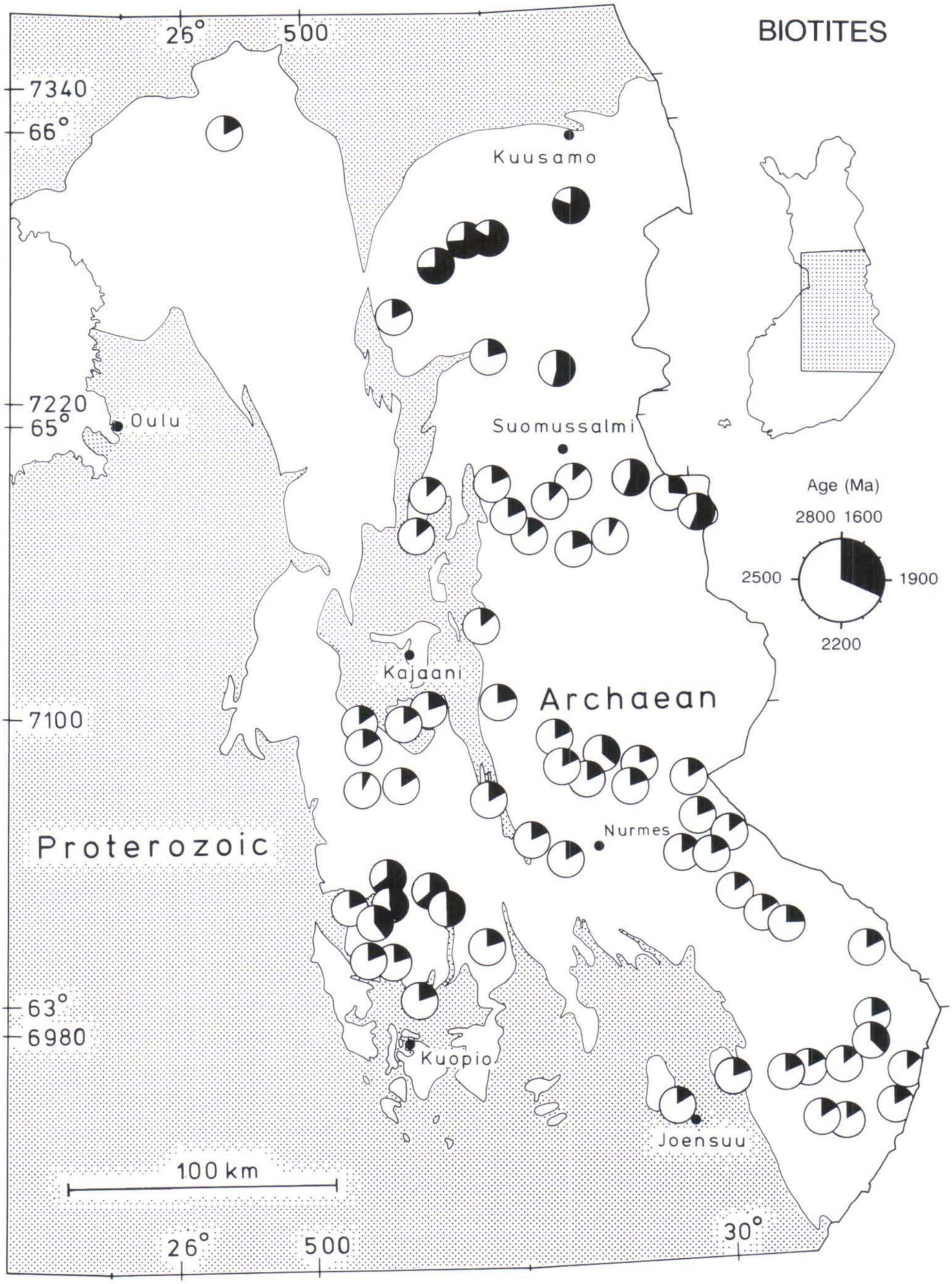

Fig. 3. The biotite K-Ar age distribution of Archaean rocks in eastern Finland.

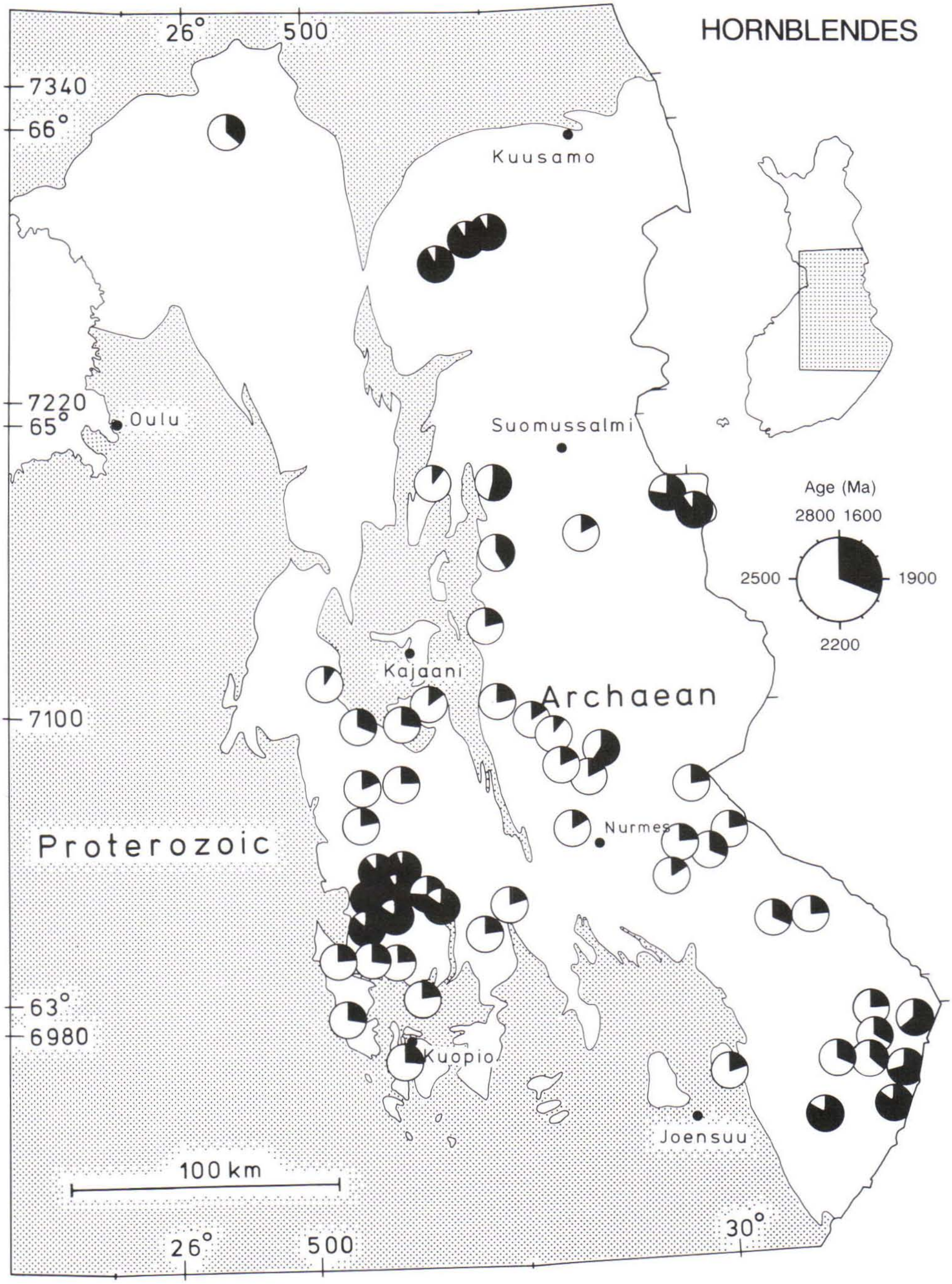

Fig. 4. The hornblende K-Ar age distribution of Archaean rocks in eastern Finland.

guished on aeromagnetic maps as domains of high magnetic response. Significantly, the Palaeoproterozoic diabase dykes within the high grade blocks are mostly anhydrous, olivine-pyroxene rocks (Matisto, 1958; Toivola, 1988), whereas the diabases of the same swarms outside the blocks exhibit epidote-amphibolite facies assemblages.

Most of the K-Ar and U-Pb (zircon) dates from the Varpaisjärvi area discussed here (Appendix) have already been published by Paavola (1986). Surprisingly, some of the K-Ar ages on hornblendes (2692—2510 Ma, n = 4) from the Varpaisjärvi enderbites are in the range of the zircon ages (2693—2682 Ma, n = 2) from the same rocks. The two enderbite biotites analysed yield an age of 2386—2387 Ma. Hornblendes of the quartz dioritic palaeosomes from the amphibolite facies gneisses flanking the Varpaisjärvi high grade block in the west exhibit similar K-Ar ages (2666—2632 Ma, n = 2) than the hornblendes from the high grade block, whereas zircons yield ages of 3095—3136 Ma (n = 2) with the U-Pb method. Hornblende K-Ar ages for the three granoblastic amphibolites (KA 003, 004 & 009) from the Varpaisjärvi area are in excess of 2.7 Ga (2747, 2710 & 2776 Ma), being the oldest K-Ar ages encountered in this study. Note that these samples come from melanocratic amphibolites, whereas the other Varpaisjärvi samples, like most of the other samples collected for this study, are from intermediate granitoids. The exceptionally high hornblende ages from the melanocratic amphibolites may reflect the influence of chemical factors, as the Mg/Fe ratios of the hornblendes, for example, are known to contribute to the Ar retention properties (Burwash et al., 1985; Deutsch & Steiger, 1985).

One sample (KA 017) from Suomussalmi, to the east of Vuokkijärvi, close to the Karelian border, also gives high K-Ar ages, for both hornblende (2677 Ma) and biotite (2284 Ma). Here, too, the high ages are clearly related to a high metamorphic grade, as verified by observations on two-pyroxene mafic gneisses from the Karelian side of the border (Beljajev et al., 1978). Like the Varpaisjärvi and Taivalkoski high-grade blocks, the Vuokkijärvi area is further characterized by a strong magnetic field and Palaeoproterozoic diabase dykes with primary minerals, e.g. well preserved olivine (Kilpelä, 1991).

The high hornblende ages from the Ilomantsi area are exceptional as they do not derive from high-grade, granulite facies metamorphic rocks. Furthermore, in contrast to those of the granulite blocks, the high hornblende ages in the Ilomantsi area are not associated with elevated biotite ages but the biotites are invariably reset close to the low 1800 Ma typical of the biotites dated in this study. In this context it is worth recalling that Lavikainen (1977) maintained that the biotite in Ilomantsi granitoids was largely Proterozoic. The aparent gradational zonation in the Ilomantsi hornblende ages, seen as younging from the Finnish-Karelian border towards the northwest (Fig. 7), is a unique feature not observed anywhere else in the study area.

Some of the biotite and hornblende ages obtained lie between the Archaean and Proterozoic clusters, as defined by the hornblende ages (Fig. 5). The situation is much the same as that in the Precambrian basement of the western Canada sedimentary basin, Churchill Province, as reported by Burwash et al. (1962). There, too, the K-Ar ages form two peaks: Kenoran (2500 Ma) and Hudsonian (1800 Ma). Burwash et al. (1962) call the dates which fall between the two peaks »survival values», and interpret them as representing only partial Hudsonian loss of the radiogenic argon that had accumulated in minerals since their crystallization during the Kenoran orogeny.

Fig. 6 illustrates the relationship between the biotite and hornblende ages in samples from which both minerals were dated. The paired dates define four distinct groups, some with a clear reference to regional geology: 1) the Taivalkoski, Varpaisjärvi and Suomussalmi high-grade samples with Archaean hornblende ages and variably lower but incompletely reset biotite ages; 2)

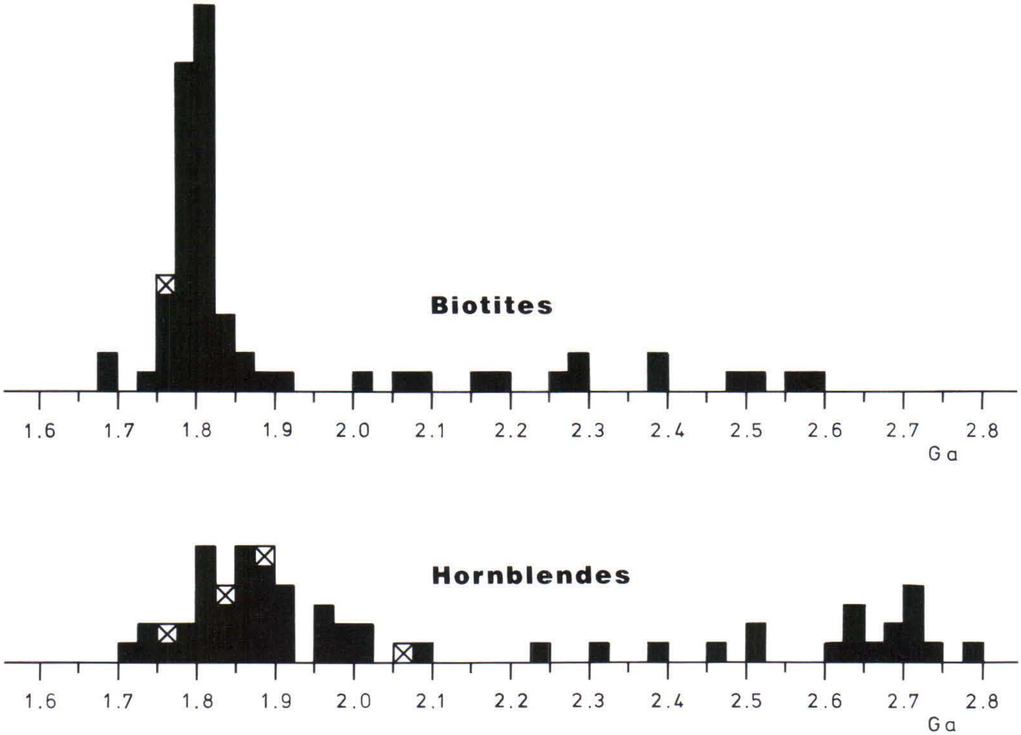

Fig. 5. Histograms of the K-Ar ages of biotites and hornblendes from eastern Finland. Crossed squares indicate Proterozoic, black squares Archaean samples.

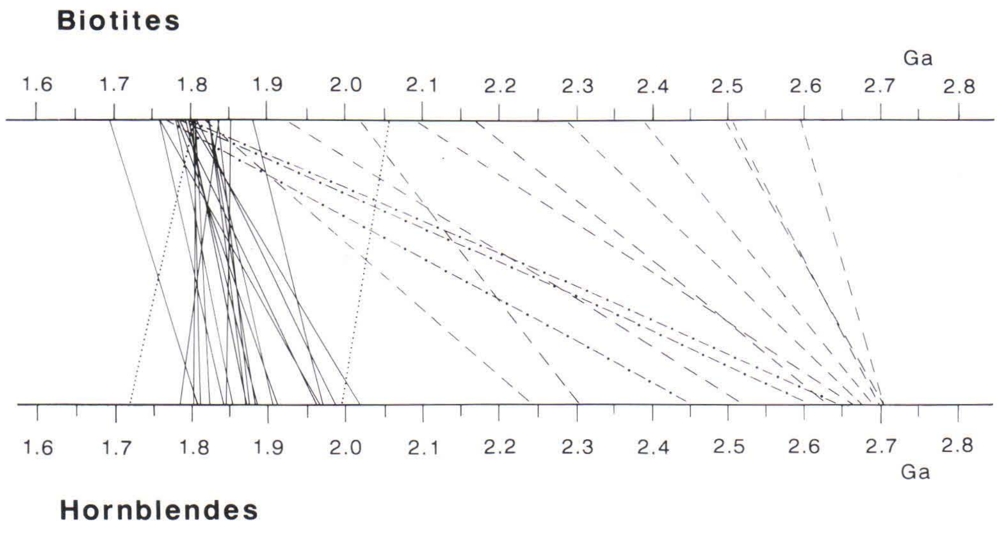

Fig. 6. The correlation between the K-Ar ages of the biotites and hornblendes from the paired Archaean samples. Taivalkoski, Varpaisjärvi and Suomussalmi samples (dashed lines), Ilomantsi samples (dash-dot lines), anomalous samples (dotted lines), the main group of samples (solid lines).

the Ilomantsi samples with variable hornblende ages up to Archaean but typically low biotite ages; 3) a few »anomalous samples» with higher biotite than hornblende ages; and 4) the majority of the samples, or the »completely» reset samples, whose biotite ages cluster around 1800 Ma and whose hornblende ages are typically 50 to 100 Ma older. These results characterize most of the study area.

The small number of anomalous paired ages in our database suggests that excess Ar is not a serious problem in interpretations of K-Ar data from eastern Finland. This may well be because the samples were carefully selected mainly from fresh, unsheared, medium to coarse-grained intermediate plutonic rocks. Distinctly young ages are also rare, probably because we tried to avoid sampling from possible young shear or fault zones.

Five reference samples were taken from Proterozoic rocks. The only biotite date (KA046, 1773 Ma) is from a quartz diorite in the Iisalmi area. Similar to the biotite ages from the Archaean rocks in the same area (KA056, 1819 Ma), it indicates contemporaneous last cooling of the Archaean and Proterozoic rocks trough biotite closure temperatures in this area.

Of the four Proterozoic hornblende samples analysed, one (KA025) comes from the Siilinjärvi area. This sample was taken from a hornblende phenocrystic mafic dyke that cuts a quartz-feldspar porphyry dyke intruded into Archaean basement gneisses. Both dykes are thought to be cogenetic with the volcanics of the nearby lower amphibolite facies Koivusaari Formation, from which a felsic metavolcanic unit has been dated to 2062 ± 2 Ma by the U-Pb zircon method (Lukkarinen, unpublished data). The hornblende separated from sample KA025 gives an age of 2056 ± 69 Ma, which is equal within analytical error to the inferred primary crystallization age of the dyke. If this match in ages is not caused by extraneous Ar, it implies that the hornblende is a primary mineral, or that it formed by autometamorphic processes immediately after emplacement of the dyke.

Sample KA029 was taken from a Palaeoproterozoic metadiabase dyke (ca. 2100 Ma) with greenschist facies mineralogy and, cross-cutting the Archaean basement in the Hyrynsalmi area, west of the Palaeoproterozoic Kainuu Schist Belt. The hornblende separated yields a K-Ar age of 1772 Ma, similar to the biotite ages from the Archaean rocks in the same area.

Hornblende samples KA060 and KA058 are both from foliated quartz diorites in an area west of Kuopio, near the western border of the Archaean basement. U-Pb zircon dates for both samples are close to 1880 Ma (Lukkarinen, unpublished data). The hornblende K-Ar dates are 1893 Ma and 1848 Ma, respectively. Hornblendes from the Archaean rocks in the same area yield 1918—1871 Ma ($n = 7$). Like the Proterozoic quartz diorites from in the Iisalmi area, the Proterozoic quartz diorites in the Kuopio area seem to have cooled through the hornblende and biotite closure temperatures contemporaneously with the Archaean country rocks.

Table 1. K-Ar mineral ages from the Archaean basement of Eastern Finland

Sample No.	Mineral	% K	Vol^{40}Ar Rad ccSTP/g x 10^{-5}	%^{40}Ar rad	Age(Ma)
001	Hornblende	1.23	28.872	98.5	2638 ± 80
		0.004	28.518	98.3	
002	Hornblende	1.41	29.843	99.3	2510 ± 75
		0.01	29.865	97.6	
003	Hornblende	0.940	23.593	99.2	2747 ± 82
		0.005	23.675	98.8	
004	Hornblende	0.438	10.705	96.8	2710 ± 80
		0.008	10.752	97.4	
005	Biotite	7.23	119.77	99.5	2199 ± 66
		0.04	121.69	99.2	
006	Biotite	8.10	156.46	99.2	2387 ± 72
		0.05	156.72	99.5	
007	Biotite	6.618	108.4819	99.9	2166 ± 65
		0.021	107.0197	99.5	
	Hornblende	1.41	32.617	98.9	2632 ± 80
		0.013	32.471	98.9	
008	Biotite	7.43	143.00	98.4	2386 ± 72
		0.01	143.98	99.2	
	Hornblende	1.05	25.451	98.3	2692 ± 80
		0.010	25.198	98.9	
009	Hornblende	1.08	27.787	98.3	2776 ± 83
		0.005	27.792	98.2	
010	Biotite	7.14	108.85	99.2	2088 ± 63
		0.02	109.73	99.1	
	Hornblende	1.32	31.291	98.4	2666 ± 80
		0.007	31.356	98.6	
011	Biotite	7.57	99.892	99.3	1922 ± 58
		0.04	102.03	99.2	
	Hornblende	1.07	22.515	98.4	2519 ± 75
		0.01	23.253	98.0	
012	Biotite	7.75	95.324	99.5	1823 ± 55
		0.04	94.690	99.5	
013	Biotite	8.05	93.039	98.9	1768 ± 53
		0.14	94.938	99.2	
014	Biotite	7.78	96.040	99.3	1824 ± 55
		0.05	94.731	98.3	
015	Biotite	8.04	144.38	99.4	2292 ± 68
		0.03	144.42	99.4	
016	Biotite	7.33	80.272	99.1	1696 ± 50
		0.07	79.956	99.1	
	Muscovite	8.76	107.55	99.1	1826 ± 55
		0.09	107.52	98.5	
017	Biotite	7.93	140.18	99.5	2284 ± 68
		0.07	143.13	99.2	
	Hornblende	0.667	15.923	99.8	2677 ± 80
		0.005	15.980	99.8	
018	Hornblende	0.286	3.2338	95.9	1727 ± 52
		0.002	3.2025	96.2	

Sample No.	Mineral	% K	Vol^{40}Ar Rad ccSTP/g x 10^{-5}	%^{40}Ar rad	Age(Ma)
019	Biotite	7.58	132.072	99.1	2253 ± 68
		0.02	132.407	99.4	
020	Biotite	7.64	96.192	99.6	1852 ± 56
		0.04	95.748	99.5	
021	Hornblende	0.132	1.5992	89.6	1803 ± 54
		0.001	1.5776	87.7	
022	Biotite	8.34	94.309	98.7	1746 ± 52
		0.10	96.666	99.0	
023	Biotite	7.77	92.765	99.3	1791 ± 54
		0.06	92.295	99.2	
024	Hornblende	0.328	5.0244	92.7	2098 ± 63
		0.003	5.0950	91.7	
025*	Hornblende	0.555	8.2087	94.5	2056 ± 62
		0.009	8.3404	95.5	
026	Biotite	7.49	91.290	91.1	1817 ± 54
		0.03	91.310	98.6	
	Hornblende	0.947	16.270	98.5	2241 ± 67
		0.008	16.449	97.7	
027	Hornblende	0.296	3.3711	88.2	1737 ± 52
		0.002	3.3617	91.4	
028	Biotite	7.75	91.183	99.2	1777 ± 53
		0.04	91.207	99.1	
029*	Hornblende	0.424	5.0198	92.9	1772 ± 53
		0.003	4.9692	94.2	
030	Biotite	7.96	93.226	99.6	1758 ± 53
		0.05	90.912	99.6	
031	Hornblende	1.398	16.390	98.4	1795 ± 71
		0.008	16.041	98.8	
032	Biotite	7.52	89.929	99.3	1796 ± 54
		0.07	90.042	99.5	
	Hornblende	4.23	51.883	98.6	1873 ± 100
		0.01	56.247	99.6	
033	Biotite	7.19	87.250	99.1	1807 ± 54
		0.01	86.510	99.2	
	Hornblende	1.48	20.657	98.1	1987 ± 60
		0.01	20.943	97.3	
034	Biotite	7.63	88.014	99.4	1760 ± 53
		0.02	88.807	99.5	
	Hornblende	0.598	7.4245	97.5	1842 ± 55
		0.002	7.4658	97.0	
035	Biotite	7.98	94.017	99.5	1778 ± 53
		0.03	93.858	99.3	
036	Biotite	8.08	95.665	99.7	1783 ± 53
		0.06	95.476	99.8	
037	Biotite	7.82	100.87	99.7	1880 ± 56
		0.01	100.35	99.1	
	Hornblende	0.679	9.5910	98.7	1970 ± 60
		0.005	9.2703	99.0	

Sample No.	Mineral	% K	Vol^{40}Ar Rad ccSTP/g x 10^{-5}	%^{40}Ar rad	Age(Ma)
038	Hornblende	0.391	5.0393	96.9	1876 ± 56
		0.001	4.9862	95.4	
039	Biotite	7.99	95.885	99.5	1801 ± 54
		0.02	96.161	99.2	
040	Biotite	7.76	90.129	99.7	1760 ± 53
		0.02	89.729	99.8	
	Hornblende	0.383	5.3465	95.6	1967 ± 59
		0.002	5.2604	95.3	
041	Biotite	7.73	89.524	99.6	1764 ± 53
		0.02	90.173	99.6	
	Hornblende	0.622	12.594	98.2	2450 ± 73
		0.007	12.602	98.1	
042	Biotite	7.59	90.802	99.2	1799 ± 54
		0.04	91.420	99.1	
	Hornblende	0.789	18.422	98.2	2649 ± 80
		0.003	18.563	97.1	
043	Biotite	7.79	92.183	99.6	1788 ± 53
		0.02	92.767	99.6	
044	Biotite	8.02	94.510	99.7	1782 ± 53
		0.03	95.001	99.7	
	Hornblende	0.700	15.9665	98.1	2612 ± 78
		0.003	15.9886	98.6	
045	Biotite	7.38	87.0108	99.8	1780 ± 56
		0.05	87.1370	99.6	
	Hornblende	0.464	5.9045	95.3	1853 ± 56
		0.004	5.7596	90.0	
046*	Biotite	7.20	84.310	99.3	1773 ± 53
		0.05	84.555	98.8	
047	Biotite	7.22	87.275	99.4	1805 ± 54
		0.06	86.871	98.9	
	Hornblende	0.748	9.1790	96.3	1824 ± 55
		0.007	9.1681	96.3	
048	Biotite	7.82	93.901	99.3	1804 ± 54
		0.03	94.469	99.2	
049	Biotite	7.47	89.441	94.1	1800 ± 54
		0.04	89.952	99.3	
050	Biotite	7.63	89.943	98.4	1782 ± 54
		0.05	90.371	98.7	
051	Biotite	7.96	96.171	99.3	1806 ± 54
		0.03	96.047	99.4	
052	Biotite	7.58	93.707	99.8	1836 ± 55
		0.05	94.018	99.7	
053	Biotite	7.40	87.403	99.4	1785 ± 54
		0.04	87.894	99.6	
054	Hornblende	0.816	10.2671	95.9	1854 ± 56
		0.010	10.2769	98.6	
055	Biotite	7.44	90.391	96.9	1814 ± 54
		0.04	90.548	97.6	

Sample No.	Mineral	% K	Vol^{40}Ar Rad ccSTP/g x 10^{-5}	%^{40}Ar rad	Age(Ma)
056	Biotite	7.40	90.157	94.3	1819 ± 55
		0.07	90.523	99.6	
057	Hornblende	0.658	8.5233	97.3	1883 ± 56
		0.005	8.4625	96.6	
058*	Hornblende	1.038	12.9433	89.5	1848 ± 55
		0.008	13.0402	96.7	
059	Hornblende	0.876	11.6591	83.0	1918 ± 57
		0.005	11.6198	92.2	
060*	Hornblende	1.116	14.5957	95.9	1893 ± 56
		0.005	14.4593	66.9	
061	Biotite	7.85	94.623	99.0	1803 ± 54
		0.02	94.329	99.1	
062	Biotite	7.85	94.373	99.5	1801 ± 54
		0.03	94.241	99.4	
063	Hornblende	0.621	7.6255	86.5	1831 ± 55
		0.001	7.7060	95.9	
064	Hornblende	0.376	4.7729	98.1	1863 ± 56
		0.003	4.7629	97.2	
065	Hornblende	0.929	11.6808	97.1	1871 ± 60
		0.008	12.0462	97.6	
066	Biotite	6.90	84.7312	99.3	1828 ± 55
		0.02	85.0344	99.4	
067	Biotite	7.55	90.641	99.5	1799 ± 54
		0.04	90.788	99.5	
	Hornblende	0.384	5.5383	96.4	2018 ± 60
		0.005	5.5622	96.8	
068	Biotite	7.67	169.539	99.8	2569 ± 77
		0.01	169.569	99.8	
069	Biotite	7.45	168.820	99.9	2596 ± 78
		0.05	167.314	99.9	
	Hornblende	1.101	26.9277	99.5	2705 ± 80
		0.010	26.7786	99.4	
070	Biotite	7.65	160.432	99.8	2496 ± 75
		0.06	160.198	99.7	
	Hornblende	0.986	24.3992	98.2	2704 ± 80
		0.004	23.6650	99.1	
071	Biotite	7.65	160.743	99.7	2503 ± 75
		0.03	161.508	99.7	
	Hornblende	0.966	23.5842	99.7	2700 ± 80
		0.009	23.4295	99.0	
072	Biotite	7.57	91.605	99.6	1812 ± 54
		0.03	92.207	99.7	
073	Hornblende	0.668	8.7799	97.4	1908 ± 57
		0.007	8.8378	96.5	
074	Biotite	6.74	79.5676	99.1	1792 ± 54
		0.06	81.2229	99.3	
	Hornblende	0.762	9.9038	98.8	1886 ± 56
		0.005	9.8094	97.5	
075	Biotite	7.70	90.9670	99.5	1793 ± 54
		0.04	93.0238	99.6	

Sample No.	Mineral	% K	Vol^{40}Ar Rad ccSTP/g x 10^{-5}	%^{40}Ar rad	Age(Ma)
076	Biotite	6.15	73.0664	99.5	1782 ± 53
		0.06	72.3039	99.4	
	Hornblende	0.455	5.9848	97.3	1912 ± 57
		0.005	6.0452	97.6	
077	Biotite	6.94	82.3673	99.6	1785 ± 53
		0.05	82.1175	99.5	
	Hornblende	0.351	4.7467	97.1	1963 ± 60
		0.002	4.9020	96.7	
078	Biotite	7.62	89.8656	97.7	1780 ± 53
		0.08	89.8969	99.4	
079	Biotite	7.383	80.3856	99.9	1694 ± 51
		0.022	80.9699	99.5	
	Hornblende	0.623	7.4509	98.6	1808 ± 54
		0.006	7.6053	98.8	
080	Hornblende	0.595	7.1000	98.9	1800 ± 54
		0.004	7.1881	98.2	
081	Biotite	7.32	88.8770	99.6	1807 ± 54
		0.01	87.9285	99.8	
	Hornblende	0.519	6.2035	98.3	1802 ± 54
		0.003	6.2770	98.8	
082	Biotite	7.50	90.3513	99.7	1803 ± 54
		0.01	90.1629	99.7	
	Hornblende	0.882	10.5982	98.2	1811 ± 54
		0.008	10.7268	99.1	
083	Biotite	7.12	85.6487	99.5	1805 ± 54
		0.04	86.1697	99.7	
	Hornblende	0.471	5.2425	97.3	1718 ± 52
		0.003	5.2734	96.8	
084	Hornblende	0.645	7.5890	98.8	1770 ± 53
		0.004	7.4903	98.7	
085	Biotite	6.99	84.1591	99.7	1822 ± 55
		0.03	86.9245	99.9	
	Hornblende	0.784	10.0118	97.9	1883 ± 56
		0.004	10.2125	97.5	
086	Biotite	6.460	93.2529	99.6	2016 ± 60
		0.055	93.1249	99.5	
	Hornblende	0.913	16.6600	99.0	2304 ± 69
		0.006	16.4608	99.9	
087	Biotite	7.090	88.8685	99.3	1852 ± 55
		0.0116	89.3713	99.6	
	Hornblende	0.862	10.8326	98.9	1845 ± 55
		0.008	10.7053	99.0	
088	Biotite	6.966	86.4014	99.8	1836 ± 55
		0.031	86.2699	99.7	
	Hornblende	0.868	10.3548	96.7	1784 ± 54
		0.007	10.1967	98.8	
089	Biotite	6.90	102.364	99.9	2056 ± 62
		0.01	103.311	99.8	
	Hornblende	0.792	11.2701	99.3	1995 ± 60
		0.004	11.1841	99.2	

Sample No.	Mineral	% K	Vol^{40}Ar Rad ccSTP/g x 10^{-5}	%^{40}Ar rad	Age(Ma)
090	Hornblende	0.522	7.3794	99.2	2014 ± 60
		0.003	7.6546	99.1	
091	Hornblende	0.539	10.6616	99.0	2389 ± 72
		0.009	10.2005	99.3	
092	Biotite	6.38	76.978	99.5	1824 ± 55
		0.06	79.549	99.8	
	Hornblende	0.695	9.0575	98.9	1871 ± 56
		0.004	8.6962	99.0	
093	Biotite	7.43	90.976	99.7	1823 ± 55
		0.05	91.004	99.9	
	Hornblende	0.661	8.5950	98.4	1906 ± 57
		0.020	8.8045	98.2	
094	Biotite	7.05	87.209	99.7	1835 ± 55
		0.04	87.228	99.8	
	Hornblende	0.553	7.0505	98.0	1876 ± 56
		0.004	7.1335	97.9	

* = Proterozoic rock

DISCUSSION

Interpretation of the K-Ar ages of hornblende and biotite

Excluding the samples from the granulite facies blocks of Varpaisjärvi and Taivalkoski and those from the Ilomantsi area, almost all our Late Archaean samples exhibit Palaeoproterozoic hornblende and biotite dates. The clear clusters in the hornblende and biotite age distributions and their relative timing suggest that a single process was responsible of the resetting. Understanding properly the mechanism that caused the resetting of the K-Ar systems in the studied rocks would be of primary importance for interpreting its tectonic significance. This subject is highly complex as the process involved may be Ar volume diffusion, recrystallization/regrowth of preexisting minerals, growth of completely new crystals or a combination of all three. Nonetheless, we can reasonably assume that it could not have been activated without an increase in ambient temperature. Detailed petrographic studies combined with the application of more advanced isotopic methods, e.g. $^{40}Ar/^{39}Ar$ and Rb-Sr analyses, are a prerequisite for a more profound understanding of the actual resetting process. Hence the following discussion is necessarily to a certain extent tentative and general in scope.

Basement units within the Karelidic Belt commonly show evidence of penetrative Proterozoic deformation. This is best seen in the basement thrust sheets within the Karelidic belt in North Karelia and Kainuu. For example, in the Nilsiä-Rautavaara area, Proterozoic shearing has widely transformed Archaean gneisses, intercalated tectonically with narrow sheets of Karelian schists, in to augen gneisses (Wegmann, 1929b; Väyrynen, 1937). Penetrative deformation and the associated mineral recrystallization and growth of new biotite/hornblende crystals probably has played a major part in resetting the K-Ar mineral ages in these basement units.

In contrast, structural studies on the Suomussalmi-Kuhmo area suggest that, there, the Archaean basement may not have been affected by any regional scale penetrative deformation and associated dynamothermic mineral growth since Late Archaean (Luukkonen, 1985, 1988). However, regional static metamorphic recrystallization cannot be ruled out, at least not for biotite, as most of our Archaean samples, also those from the Suomussalmi-Kuhmo area, show the existence of biotite recrystallized as a fine-grained mass of randomly oriented laths. Samples with old biotite, in contrast, have large laths, texturally compatible with the petrographic fabric of the ambient rock. Unfortunately, there is no easy way to prove unambiguously that the recrystallization was explicitly related to the observed K-Ar isotopic resetting. As for amphibole, recrystallization may have been less important, as several of the totally reset samples show unaltered, coarse grains compatible with the rock fabric. In general, however, the reset hornblendes are finer-grained than the unreset hornblendes; they are also more often nematoblastic, poikiloblastic (quartz) and blue-green rather than green-brown. What is more, several of the samples with partially reset hornblendes (e.g. KA 033, 037, 040) show evidence of patchy and/or marginal recrystallization of older, large, green-brown, fabric-compatible grains into blue-green hornblende with small, amoeboid quartz inclusions. Thus, the possibility of extensive Palaeoproterozoic static, metamorphic recrystallization/growth of both biotite and hornblende crystals within the whole Archaean terrain of eastern Finland cannot be totally excluded.

We recognize that, in theory, thermal resetting due to tectonic or sedimentary burial and associated relative uplift of crustal isotherms is not the only conceivable explanation for the apparent rejuvenation of minerals in the Archaean rocks studied. It is feasible, too, that the biotites and hornblendes of the present erosional surface rose from depth and from ambient temperatures higher than the hornblende and biotite K-Ar blocking temperatures at 1900—1800 Ma, after continuous residence between 2700 and 1900 Ma below a critical depth (cf. Neuvonen, 1961). This uplift-only scenario is unlikely, however, as the existence of remnants of autochthonous Jatulian shallow marine sediments over large parts of the Archaean craton (eg. Sokolov et al., 1970; Sokolov & Heiskanen, 1985) indicate that no significant thickness of crust, in a regional scale, has been eroded since deposition of these sediments 2300—2100 Ma ago. On the other hand, deep tectonic burial, followed by compensating uplift, is indicated by the fact that the Jatulian remnants show over the whole Karelia Province at least greenschist facies metamorphic assemblages (Ojakangas, 1964; Piirainen, 1968; Sokolov et al., 1970; Mäkelä, 1976; Pekkarinen 1979; Kohonen, 1987; Gehör & Havola, 1988). Significance of this fact is discussed further in a section below.

Our data indicate that only rocks of the high-grade metamorphic blocks of the Varpaisjärvi and Taivalkoski areas have preserved significant parts of their Archaean K-Ar signature. Considering that some of the hornblende ages are close to the zircon ages of the same rocks, the hornblende data on the granulites may record rapid cooling after the Archaean igneous/metamorphic crystallization events. The biotite ages of the paired samples are so much lower and so variable (Fig. 6) that they probably do not record the same process as the hornblendes. Present understanding of the tectonics of the Varpaisjärvi area suggests that the granulite facies blocks were emplaced to their present high level crustal positions during the Palaeoproterozoic by thrusting (Paavola, 1986) or extensional, rotational listric faulting followed by thrusting (Ward & Kohonen, 1989). Before that they may have resided relatively deep in the crust and consequently at relatively high temperatures. Paavola (1984) has estimated that the Varpaisjärvi Late Archaean granulites record at least 700 °C at 8 kb.

As there is little reason to invoke a post-kinematic Svecokarelidic tectonothermal history for the high-grade blocks drastically different from that for the rest of the Archaean domain of eastern Finland, internal factors of the high-grade blocks must have contributed to the exceptional preservation of the Archaean mineral ages in these blocks. Under the microscope samples from the Varpaisjärvi and Taivalkoski high-grade blocks show very little textural evidence of possible post Archaean penetrative deformation. Nor do the amphibole and biotite grains, that in the samples studied, are typically medium- to coarse-grained, display any significant static hydrous retrogression. Additional evidence that these rocks have had very low fluid activity since the Late Archaean is the preservation of primary mineralogy in the cross-cutting Palaeoproterozoic (about 2100 Ma) diabase dykes, which have invariably been transformed to greenschist facies hydrous assemblages in the surrounding lower grade, amphibolite facies blocks. Thus, there are numerous indications that the rigidity and dryness of the granulites protected their biotites and hornblendes from resetting (recrystallizing) during Svecokarelidic heating.

Sample KA068, which was taken from the Kuusamo area, from above the 2440 Ma Kostonjärvi-Näränkävaara layered intrusion (Alapieti, 1982), is of special interest in this respect. According to gravimetric interpretations (Ruotsalainen, 1977), the upper surface of this intrusion is about 1—2 km below the ground surface. Its estimated width is 3—5 km and thickness 3—4 km. Despite the undoubtedly high heating effect of this ultrabasic-basic subsurface intrusion, which was sufficent to reset the pole of remanent magnetism (the Curie point of magnetite is at about 600 °C) in the overlying charnockitic granite to that typical of layered intrusions (Neuvonen, pers. comm., 1990), it was not able to reset the K-Ar clock of the biotite of the same »dry» granite.

In summary, our data on the granulite hornblendes and biotites strongly support the view that universal blocking or opening temperatures did not exist for these minerals as K-Ar systems but that the temperatures depended on the matrix factors such as whole-rock composition, mineralogy (metamorphic grade) and, above all, fluid activity and the type of accompanying deformation (cf. Chopin and Maluski, 1980; Baksi and Poupeau, 1984; Barry and McDougal, 1986; Itaya & Takasugi, 1988). In addition, the opening/blocking idea is based on volume diffusion; yet it is possible, particularly in our case, that the minerals are in reality often reset by recrystallization, which further complicates interpretation of the age results.

Nevertheless, considering the obvious cooling age clusters defined by the main part of the reset hornblende (1851 $\pm$ 41 Ma, n = 30) and, especially, the biotite ages (1795 $\pm$ 21, n = 48), it seems reasonable to assume that the Late Archaean crust of eastern Finland was heated during the Svekokarelidic orogeny througout its whole extent to temperatures at least above the 300 °C generally claimed for the blocking of magmatic or low to medium grade metamorphic biotites, and over large areas obviously to those close/above the corresponding hornblende blocking temperature of 500 °C. These seem to be safe assumptions, as Svekokarelidic heating temperatures of over 300 °C are indicated also by the greenschist facies to amphibolite facies metamorphic mineral parageneses of the Palaeoproterozoic autochthonous cover rocks. The statically overprinted late mineral assemblages common in the medium-grade basement rocks (typically biotite-epidote + —blue-green amphibole) compare well with these temperatures, too (Lavikainen, 1977). This may be a coincidence but it still requires careful consideration because of the apparent connections between the K-Ar ages and the mineral recrystallization features described above.

Tectonic implications

The nature of the actual tectonic process related to the Svecokarelidic orogeny and that caused the heating of its Late Archaean foreland is a fundamental question. Answering it requires studies combining extensively isotopic, metamorphic, structural geological and geophysical study methods, a task largely beyound the scope of this work. However, starting from the inference that the present erosion surface of the Karelia Province differs little from that reached before 2200 Ma, crustal thickening by overthrusting remains practically the only reasonable explanation for the heating of this surface — over large areas to above 500 °C. We therefore link the tectonic processes involved to the west-east directed Svecokarelidic thrusting which is thought to have strongly deformed the eastern margin of the Archaean craton about 1900 Ma ago. Most evidence of Svecokarelidic thrusting comes from North Karelia (Wegmann, 1928, 1929a, b; Väyrynen, 1937; Koistinen, 1981; Park & Bowes, 1983), but some also from Kainuu (Wegmann, 1929b; Laajoki & Tuisku, 1990) and Nilsiä-Rautavaara area (Väyrynen, 1937). There are no estimates of how far and thickly the thrust nappes were pushed eastwards onto the Kuhmo Complex. In the light of our K-Ar data as T indicators and available P-T data from North Karelia indicate thrust sheet thicknesses well in excess of 10 km (Fig. 8), even if heat flow much greater than that typical of the currently stable continents is assumed (cf. Thompson and England, 1984). The low metamorphic grade of the Palaeoprotrozoic cover rocks in the lake Onega area (eg. Eskola, 1925), some 300 km east of the Svecofennidic front, may indicate that either the inferred overthrust complex thinned rapidly eastwards, or that the crustal heat flow decreased rapidly eastwards.

If the thrust-related burial was associated with large-scale, pervasive flow of hot fluids in the basement, model-required burial depths could be smaller. In addition to that, the overthrust complex itself may have been hot and thus it could have heated the underlying basement not only by means of burial and associated thermal relaxation of the crustal isotherms but also by introducing heat directly. In North Karelia there exists evidence for this »hot iron effect» as the overthrust Kalevian units show at their base mineral assemblages indicating considerably higher peak temperatures (amphibolite facies, Nykänen, 1968, 1971; 675 °C at 5 kb, Cambell et al., 1979) than the parageneses in the underlying, autochtonous Jatulian sediments (greenschist facies, Pekkarinen, 1979). The Karelidic Belt has been interpreted as including remnants of a closed rift or back-arc basin narrowly floored by 1970 Ma old oceanic crust (Park, 1985; Kontinen, 1987). It is tempting to propose that oceanic crust-mantle and hot sedimentary and basement rocks heated initially in the rifted environment, typically characterized by a high heat flow, constituted a significant component of the overthrust nappe complex not only close to the nappe root zones in the west but also further east.

The Kiihtelysvaara-Ilomantsi area in North Karelia is very promising for studies seeking to provide insight into the above process (cf. Fig. 7 and 8). First, the preservation of the Pre-Jatulian erosion surface in the west provides an important control surface for tectonothermal modelling. Second, remnants of the inferred thrust sheets in the west can yield information at least about the Proterozoic peak-T conditions and, it is to be hoped, also about the P-T-t path at the base of the inferred overthrust nappe complex. Third, the gradual younging of hornblende ages towards the northwest (Fig. 7) enables us to study hornblende K-Ar age reduction problematics in an obvious burial/uplift-related profile. Fourth, the Kiihtelysvaara-Ilomantsi area offers a good opportunity to collect lithologically exceptionally uniform sample sets. However, detailed, integrated isotopic and petrographic data on both the basement and autochthonous/allochthonous cover rocks are needed before truly useful constraints for tectonic-metamorphic modelling can be established. We have started a project to collect such data from the Kiihtelysvaara-Ilomantsi area. Working hypothesis to test include; 1) the above speculated possible »hot iron effect» of the Svecokarelidic thrusting; and 2) the obvious deeper burial and/or higher metamorphic heating towards the north, which is indicated not only

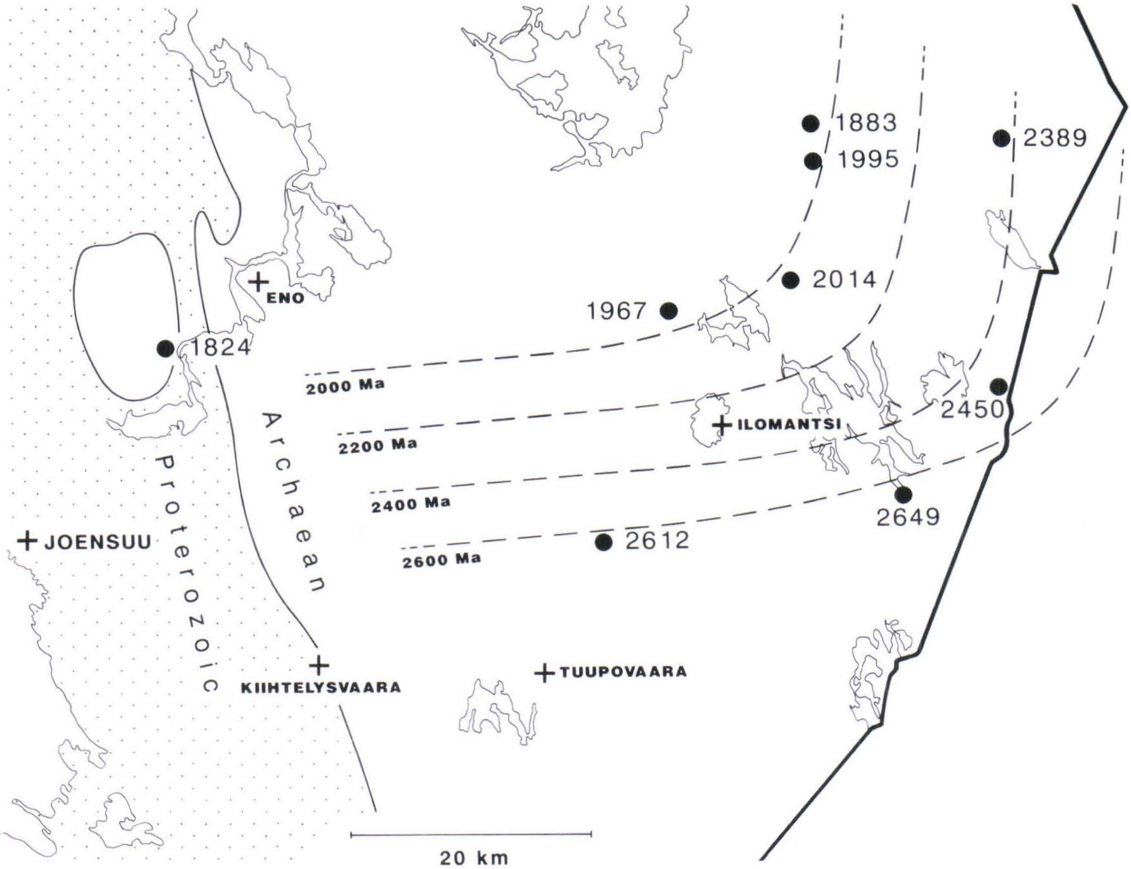

Fig. 7. Gradational zonation of the northward lowering hornblende K-Ar ages in the Ilomantsi area. The inferred isotherms are tentative, the pattern is sensible to change along with new data, especially in the area to E-NE of Eno.

by our K-Ar data but also by the increase in the metamorphic grade of the Jatulian cover from the Värtsilä area, where the Jatulian quartzites/intercalated meta-argillitic sediments are not reported to contain alumina silicates, towards the Koli area, where they locally contain abundant kyanite and andalusite (eg. Nykänen, 1968, 1971; Piirainen, 1968; Pekkarinen, 1979).

Other tectonic explanations for the observed extensive age reduction in the Archaean basement apart from tectonic burial/uplift would mean invoking special circumstances at the mantle-crust interface, e.g. shield-wide rise of the asthenospheric mantle or magma underplating about 1900 Ma ago. It is likely that such phenomena would have been associated with crustal extension, mantle-derived mafic magmatism and probably also infracrustal anatexis-plutonism, for which there is little evidence from eastern Finland, except from within the western margin of the Karelidic Belt. It is also difficult to envisage how such processes alone, without associated burial by enormously thick sedimentary piles or an unrealistically steep crustal thermogradient, could have been responsible for metamorphism of the Jatulian shallow marine cover sediments and for resetting of K-Ar mineral clocks in the basement rocks immediately below. Consequently, and with reference to our above discussion on the uplift-only scenario, we see the burial by

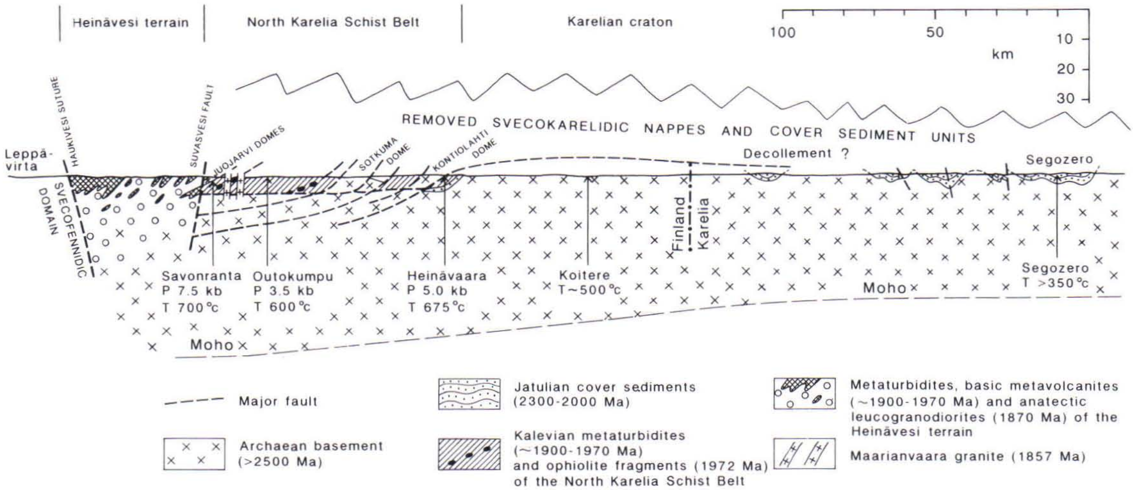

Fig. 8. Schematic, roughly W-E crustal cross-section of eastern Finland and Karelia showing the Svecofennidic arc domain in the west, the Heinävesi migmatite terrain in the middle, and the North Karelia Schist Belt and Karelia Province in the east. The cross-section is based on geological and geophysical data and interpretations mainly from Väyrynen (1937), Sokolov et al. (1970), Koistinen (1981), Bowes et al. (1984), Ward & Kohonen, 1989, Luosto (1991), Kohonen and Elo (1991) and Korja (1991). Age data are from Huhma (1986). P-T estimates for climatic Svecokarelidic metamorphic conditions for the North Karelia Schist Belt are from Campbell et al. (1979), Treloar et al., (1981) and Halden & Bowes (1984). The completly reset hornblende (KA 085) at Koitere lake, and the greenschist facies metamorphic assemblages at Segozero lake (Sokolov et al., 1970) suggest local Svecokarelidic peak heating temperatures of about 500 °C, and at least 350 °C, respectively. The Svecokarelidic heating of the basement east from the North Karelia Schist Belt is explained by burial under massive nappe complex about 1900 Ma ago. Deep-seated thrusts in the basement below the North Karelia Schist Belt are thought to explain the also presently thickened crust. Low-angle Svecokarelidic detachment surfaces may be present also in the basement terrain east from North Karelia Schist Belt.

thrusting as the most likely primary cause of heating of the basement. This process may naturally have been preceded by events of crustal extension (as argued above) and/or local infracrustal melting.

A compilation of K-Ar data from the Svecofennidic domain indicates that uplift and cooling of the present erosional surface through the 300 °C isotherm, i.e. through the biotite blocking temperature, occurred there about 1750 — 1800 Ma ago (Gerling & Polkanov, 1958; Wetherill et al., 1962; Kouvo & Tilton, 1966; Korsman et al., 1984; Haudenschild 1988a, b), that is, close to or somewhat later than suggested by our data from eastern Finland. It appears that, disregarding local complexities, both domains were cooled and uplifted after the Svecokarelidic orogeny in a related way as part of a single unroofing process. This conclusion can possibly be extended to concern the entire southeastern part of the Fennoscandian Shield, as K-Ar biotite ages from its whole area between the White Sea and the Bothnian Bay appear to be close to those reported here for eastern Finland (Gerling & Polkanov, 1958; Wetherill et al., 1962; Kouvo & Tilton, 1966; Korsman et al., 1984; Haudenschild 1988a, b; this work). However, the K-Ar age data for the entire shield is too scattered yet to allow any meaningfull investigation of details of the shield-wide unroofing.

If calculations are based on the averages of the post-orogenic cooling-age clusters defined by the K-Ar ages for the hornblendes (blocking at 500 °C) and biotites (blocking at 300 °C) of eastern Finland, that is 1851 Ma and 1795 Ma, respectively, we obtain a time-integrated post Svecokarelidic average crustal cooling rate of 3.6 °C/Ma and an uplift rate of at least 0.072

km/Ma. The latter estimate depends on selection of an appropriate crustal thermogradient. To provide a minimum estimate, the calculation was based on a gradient as steep as 50 °C/km (cf. Treloar et al., 1981). Selection of less steep, probably more realistic gradients would yield higher values. These cooling/uplift estimates are reasonable and within the range typically inferred for postorogenic crustal cooling/uplift (e.g. Clark & Jäger, 1969; Wagner et al., 1977; Harrison et al., 1985; Cosca et al., 1992). However, such estimates are always subject to many uncertainties (e.g. Baksi & Poupeau, 1984).

Finally we stress that our data indisputably demonstrate that the Svecokarelian orogeny had a strong tectonothermal effect on its foreland. To appreciate the scope of the tectonic processes involved, we should remember that thermogradients inferred for the Palaeoproterozoic stable continental upper crust imply that biotite and hornblende should be open for loss of radiogenic Ar at depths below about 20 and 30 km, respectively (cf. e.g. Barton & Van Reenen, 1992). These figures give some idea of the magnitude of the required total burial/uplift movements. Further study is neccesary to further clarify the actual tectonic processes involved. We hope that our data and the viewpoints outlined in our discussion will provide useful starting points for and hypothesis to test in such studies.

CONCLUSIONS

The main results of this work can be summarized as follows:

1) The K-Ar biotite and hornblende ages of the Late Archaean basement rocks of eastern Finland are widely reset to average 1795 ± 21 Ma and 1851 ± 41 Ma, respectively. Biotite and hornblende have totally or partially retained their Archaean K-Ar isotopic signature almost only in areas where Late Archaean granulite facies rocks are exposed. This is probably due to the rigidity and low fluid concentration of the granulites, which protected their hornblendes and biotites from Proterozoic resetting (rehydration/recrystallization).

2) The observed extensive age reduction was obviously due to regional heating and metamorphism/recrystallization of the basement rocks/minerals in association with the Svecokarelidic orogeny about 1900 Ma ago. The K-Ar data suggest that the whole basement was heated to temperatures of above 300 °C, and large parts of it to over 500 °C. The K-Ar ages register subsequent cooling and uplift.

3) The heating of the basement was most probably due to its deep burial about 1900 Ma ago under massive, from the west overthrust Svecokarelidic nappe units, which were for most part removed by subsequent uplift and erosion.

4) The entire Fennoscandian Shield, including the Svecofennidic domain, appears to have been unroofed in a related way after the Svecokarelidic orogenesis. K-Ar data from eastern Finland suggests for the time period between 1850 and 1800 Ma an average cooling rate of 3.6 °C/Ma and an uplift rate of at least 0.072 km/Ma.

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Appendix

List of samples

Sample Locality, Municipality
Map sheet
Northing, Easting
Rock type, comments

KA 001 Jonsa, Varpaisjärvi
3334 03A
x = 7031.90 y = 540.72
Massive enderbite, Zr(U-Pb) age 2682 Ma (Neuvonen et al., 1980)

KA 002 Hevosmäki, Varpaisjärvi
3332 12C
x = 7034.60 y = 536.98
Massive enderbite

KA 003 Pällikäs, Lapinlahti
3332 12B
x = 7039.62 y = 531.20
Granoblastic amphibolite

KA 004 Pällikäs, Lapinlahti
3332 12B
x = 7038.04 y = 530.29
Granoblastic amphibolite

KA 005 Kuikkala, Varpaisjärvi
3334 02D
x = 7028.30 y = 547.74
Garnet-cordierite-sillimanite rock

KA 006 Jonsa, Varpaisjärvi
3334 03A
x = 7032.10 y = 543.46
Massive enderbite

KA 007 Romonmäki, Lapinlahti
3332 08D
x = 7028.24 y = 528.73
Gneissic quartz diorite, Zr(U-Pb) age 3095 Ma (Paavola, 1986)

KA 008 Lampiensalmi, Lapinlahti
3332 09D
x = 7039.44 y = 527.90
Massive enderbite, Zr(U-Pb) age 2693 Ma (Paavola, 1986)

KA 009 Jukola, Lapinlahti
3332 08D
x = 7027.81 y = 525.39
Granoblastic amphibolite

KA 010 Kiikkukallio, Lapinlahti
3332 08C
x = 7024.80 y = 525.60
Foliated diorite, Zr(U-Pb) age 3136 Ma (Paavola, 1986)

KA 011 Eerikinsuo, Suomussalmi
4423 12B
x = 7185.20 y = 490.58
Quartz diorite

KA 012 Nurmiaho, Hyrynsalmi
4421 10A
x = 7163.24 y = 453.30
Foliated biotite tonalite

KA 013 Säynäjävaara, Suomussalmi
4421 12B
x = 7188.02 y = 454.06
Foliated biotite tonalite

KA 014 Konivaara, Hyrynsalmi
4421 05B
x = 7177.50 y = 431.90
Granodiorite, Zr(U-Pb) age 2697 Ma (Luukkonen, 1988)

KA 015 Honkajärvenkangas, Suomussalmi
4423 06D
x = 7188.08 y = 478.45
Biotite tonalite

KA 016 Tulilammet, Hyrynsalmi
4423 01D
x = 7165.40 y = 467.95
Potassium granite

KA 017 Yrttipuro, Suomussalmi
4441 02A
x = 7173.75 y = 501.40
Garnet-pyroxene gneiss

KA 018 Otanmäki, Vuolijoki
3431 02C
x = 7111.62 y = 505.44
Tonalitic-trondhjemitic gneiss

KA 019 Hiisivaara, Suomussalmi
4511 11A
x = 7230.50 y = 451.05
Tonalitic-trondhjemitic gneiss

KA 020 Näljänkä, Suomussalmi
3533 08D
x = 7235.28 y = 566.17
Gneissic tonalite

KA 021 Moisiovaara, Hyrynsalmi
4421 10D
x = 7167.04 y = 458.08
Gabbro, Zr(U-Pb) age 2790 Ma
(Luukkonen, 1988)

KA 022 Kelkkakangas, Hyrynsalmi
4421 09C
x = 7181.60 y = 446.14
Hornblende tonalite

KA 023 Nuottimäki, Hyrynsalmi
4421 05A
x = 7172.92 y = 433.02
Hornblende tonalite

KA 024 Myhkyri, Hyrynsalmi
3443 07C
x = 7160.78 y = 569.98
Gneissic quartz diorite

KA 025 Kuivasteenlampi, Siilinjärvi
3331 08D
x = 6999.25 y = 526.58
Porphyritic tonalite (Proterozoic dyke)

KA 026 Kattilavaara, Hyrynsalmi
3443 09D
x = 7187.86 y = 567.54
Gneissic hornblende tonalite

KA 027 Keski-Pussinen, Puolanka
3443 03D
x = 7187.08 y = 546.02
Biotite-hornblende gneiss

KA 028 Raatteikonsuo, Puolanka
3443 01B
x = 7167,32 y = 540,08
Gneissic trondhjemite

KA 029 Myllykoski, Hyrynsalmi
4421 05D
x = 7179.31 y = 437.09
Metadiabase (Proterozoic, Jatulian)

KA 030 Matosärkät, Puolanka
3443 03A
x = 7183.73 y = 544.04
Gneissic trondhjemite

KA 031 Riihivaara/Vieki, Lieksa
4323 07C
x = 7043.36 y = 487.32
Tonalitic gneiss

KA 032 Riihivaara/Vieki, Lieksa
4323 07C
x = 7044.20 y = 488.66
Hornblende tonalite

KA 033 Nurmijärvi, Lieksa
4323 10C
x = 7044.25 y = 498.64
Tonalitic biotite-hornblende gneiss

KA 034 Äkätinlinja, Lieksa
4341 02A
x = 7051.66 y = 504.44
Gneissic tonalite

KA 035 Löppö, Lieksa
4332 02D
x = 7029.18 y = 506.98
Gneissic hornblende-biotite tonalite

KA 036 Pesälampi, Lieksa
4332 04D
x = 7018.50 y = 517.96
Gneissic biotite tonalite

KA 037 Pitkäjärvi, Lieksa
4332 07B
x = 7017.73 y = 521.48
K-feldspar porphyric/porphyroblastic granodiorite

KA 038 Varpovaara, Lieksa
4332 10B
x = 7017.44 y = 534.34
Gneissic biotite tonalite

KA 039 Lamminvaara, Ilomantsi
4333 06B
x = 7006.38 y = 552.92
Gneissic granodiorite
(Koitere pluton, Lavikainen, 1977)

KA 040 Repovaara, Ilomantsi
4244 02A
x = 6962.66 y = 542.54
Cataclastic quartz diorite
(Hakovaara pluton, Lavikainen. 1977)

KA 041 Kalliovaara, Ilomantsi
4244 07D
x = 6955.71 y = 569.98
Foliated quartz diorite
(Sysmä pluton, Lavikainen, 1977)

KA 042 Oinassalmi, Ilomantsi
4243 09B
x = 6946.73 y = 561.80
Foliated quartz diorite
(Sysmä pluton, Lavikainen, 1977)

KA 043 Paavonvaara, Ilomantsi
4243 03A
x = 6940.53 y = 541.68
Foliated quartz diorite
(Lake Ilomantsi pluton, Lavikainen, 1977)

KA 044 Marjovaara, Ilomantsi
4241 12C
x = 6942.97 y = 536.90
Foliated quartz diorite

KA 045 Loso, Sotkamo
3434 07B
x = 7135.10 y = 563.20
Gneissic hornblende tonalite

KA 046 Palomäki, Iisalmi
3341 04D
x = 7045.60 y = 519.36
Quartz diorite (Proterozoic)

KA 047 Poppavaara, Kontiolahti
4242 01B
x = 6959.25 y = 500.56
Foliated granodiorite

KA 048 Kuisma, Eno
4242 08A
x = 6960.08 y = 523.87
Foliated granodiorite

KA 049 Kuluvaara, Ilomantsi
4242 11A
x = 6961.44 y = 530.65
Foliated quartz diorite

KA 050 Onttola, Joensuu
4223 09B
x = 6948.78 y = 482.20
Foliated quartz diorite

KA 051 Mujejärvi, Nurmes
4324 04B
x = 7079.39 y = 472.80
Migmatitic mica gneiss

KA 052 Pöytävaara, Nurmes
4324 04B
x = 7076.62 y = 470.95
Hornblende-biotite tonalite

KA 053 Teljonvaara, Kuhmo
4324 10A
x = 7072.85 y = 492.17
Biotite tonalite

KA 054 Teljonvaara, Kuhmo
4324 10A
x = 7071.30 y = 493.05
Hornblende tonalite (dyke)

KA 055 Pilpasenvaara, Nurmes
4323 11B
x = 7058.55 y = 493.75
Biotite tonalite

KA 056 Väisälänmäki, Lapinlahti
3332 05B
x = 7025.41 y = 513.93
Tonalitic part in banded migmatite

KA 057 Kivimäki, Maaninka
3331 03D
x = 7008.32 y = 509.38
Gneissic quartz diorite, Zr(U-Pb) age 2640 Ma (GSF, Ann. Rep.1984)

KA 058 Hirvilahti, Kuopio
3331 05C
x = 6990.50 y = 516.86
Quartz diorite (Proterozoic)

KA 059 Niemisjärvi, Kuopio
3331 04A
x = 6983.98 y = 511.35
Gneissic quartz diorite

KA 060 Luvelahti, Karttula
3331 01A
x = 6980.03 y = 500.53
Hornblende-biotite tonalite (Proterozoic)

KA 061 Ylä-Keyritty, Rautavaara
4321 05A
x = 7051.70 y = 530.60
Gneissic biotite tonalite

KA 062 Pennasenvaara, Nurmes
4321 07B
x = 7045.04 y = 442.78
Gneissic tonalite

KA 063 Hankamäki, Rautavaara
3334 11B
x = 7027.40 y = 573.20
Biotite-bearing amphibolite

KA 064 Mukelinmäki, Sonkajärvi
3341 05D
x = 7058.76 y = 518.79
Tonalitic-trondhjemitic gneiss

KA 065 Raatti, Nilsiä
3334 07B
x = 7016.80 y = 564.28
Hornblende gneiss

KA 066 Lastulahti, Nilsiä
3334 07A
x = 7011.40 y = 563.63
Gneissic tonalite

KA 067 Nuupas, Ranua
3524 05A
x = 7321.70 y = 470.30
Diorite

KA 068 Vähäjärvi, Kuusamo
4523 02A
x = 7293.78 y = 460.85
Granite

KA 069 Kalliomaa, Taivalkoski
3543 07A
x = 7280.73 y = 563.68
Hypersthene diorite

KA 070 Portinmaa, Taivalkoski
3543 07A
x = 7280.20 y = 563.00
Hypersthene granite

KA 071 Majavanoja, Taivalkoski
3534 03C
x = 7270.36 y = 548.55
Hypersthene-bearing quartz diorite

KA 072 Yli-Kurki, Pudasjärvi
3532 10A
x = 7251.45 y = 531.32
Tonalite

KA 073 Petosenmäki, Kuopio
3242 12A
x = 6971.24 y = 531.78
K-feldspar porphyric gneissic granodiorite

KA 074 Kulvenmäki, Sonkajärvi
3342 10A
x = 7073.90 y = 532.00
Gneissic quartz diorite

KA 075 Sompasuo, Sotkamo
3343 09B
x = 7067.87 y = 563.46
Gneissic tonalite

KA 076 Parsikangas, Kajaani
3342 12B
x = 7097.10 y = 534.70
Hornblende quartz diorite

KA 077 Tavilampi, Sonkajärvi
3342 06D
x = 7096.73 y = 518.65
Hornblende tonalite

KA 078 Kaakkurimäki, Sonkajärvi
3342 05D
x = 7089.90 y = 519.15
Hornblende-biotite tonalite

KA 079 Tuohimäki, Sonkajärvi
3342 04C
x = 7072.75 y = 519.50
Hornblende-biotite tonalite

KA 080 Talasvaara, Nurmes
4321 08D
x = 7056.90 y = 447.50
Hornblende gabbro

KA 081 Sivakka, Nurmes
4322 10B
x = 7077.20 y = 453.10
Biotite-bearing amphibolite

KA 082 Kalliosuo, Nurmes
4322 08C
x = 7080.05 y = 445.60
Biotite-hornblende tonalite

KA 083 Kuikkalampi, Sotkamo
4322 09A
x = 7090.30 y = 441.50
Hornblende tonalite

KA 084 Repokallio, Sotkamo
4322 06D
x = 7098.20 y = 435.40
Hornblende tonalite

KA 085 Silvenvaara, Ilomantsi
4244 06B
x = 6977.87 y = 554.38
Granodiorite

KA 086 Porkanrouveikko, Kuhmo
4322 11C
x = 7083.80 y = 459.20
Hornblende tonalite

KA 087 Ketunvaara, Sotkamo
3433 07D
x = 7105.46 y = 569.44
Hornblende gneiss

KA 088 Luotonen, Kajaani
3433 01A
x = 7102.91 y = 542.56
Hornblende-biotite gneiss

KA 089 Tompsankangas, Ilomantsi
4244 06A
x = 6974.70 y = 554.17
Foliated granodiorite

KA 090 Jokikangas, Ilomantsi
4244 05A
x = 6964.71 y = 552.54
Leucodiorite

KA 091 Vattuaho, Ilomantsi
4244 12B
x = 6976.25 y = 570.31
Gneissic granodiorite

KA 092 Jälä, Siilinjärvi
3331 11C
x = 6992.61 y = 539.43
Hornblende-biotite tonalite

KA 093 Naarvanlahti, Siilinjärvi
3331 09B
x = 7009.79 y = 524.59
Biotite-hornblende tonalite

KA 094 Mikka, Siilinjärvi
3331 09D
x = 7007.61 y = 528.35
Biotite-hornblende tonalite

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