Estimating the distribution of strontium isotope ratios (^{87}Sr/^{86}Sr) in the Precambrian of Finland

Lars Kaislaniemi

Department of Geosciences and Geography, University of Helsinki, Finland

Abstract

A method to estimate the ^{87}Sr/^{86}Sr ratio of a rock based on its age and Rb/Sr ratio is presented. This method, together with data from the Rock Geochemical Database of Finland (n=6544) is used to estimate the ^{87}Sr/^{86}Sr ratios in the Precambrian of Finland and in its different major units. A generalization to cover the whole area of Finland is achieved by smoothing of estimation points. The estimation method is evaluated by comparing its results to published Rb-Sr isotope analyses (n=138) obtained on the Finnish Precambrian. The results show correspondence to different geological units of Finland, but no systematic difference between Archaean and younger areas is evident. Evaluation of the method shows that most of the estimates are reliable and accurate to be used as background material for provenance studies in archaeology, paleontology and sedimentology. However, some granitic rocks may have large (>1.0 %) relative errors. Strontium concentration weighted average of the estimates differs only by 0.001 from the average ^{87}Sr/^{86}Sr ratio (0.730) of the rivers on the Fennoscandian shield.

1. Introduction

Strontium isotopes are commonly used in palaeontology and archaeology to find out the territory and migration paths of organisms and the origins of tools and organic building materials (e.g. Beard and Johnson, 2000; Curran et al., 2001; English et al., 2001; Hodell et al., 2004; Feranec et al., 2007) as well as in sedimentological provenance (e.g. Krom et al., 1999) and environmental change studies (e.g. Åberg, 1995). The age and rock type dependent variations of the strontium isotope ratios in the bedrock are induced by the decay of ^{87}Rb to ^{87}Sr and by the differences in compatibility of strontium and rubidium in magmatic systems (Faure & Mensing, 2005).

The isotopic fractionation of strontium is close to nil in physical and chemical processes in sediments, hydrosphere and food chain, and thus the isotope ratio measured from an organism reflects the isotope ratios of its nutriment and, ultimately, of its environment (Capo, 1998; Price et al., 1985;

Halicz et al., 2008). For provenance studies it is necessary to estimate the strontium isotope ratios of this environment – soil, sediment, vegetation, etc. – in potential provenance areas, which requires sampling. However, the source of strontium is in the bedrock (local or allogenic weathered) and, to some extent, in atmospheric inputs (Gosz & Moore, 1989; Miller et al., 1993). This allows the estimation of the strontium isotope ratios ($^{87}Sr/^{86}Sr$) in the environment if the ratios of the underlying Precambrian basement are known and atmospheric inputs are assumed to be small.

The strontium isotope analyses available from the bedrock of Finland are sparse, not allowing to obtain a general view of the strontium isotope ratios of the bedrock. This study estimates the spatial distribution of the $^{87}Sr/^{86}Sr$ ratios in the Finnish bedrock using data from elemental Rb and Sr analyses and age determinations of the rocks; considers the usability of the estimate; and discusses the possible regularities in the estimated spatial distribution of the isotope ratios. The aim is to provide a sufficiently precise and accurate estimate that can be used as background material for sedimentological, archaeological and palaeontological provenance studies.

1.1 Rb and Sr in geological processes

Rubidium has two naturally occurring isotopes, ^{85}Rb and ^{87}Rb. ^{87}Rb is radioactive and decays to stable ^{87}Sr with an half-life of 48.8 Ga. Rb^+ substitutes K^+ in potassium-bearing minerals like muscovite, biotite, phlogopite and lepidolite, in potassium feldspar and in some clay and evaporite minerals. Strontium has four stable isotopes: ^{84}Sr, ^{86}Sr, ^{88}Sr and radiogenic ^{87}Sr. Sr^{2+} substitutes Ca^{2+} in 8-fold coordination. Thus Sr occurs in minerals like plagioclase, apatite and calcite. Both elements are incompatible in silicate magmatic systems during the early stages of fractional crystallization, Rb, however, more strongly. This causes the elemental Rb/Sr ratio to increase with the degree of differentiation, the highest ratios exceeding ten, for example in pegmatites, while the lowest ratios are close to zero, in carbona-

tites and Ca-rich plutonic rocks. Sr is also more prone to weathering than Rb. (Faure & Mensing, 2005)

Rb and Sr start to diffuse through the crystal lattice and grain boundaries even in a modest temperature increment of 100–200°C. Furthermore, radiogenic ^{87}Sr has different charge and ionic radius than the original replaced ^{87}Rb, causing ^{87}Sr to break more readily from the crystal lattice. As a consequence, the concentrations of Sr, Rb and especially ^{87}Sr may balance between the minerals in the rock. The Rb-Sr system of the minerals is reset, but the whole rock Rb and Sr concentrations and isotope ratios remain constant, apart from immediate vicinity of rock unit contacts. Rb and Sr are both mobile elements and, if present, fluid transportation may cause them to move long distances also between rock units. (Faure & Mensing, 2005)

2. Materials

The Rb and Sr elemental analyses from the Rock Geochemical Database of Finland (2008) (RGDB, n=6544) have been used. The ages of the samples in the database are classified to discrete classes (> 2500 Ma; 2500–2300 Ma; 2300–2000 Ma; 2000–1950 Ma; 1950–1850 Ma; 1850–1800 Ma; 1800–1600 Ma; < 1600 Ma), based on the age of the bedrock unit from which the sample has been taken. The strontium isotope ratio has been estimated based on RGDB data (for database sample coverage and bedrock units to be discussed, see Fig. 1).

Published Rb-Sr isotope analyses from Finnish Precambrian have been gathered together (Fig. 1 and Table 1) and they have been used to evaluate the method of Sr isotope ratio estimation. Rb-Sr isotope analyses in Finland are used to reveal petrological problems and for age determinations. However, the amount of analyses is limited and spatial distribution unequal because age determinations are usually conducted with the U-Pb method on zircon. The spatial distribution of the collected analyses covers small areas from Central Finland, greenstone belts in Eastern Finland and from the granulite belt in Lapland.
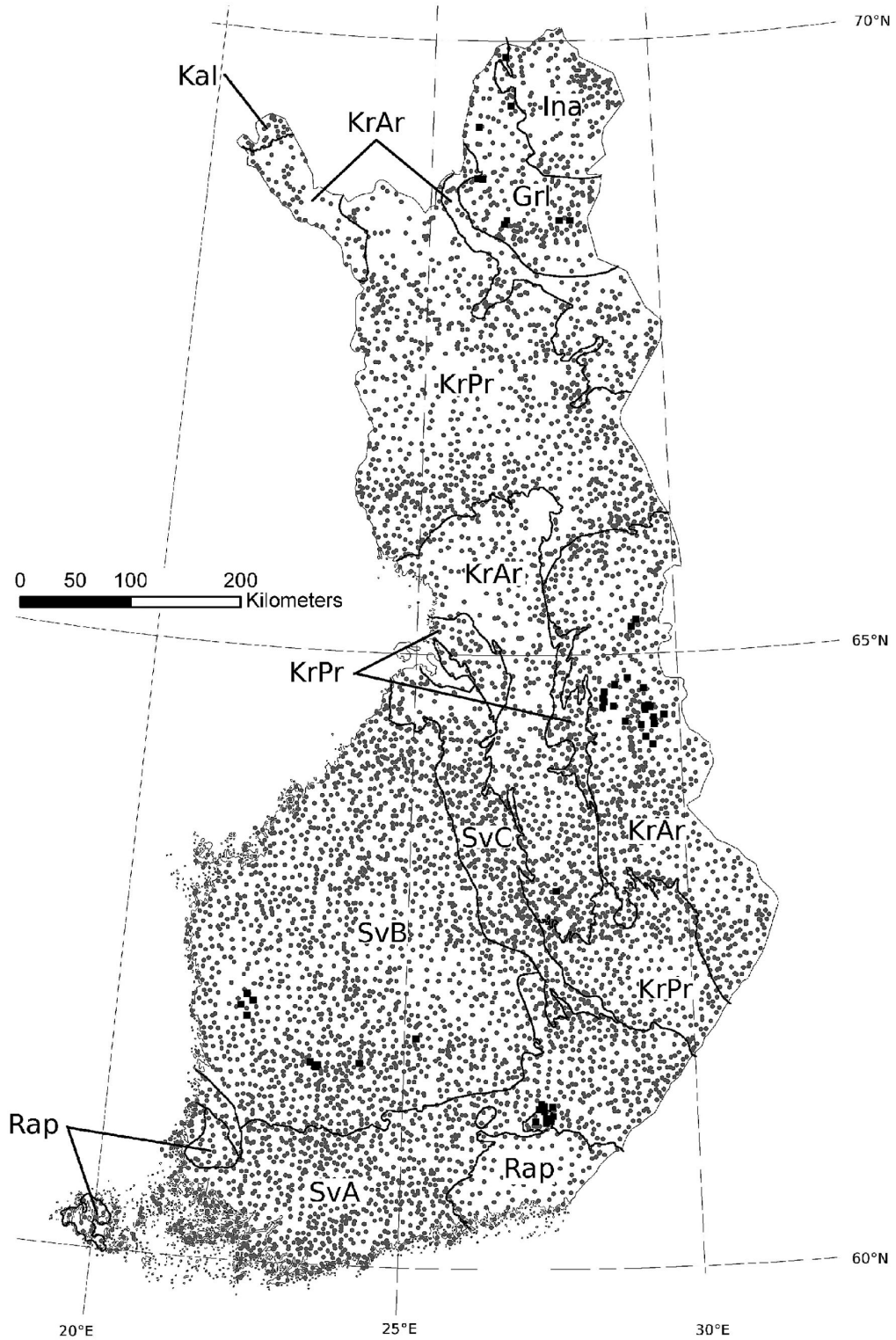
Fig. 1. The distribution of the RGDB sample points (grey dots) and of the sample points from published Sr isotope analyses (black box). Major bedrock units are marked according to Korsman *et al.* (1997).

Table 1. The published Rb-Sr isotope analyses used in the study, the absolute and relative errors of the $^{87}Sr/^{86}Sr$ estimates, and the initial isotope approximations used in the estimation.

Sample	Location*		Rock	Age (Ma)	Analysis:	
	E	N			Rb	Sr
G7	28.97	64.45	granite	2410 ± 40	233	33
G4	28.97	64.45	granite	2410 ± 40	226	31
2b	29.42	64.58	granite	2290 ± 110	256	118
1a	27.64	63.08	carbonatite	2610 ±	78	154
6874	23.53	61.63	dacite	1898 ± 50	100	186
6867	24.25	61.65	trachyte	1847 ± 92	79	562
6877	23.53	61.62	basalt	1898 ± 50	29	213
1e	28.56	64.65	granite	2500 ± 270	142	260
9a	27.64	63.08	carbonatite	2610 ±	167	2146
H395	29.27	64.42	TTG	2670 ± 300	91	266
6875	23.53	61.63	andesite	1898 ± 50	40	172
H405	29.27	64.42	TTG	2670 ± 300	70	302
OTR-83-40	22.27	61.99	granite	1867 ± 5.6	164	214
5a	27.64	63.08	carbonatite	2610 ±	1	8842
OTR-83-16	22.35	62.12	gabbro	1823 ± 15	11	472
2	27.64	63.08	carbonatite	2610 ±	51	6211
OTR-83-11	22.35	62.12	quartz diorite	1823 ± 15	16	554
OTR-83-14,8	22.35	62.12	diorite	1823 ± 15	31	521
R5-53,4	22.35	62.12	gabbronorite	1823 ± 7	8	92
5	27.64	63.08	carbonatite	2610 ±	3	8200
H406	29.27	64.42	TTG	2670 ± 300	61	269
9b	27.64	63.08	carbonatite	2610 ±	2	5125
5b	27.64	63.08	carbonatite	2610 ±	3	8827
4435	26.65	68.51	charnockite	1918 ± 107	40	475
82a-MN-94	25.19	61.87	quartz monzonite	1851 ± 80	44	252
6928	23.49	61.62	feldspar porphyry	1740 ± 70	157	168
9	27.64	63.08	carbonatite	2610 ±	26	4030
1c	28.56	64.57	granodiorite	2500 ± 270	91	362
G149	28.97	64.45	metagranite	2500 ± 70	143	301
4445	26.65	69.87	charnockite	1918 ± 107	5	405
106-BAE-96	25.19	61.87	granite	1851 ± 80	132	262
6695	23.48	61.62	granite	1775 ± 52	144	186
H70	29.47	64.26	TTG	2860 ± 90	57	596
6869	24.24	61.65	basaltic trachyandesite	1847 ± 92	69	860
H391	29.27	64.42	TTG	2670 ± 300	75	264
231-MN-94	25.19	61.87	granite	1851 ± 80	171	306
H396	29.27	64.42	TTG	2670 ± 300	58	238
4438	26.65	68.51	charnockite	1918 ± 107	57	488
H34	29.71	64.50	TTG	2620 ± 70	75	716
3753	26.70	68.54	charnockite	1918 ± 107	52	300
H50	29.35	64.33	TTG	2860 ± 90	104	340
2c	29.35	64.56	granite	2290 ± 110	316	49
G155	28.97	64.45	metagranite	2500 ± 70	100	686
H74	29.47	64.26	TTG	2620 ± 70	67	290
G224	28.97	64.45	metagranite	2500 ± 70	47	918
H402	29.51	64.48	granodiorite-granite	2500 ±	52	349
7	27.64	63.08	carbonatite	2610 ±	82	2394

		Estimate:		Estimate error:		Analysis
$(^{87}Sr/^{86}Sr)_0$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$	$^{87}Sr/^{86}Sr$	Absolute	Relative	Source**
0.7080	1.4173	0.7027	1.4575	-0.0402	-2.83 %	MQ84
0.7080	1.4585	0.7027	1.4900	-0.0315	-2.16 %	MQ84
0.7036	0.8998	0.7029	0.9105	-0.0107	-1.19 %	HA88
0.6947	0.7501	0.7024	0.7567	-0.0066	-0.88 %	TI06
0.7020	0.7400	0.7036	0.7453	-0.0053	-0.72 %	KÄ89
0.7025	0.7100	0.7037	0.7142	-0.0042	-0.60 %	KÄ89
0.7020	0.7100	0.7036	0.7140	-0.0040	-0.56 %	KÄ89
0.7044	0.7545	0.7026	0.7587	-0.0042	-0.55 %	HA88
0.7005	0.7090	0.7024	0.7107	-0.0017	-0.24 %	TI06
0.7011	0.7381	0.7023	0.7397	-0.0016	-0.21 %	MA89
0.7020	0.7200	0.7036	0.7215	-0.0015	-0.21 %	KÄ89
0.7011	0.7263	0.7023	0.7278	-0.0015	-0.21 %	MA89
0.7009	0.7610	0.7037	0.7623	-0.0013	-0.17 %	RÄ01
0.7014	0.7014	0.7024	0.7024	-0.0010	-0.14 %	TI06
0.7028	0.7046	0.7038	0.7054	-0.0009	-0.12 %	RÄ01
0.7015	0.7024	0.7024	0.7032	-0.0008	-0.12 %	TI06
0.7028	0.7050	0.7038	0.7059	-0.0008	-0.12 %	RÄ01
0.7027	0.7074	0.7038	0.7082	-0.0008	-0.11 %	RÄ01
0.7027	0.7097	0.7038	0.7105	-0.0007	-0.10 %	RÄ01
0.7017	0.7017	0.7024	0.7024	-0.0007	-0.09 %	TI06
0.7011	0.7263	0.7023	0.7269	-0.0006	-0.08 %	MA89
0.7018	0.7018	0.7024	0.7024	-0.0006	-0.08 %	TI06
0.7018	0.7019	0.7024	0.7024	-0.0005	-0.07 %	TI06
0.7036	0.7096	0.7036	0.7101	-0.0005	-0.07 %	BG84
0.7028	0.7163	0.7037	0.7167	-0.0005	-0.07 %	RÄ01
0.7033	0.7700	0.7039	0.7705	-0.0005	-0.06 %	KÄ89
0.7019	0.7026	0.7024	0.7030	-0.0004	-0.06 %	TI06
0.7044	0.7280	0.7026	0.7284	-0.0004	-0.05 %	HA88
0.7030	0.7510	0.7026	0.7514	-0.0004	-0.05 %	MQ84
0.7036	0.7043	0.7036	0.7045	-0.0003	-0.04 %	BG84
0.7022	0.7416	0.7037	0.7418	-0.0002	-0.03 %	RÄ01
0.7030	0.7600	0.7038	0.7601	-0.0001	-0.01 %	KÄ89
0.7023	0.7130	0.7019	0.7130	0.0000	-0.01 %	MA83
0.7025	0.7100	0.7037	0.7098	0.0002	0.03 %	KÄ89
0.7011	0.7335	0.7023	0.7332	0.0003	0.04 %	MA89
0.7025	0.7464	0.7037	0.7461	0.0003	0.05 %	RÄ01
0.7011	0.7295	0.7023	0.7291	0.0004	0.05 %	MA89
0.7036	0.7131	0.7036	0.7127	0.0004	0.05 %	BG84
0.7024	0.7140	0.7023	0.7136	0.0004	0.05 %	MA83
0.7036	0.7174	0.7036	0.7171	0.0004	0.05 %	BG84
0.7023	0.7383	0.7019	0.7379	0.0004	0.05 %	MA83
0.7036	1.3413	0.7029	1.3405	0.0007	0.05 %	HA88
0.7030	0.7179	0.7026	0.7174	0.0005	0.06 %	MQ84
0.7024	0.7275	0.7023	0.7270	0.0005	0.07 %	MA83
0.7030	0.7083	0.7026	0.7078	0.0005	0.07 %	MQ84
0.7011	0.7183	0.7026	0.7178	0.0005	0.08 %	MA89
0.7028	0.7066	0.7024	0.7060	0.0005	0.08 %	TI06

Sample	Location*		Rock	Age (Ma)	Analysis:	
	E	N			Rb	Sr
H52	29.27	64.42	TTG	2670 ± 300	93	250
3525	26.79	69.48	charnockite	1918 ± 107	2	661
G154	28.97	64.45	metagranite	2500 ± 70	102	662
6690	23.50	61.61	granodiorite	1775 ± 52	131	268
6870	24.24	61.65	trachyte	1847 ± 92	173	511
G195	28.97	64.45	metagranite	2500 ± 70	121	659
H77	29.47	64.26	TTG	2860 ± 90	266	258
H32	29.47	64.26	TTG	2860 ± 90	71	1285
6873	23.53	61.63	rhyolite	1898 ± 50	81	97
H49	29.35	64.33	TTG	2860 ± 90	121	314
H397	29.51	64.48	granodiorite-granite	2500 ±	72	822
G6	28.97	64.45	metagranite	2500 ± 70	107	764
6929	23.49	61.62	plagioclase porphyry	1740 ± 70	161	329
6926	23.49	61.62	plagioclase porphyry	1740 ± 70	92	441
H446	29.14	65.23	granodiorite	2550 ± 250	55	575
H399	29.51	64.48	granodiorite-granite	2500 ±	94	816
H451	29.14	65.23	granodiorite	2550 ± 250	44	713
G187	28.97	64.45	metagranite	2500 ± 70	165	244
6876	23.53	61.63	basalt	1898 ± 50	39	202
H447	29.14	65.23	granodiorite	2550 ± 250	53	500
H450	29.14	65.23	granodiorite	2550 ± 250	56	522
6872	23.53	61.63	dacite	1898 ± 50	91	158
H53	29.52	64.43	TTG	2860 ± 90	136	706
1f	28.57	64.65	granite	2500 ± 270	130	141
1d	28.60	64.70	granite	2500 ± 270	91	244
H449	29.14	65.23	granodiorite	2550 ± 250	49	670
G193	28.97	64.45	metagranite	2500 ± 70	125	509
1a	28.59	64.61	tonalite	2500 ± 270	37	554
3933	26.03	68.88	khondalite	1918 ± 107	58	252
6	27.64	63.08	carbonatite	2610 ±	16	8069
6689	23.40	61.65	granodiorite	1775 ± 52	129	173
H46	29.35	64.33	TTG	2860 ± 90	121	351
G148	28.97	64.45	metagranite	2500 ± 70	132	344
H60	28.80	64.76	metagranite/-granodiorite	2510 ± 110	59	554
6927	23.49	61.62	feldspar porphyry	1740 ± 70	81	413
H59	29.04	64.81	metagranite/-granodiorite	2510 ± 110	102	774
S17	29.25	65.28	metatuff	2500 ± 100	26	243
H356	28.80	64.76	metagranite/-granodiorite	2510 ± 110	47	323
S70	29.25	65.28	metatuff	2500 ± 100	39	541
4	27.64	63.08	carbonatite	2610 ±	34	2223
6878	23.53	61.62	basaltic andesite	1898 ± 50	13	254
1	27.64	63.08	carbonatite	2610 ±	104	2680
S29	29.25	65.28	metatuff	2500 ± 100	9	223
S160	29.25	65.28	metatuff	2500 ± 100	48	410
6694	23.49	61.62	monzodiorite	1775 ± 52	109	339
6692	23.50	61.61	granodiorite	1775 ± 52	70	379
6691	23.40	61.65	granodiorite	1775 ± 52	127	277
6693	23.50	61.61	granodiorite	1775 ± 52	73	400
4698	27.86	68.54	khondalite	1918 ± 107	82	198
H62	29.04	64.81	metagranite/-granodiorite	2510 ± 110	96	273

| (^{87}Sr/^{86}Sr)$_0$ | ^{87}Sr/^{86}Sr | Estimate: | | Estimate error: | | Analysis |
		(^{87}Sr/^{86}Sr)$_0$	^{87}Sr/^{86}Sr	Absolute	Relative	Source**
0.7011	0.7438	0.7023	0.7432	0.0006	0.08 %	MA89
0.7036	0.7045	0.7036	0.7039	0.0006	0.09 %	BG84
0.7030	0.7190	0.7026	0.7183	0.0007	0.10 %	MQ84
0.7030	0.7400	0.7038	0.7393	0.0007	0.10 %	KÄ89
0.7025	0.7300	0.7037	0.7292	0.0008	0.11 %	KÄ89
0.7030	0.7222	0.7026	0.7214	0.0008	0.12 %	MQ84
0.7023	0.8253	0.7019	0.8243	0.0010	0.13 %	MA83
0.7023	0.7093	0.7019	0.7084	0.0009	0.13 %	MA83
0.7020	0.7700	0.7036	0.7689	0.0011	0.14 %	KÄ89
0.7023	0.7484	0.7019	0.7473	0.0011	0.15 %	MA83
0.7011	0.7126	0.7026	0.7115	0.0011	0.15 %	MA89
0.7030	0.7180	0.7026	0.7169	0.0011	0.15 %	MQ84
0.7033	0.7400	0.7039	0.7387	0.0013	0.18 %	KÄ89
0.7033	0.7200	0.7039	0.7187	0.0013	0.18 %	KÄ89
0.7011	0.7137	0.7025	0.7124	0.0013	0.18 %	MA89
0.7011	0.7157	0.7026	0.7144	0.0013	0.18 %	MA89
0.7011	0.7102	0.7025	0.7089	0.0013	0.18 %	MA89
0.7030	0.7736	0.7026	0.7722	0.0014	0.19 %	MQ84
0.7020	0.7200	0.7036	0.7185	0.0015	0.21 %	KÄ89
0.7011	0.7151	0.7025	0.7136	0.0015	0.21 %	MA89
0.7011	0.7153	0.7025	0.7137	0.0016	0.23 %	MA89
0.7020	0.7500	0.7036	0.7483	0.0017	0.23 %	KÄ89
0.7023	0.7263	0.7019	0.7246	0.0017	0.24 %	MA83
0.7044	0.7998	0.7026	0.7978	0.0020	0.25 %	HA88
0.7044	0.7427	0.7026	0.7409	0.0019	0.25 %	HA88
0.7011	0.7119	0.7025	0.7101	0.0018	0.26 %	MA89
0.7030	0.7296	0.7026	0.7277	0.0019	0.26 %	MQ84
0.7044	0.7113	0.7026	0.7095	0.0018	0.26 %	HA88
0.7036	0.7235	0.7036	0.7216	0.0019	0.26 %	BG84
0.7042	0.7044	0.7024	0.7026	0.0019	0.26 %	TI06
0.7030	0.7600	0.7038	0.7580	0.0020	0.27 %	KÄ89
0.7023	0.7447	0.7019	0.7425	0.0022	0.30 %	MA83
0.7030	0.7442	0.7026	0.7419	0.0023	0.30 %	MQ84
0.7049	0.7156	0.7025	0.7134	0.0022	0.31 %	MA83
0.7033	0.7200	0.7039	0.7178	0.0022	0.31 %	KÄ89
0.7049	0.7184	0.7025	0.7161	0.0023	0.32 %	MA83
0.7050	0.7160	0.7026	0.7136	0.0024	0.33 %	MQ84
0.7049	0.7198	0.7025	0.7173	0.0025	0.34 %	MA83
0.7050	0.7124	0.7026	0.7099	0.0025	0.35 %	MQ84
0.7048	0.7065	0.7024	0.7040	0.0025	0.35 %	TI06
0.7020	0.7100	0.7036	0.7075	0.0025	0.36 %	KÄ89
0.7049	0.7091	0.7024	0.7065	0.0026	0.37 %	TI06
0.7050	0.7094	0.7026	0.7067	0.0027	0.38 %	MQ84
0.7050	0.7173	0.7026	0.7146	0.0027	0.38 %	MQ84
0.7030	0.7300	0.7038	0.7271	0.0029	0.39 %	KÄ89
0.7030	0.7200	0.7038	0.7171	0.0029	0.40 %	KÄ89
0.7030	0.7400	0.7038	0.7371	0.0029	0.40 %	KÄ89
0.7030	0.7200	0.7038	0.7171	0.0029	0.40 %	KÄ89
0.7036	0.7391	0.7036	0.7359	0.0031	0.42 %	BG84
0.7049	0.7420	0.7025	0.7388	0.0032	0.43 %	MA83

Sample	Location*		Rock	Age (Ma)	Analysis:	
	E	N			Rb	Sr
S64	29.25	65.28	metatuff	2500 ± 100	76	381
6879	23.53	61.62	basaltic andesite	1898 ± 50	28	162
6925	23.49	61.62	feldspar porphyry	1740 ± 70	129	214
H355	29.04	64.81	metagranite/-granodiorite	2510 ± 110	72	827
H63	29.04	64.81	metagranite/-granodiorite	2510 ± 110	108	379
A1040	27.41	61.29	granite	1600 ± 7	255	151
6868	24.25	61.65	basaltic trachyandesite	1847 ± 92	39	1046
6871	24.24	61.65	trachyte	1847 ± 92	127	752
3931	26.16	68.88	khondalite	1918 ± 107	83	249
1b	27.64	63.08	carbonatite	2610 ±	17	4572
A1042	27.36	61.34	granite	1600 ± 7	229	98
G60	28.97	64.45	granite	2410 ± 40	152	92
OTR-84-103a	22.27	61.99	granite	1867 ± 5.6	152	218
2a	29.34	64.72	granite	2290 ± 110	202	254
4695	28.11	68.54	khondalite	1918 ± 107	76	311
A1043	27.52	61.21	granite	1600 ± 7	177	169
6688	23.40	61.65	granodiorite	1775 ± 52	130	297
G15	28.97	64.45	granite	2410 ± 40	188	115
1b	28.77	64.58	tonalite	2500 ± 270	70	389
4694	26.05	69.30	khondalite	1918 ± 107	88	290
A1041	27.55	61.32	granite	1600 ± 7	351	58
A1044	27.44	61.23	granite	1600 ± 7	322	66
4699	27.86	68.54	khondalite	1918 ± 107	117	140
MKT-86-195,2	27.44	61.19	granite	1600 ± 7	182	156
4696	28.11	68.54	khondalite	1918 ± 107	86	214
G16	28.97	64.45	granite	2410 ± 40	136	178
G59	28.97	64.45	granite	2410 ± 40	172	162
G63	28.97	64.45	granite	2410 ± 40	198	154
OTR-87-202,1	27.56	61.25	granite	1600 ± 7	145	190
4697	27.86	68.54	khondalite	1918 ± 107	118	260
A1045	27.26	61.21	granite	1600 ± 7	239	79
H392	29.27	64.42	TTG	2670 ± 300	85	290
A1358	22.15	62.08	granite	1867 ± 6	217	206
G61	28.97	64.45	granite	2410 ± 40	172	178
A1097	27.41	61.32	granite	1600 ± 7	696	9
G5	28.97	64.45	granite	2410 ± 40	176	119
2e	29.46	64.57	granite	2290 ± 110	445	24
MKT-87-664,2	27.32	61.30	granite	1600 ± 7	683	19
2f	29.36	64.54	granite	2290 ± 110	502	12
A588	22.24	62.17	granite	1867 ± 6	139	83
2d	29.35	64.58	granite	2290 ± 110	403	27

* Coordinates (E, N) are in geographical EUREF-FIN system (corresponds approximately to WGS84). If no coordinates were given in the original publication, coordinates were approximated from the sample localities map in the publication.

** Sources: BG84 = Bernard-Griffiths et al. (1984); HA88 = Halliday et al. (1988); KÄ89 = Kähkönen et al. (1989); MA89 = Martin (1989); MQ84 = Martin and Querré (1984); MA83 = Martin et al. (1983); RÄ99 = Rämö (1999); RÄ01 = Rämö et al. (2001); TI06 = Tichomirowa et al. (2006).

TTG = tonalite-trondhjemite-granodiorite in rock names. Rb and Sr concentrations are in ppm. Constants used in estimate calculation are: λ_{Rb-87} = 1.42×10^{-11} y^{-11}; $^{84}Sr/^{86}Sr$ = 0.056584; $^{88}Sr/^{86}Sr$ = ($^{86}Sr/^{88}Sr$)$^{-1}$ = 0.1194^{-1}.

		Estimate:		Estimate error:		Analysis
$(^{87}Sr/^{86}Sr)_0$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$	$^{87}Sr/^{86}Sr$	Absolute	Relative	Source**
0.7050	0.7260	0.7026	0.7229	0.0031	0.43 %	MQ84
0.7020	0.7200	0.7036	0.7169	0.0031	0.43 %	KÄ89
0.7033	0.7500	0.7039	0.7468	0.0032	0.43 %	KÄ89
0.7049	0.7147	0.7025	0.7115	0.0032	0.44 %	MA83
0.7049	0.7352	0.7025	0.7319	0.0033	0.45 %	MA83
0.7055	0.8189	0.7042	0.8151	0.0038	0.46 %	RÄ99
0.7025	0.7100	0.7037	0.7065	0.0035	0.49 %	KÄ89
0.7025	0.7200	0.7037	0.7164	0.0036	0.50 %	KÄ89
0.7036	0.7334	0.7036	0.7298	0.0036	0.50 %	BG84
0.7059	0.7063	0.7024	0.7027	0.0036	0.50 %	TI06
0.7055	0.8626	0.7042	0.8579	0.0048	0.55 %	RÄ99
0.7080	0.8738	0.7027	0.8689	0.0049	0.57 %	MQ84
0.7067	0.7616	0.7037	0.7571	0.0044	0.58 %	RÄ01
0.7036	0.7824	0.7029	0.7778	0.0046	0.59 %	HA88
0.7036	0.7271	0.7036	0.7228	0.0043	0.59 %	BG84
0.7072	0.7774	0.7042	0.7728	0.0046	0.59 %	RÄ99
0.7030	0.7400	0.7038	0.7356	0.0044	0.60 %	KÄ89
0.7080	0.8718	0.7027	0.8663	0.0055	0.63 %	MQ84
0.7044	0.7257	0.7026	0.7210	0.0047	0.64 %	HA88
0.7036	0.7325	0.7036	0.7273	0.0052	0.71 %	BG84
0.7033	1.1192	0.7042	1.1112	0.0080	0.72 %	RÄ99
0.7044	1.0392	0.7042	1.0317	0.0075	0.73 %	RÄ99
0.7036	0.7750	0.7036	0.7693	0.0057	0.74 %	BG84
0.7083	0.7863	0.7042	0.7805	0.0059	0.75 %	RÄ99
0.7036	0.7406	0.7036	0.7350	0.0056	0.75 %	BG84
0.7080	0.7845	0.7027	0.7785	0.0060	0.76 %	MQ84
0.7080	0.8149	0.7027	0.8084	0.0065	0.80 %	MQ84
0.7080	0.8377	0.7027	0.8310	0.0067	0.80 %	MQ84
0.7095	0.7604	0.7042	0.7540	0.0065	0.85 %	RÄ99
0.7036	0.7458	0.7036	0.7392	0.0066	0.88 %	BG84
0.7078	0.9132	0.7042	0.9051	0.0081	0.89 %	RÄ99
0.7011	0.7412	0.7023	0.7345	0.0067	0.91 %	MA89
0.7090	0.7920	0.7037	0.7846	0.0075	0.94 %	RÄ01
0.7080	0.8072	0.7027	0.7988	0.0084	1.04 %	MQ84
0.6887	10.8487	0.7042	10.6851	0.1636	1.51 %	RÄ99
0.7080	0.8638	0.7027	0.8505	0.0133	1.54 %	MQ84
0.7036	2.8821	0.7029	2.8228	0.0593	2.06 %	HA88
0.7201	3.8202	0.7042	3.7346	0.0857	2.24 %	RÄ99
0.7036	7.7627	0.7029	7.4278	0.3349	4.31 %	HA88
0.6952	0.8710	0.7037	0.8326	0.0384	4.41 %	RÄ01
0.7036	2.4560	0.7029	2.3351	0.1209	4.92 %	HA88

3. Methods

3.1 Estimating the $^{87}Sr/^{86}Sr$ ratio of the rock

In the following a method to estimate the $^{87}Sr/^{86}Sr$ ratio of a rock based on its measured Rb/Sr concentration and age information is derived.

The equation of radioactive decay for Rb-Sr system is

$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_o + \frac{^{87}Rb}{^{86}Sr}\ (e^{\lambda t} - 1) \qquad , \rightarrow (1)$$

$^{87}Rb/^{86}Sr$ can be expressed as

$$\frac{^{87}Rb}{^{86}Sr} = \frac{Rb}{Sr}\ \frac{(Ab^{87}Rb)\ (WSr)}{(Ab^{86}Sr)\ (WRb)}, \rightarrow (2)$$

where W to refers to the atomic weight of an element and Ab to the abundance (%) of an isotope. WSr/Ab^{86}Sr can be written as

$$\frac{WSr}{Ab^{86}Sr} = 84\ \frac{^{84}Sr}{^{86}Sr} + 86 + 87\ \frac{^{87}Sr}{^{86}Sr} + 88\ \frac{^{88}Sr}{^{86}Sr}, (3)$$

We can now substitute (3) and (2) to (1), solve for $^{87}Sr/^{86}Sr$ and obtain an estimation (S) for the isotope ratio $^{87}Sr/^{86}Sr$. $I = (^{87}Sr/^{86}Sr)_0$ is used to denote the initial isotope ratio of a rock:

$$S(Rb,Sr,I,t) = \frac{I + \dfrac{Rb}{Sr}\ \dfrac{Ab^{87}Rb}{WRb}\left(84\ \dfrac{^{84}Sr}{^{86}Sr} + 86 + 88\ \dfrac{^{88}Sr}{^{86}Sr}\right)(e^{\lambda t} - 1)}{1 - 87\dfrac{Rb}{Sr}\ \dfrac{Ab^{87}Rb}{WRb}\ (e^{\lambda t} - 1)} \qquad . (4)$$

Unknowns are I, Rb, Sr and t. $^{84}Sr/^{86}Sr$ and $^{88}Sr/^{86}Sr$ are known and constants. An approximation for the initial isotope ratio I is made using an assumption that rocks originate from the mantle. The $^{87}Sr/^{86}Sr$ ratios of the hypothesized magma sources in the mantle (depleted MORB mantle, enriched mantle type 1 and 2, "high μ" mantle) fall approximately between 0.702 and 0.707 (today's values) (Faure & Mensing, 2005). On the other hand, the initial $^{87}Sr/$

^{86}Sr ratios of basaltic achondrites are 0.69899 ± 0.000047 (Faure & Powell, 1972). Based on this information, the evolution of the initial isotope ratio of the mantle source can be approximated if assumed that the evolution of their isotope ratios has been linear through the history of the Earth. In this study, the rocks are assumed to have a mantle source, and a rough linear approximation of their initial $^{87}Sr/^{86}Sr$ ratios has been used to include the plausible variation of different possible magma sources:

$$I(t) = 0.699 + \frac{(4500\ Ma - t)\ (0.707 - 0.699)}{4500\ Ma} \qquad . \rightarrow (5)$$

Where t is the age of the sample, and the range of 0.699 to 0.707 is chosen to represent all possible mantle sources (sampling of heterogenous mantle).

3.2 Spatial interpolation of the estimates for the area of Finland

Below a method to generalize the estimated isotope ratios at single RGDB sample points to cover the whole area of Finland is described.

Number of suitable points (*Sr* and *Rb* concentration and age *t* given) in RGDB for estimate calculation is 6379. For every sample in RGDB the bedrock unit has been reported using the unit classification of the bedrock map 1:1 000 000 of Finland (Korsman *et al.*, 1997). Using this same classification the estimations at the sample points have been divided to eleven major units, for which the quartiles Q_1 and Q_3 and medians of the estimated values have been calculated. Average values and standard deviations are not supposed to be proper parameters to describe isotope ratios because of significant skewness of distributions and single large values outside the distributions.

To develop an estimate covering the whole area of Finland, the estimated $^{87}Sr/^{86}Sr$ values (S_j) at RGDB sample points have been interpolated using smoothing. The smoothed estimate S_s at any given point $\boldsymbol{p}$ is

$$S_S(\mathbf{p}) = \frac{\sum_j S(Rb_j, Sr_j, I_j, t_j)\ k(\mathbf{p} - \boldsymbol{x}_j, \sigma)}{\sum_j k(\mathbf{p} - \boldsymbol{x}_j, \sigma)} \qquad , \rightarrow (6)$$

where j runs over the sample points, S is the estimated ^{87}Sr/^{86}Sr ratio at the sample point, x_j is the sample point, and k is a Gaussian smoothing kernel as a function of standard deviation σ and distance between estimation point and point p.

In addition, the smoothing has been weighted by the measured Sr concentration, resulting a weighted smoothed estimate S_{sw}:

$$S_{SW}(\mathbf{p}) = \frac{\sum_j S(Rb_j, Sr_j, I_j, t_j) \, k(\mathbf{p} - \mathbf{x}_j, \sigma)Sr_j}{\sum_j k(\mathbf{p} - \mathbf{x}_j, \sigma)Sr_j}, \rightarrow \quad \rightarrow (7)$$

3.3 Evaluation of the method

The following sections consider the significance of the initial ratio approximation to the accuracy of the final estimate, and describe how to evaluate the method using published strontium isotope analyses.

3.3.1 Significance of the initial ratio approximation

The estimation method is easy to generalize to wide areas, if elemental analyses are available. The downside of the method is the troublesome estimation of the initial isotope ratio. On account of easy generalization it is not possible to estimate the initial ratio using information about the possibly known petrological history and age of each sample. However, examining the effect of changes in the approximated initial isotope ratio by differentiating equation (4) with respect to the initial ratio I gives

$$\frac{dS}{dI} = \frac{1}{1 - 87\dfrac{Rb}{Sr}\dfrac{Ab^{87}Rb}{WRb}(e^{\lambda t} - 1)} \approx \frac{1}{1 - 0.0085\dfrac{Rb}{Sr}} \approx 1 \quad , \rightarrow (8)$$

when 3.0 Ga < t < 1.5 Ga and Rb/Sr < 10. Thus the change in the estimated value of the isotope ratio is equal to the change (ie. error) in the approximated initial isotope ratio. This means that the error of initial isotope approximation I propagades directly to the error of the final ^{87}Sr/^{86}Sr estimate.

The ^{87}Sr/^{86}Sr ratios of today's oceanic island basalts (OIB) representing mantle derived magmas variate between 0.703–0.707 (Faure & Mensing,

2005). The upper part of the sub-oceanic convective mantle represents depleted mantle (DM), which is the source for the mid-ocean ridge basalts, MOR-Bs (^{87}Sr/^{86}Sr increasing from 0.7005 to 0.7025 during the time from 3 Ga to today) (Workman & Hart, 2005). Therefore, when dealing with rocks with age of 3–1.6 Ga, as is the case with Finnish Precambrian, the maximum error of the linear approximation of the initial isotope ratios due to source (mantle) heterogeneity is 0.707–0.7005=0.0065. This difference between depleted and enriched mantle source isotope ratios narrows down to 0.0029 at 1,6 Ga and 0.0015 at 3 Ga, assuming linear evolution of isotope ratios in the mantle reservoirs (that is, growing mantle heterogeneity). It is therefore plausible to assume that, if a rock is undifferentiated and originates from such a source, the maximum error in the approximated value 0.699–0.707 of the initial ratio in equation (5) is insignificant for the final ^{87}Sr/^{86}Sr ratio estimation in desired accuracy. On the other hand, in differentiated magma Rb is enriched in the melt relative to Sr, raising the Rb/Sr ratio and thus leading to higher ^{87}Rb concentration and, in time, higher ^{87}Sr/^{86}Sr ratios. This reduces the significance of the error in the approximation of the initial isotope ratio relative to the increase of the ^{87}Sr/^{86}Sr ratio caused by the decay of ^{87}Rb.

It is noteworthy that equation (5) is an upper limit approximation of the initial isotope ratios (today's value of 0.707 accounting for enriched mantle sources). The approximation gives the best correspondence between measured initial isotope ratios and approximated initial isotope ratios in the sample set. This merely demonstrates the fact that the isotope evolution has not been linear, and that for example at 3 Ga the DM value 0.7005 (Workman & Hart, 2005) is underestimated by the linear approximation giving a value 0.7002.

3.3.2 Strontium isotope analyses

The method is evaluated by applying it to published Rb-Sr isotope analyses from bedrock samples. The method together with age and Rb/Sr data from the published analysis is used to calculate an estimated

$^{86}Sr/^{86}Sr$ ratio (S), which then is compared to the measured value given by the analysis. The absolute and relative errors are calculated.

4. Results

All results were calculated and all figures produced using software **R** (R Development Core Team, 2009) and its **sp** library (Pebesma & Bivand, 2005).

4.1 Spatial interpolation of the estimates for the area of Finland

Table 2 and Fig. 2 show the Sr isotope ratio estimates of the bedrock of Finland by bedrock units. Bedrock units are listed in Table 2 and can be divided into Archaean units of Karelian Domain (*KrAr*, predominantly gneisses of TTG composition), Lapland Granulite Belt and Inari Complex (*Grl*, *Ina*), and Proterozoic units of Svecofennian Domain (*SvA, SvB, SvC, SvGr, SvCol*, arc complexes and orogeny related intrusions; *Rap*, Rapakivi intrusions and related mafic rocks) and of Karelian Domain (*KrPr*, mainly supracrustal rocks). Figures 3 and 4 show the smoothed estimation for the isotope ratio in the Finnish bedrock. The Sr concentration (ppm in RGDB samples) weighted average of estimated $^{87}Sr/^{86}Sr$ ratios is 0.7293.

Table 2. The medians and interquartile ranges (Q_3-Q_1) of the $^{87}Sr/^{86}Sr$ estimates by bedrock unit.

Unit	N	Median	Q_3-Q_1	Skewness	Kustosis	Sr conc weighted mean
Svecofennian Domain, Accretionary arc complex of southern Finland (SvA)	825	0.7637	0.1077	4.39	35.75	0.751
Svecofennian Domain, Accretionary arc complex of central and western Finland (SvB)	705	0.7335	0.0390	3.83	34.33	0.728
Svecofennian Domain, Primitive arc complex of central Finland (SvC)	227	0.7184	0.0243	2.60	11.59	0.720
Svecofennian Domain, Collision-related intrusions (SvCol), overlaps SvA, SvB, SvC	1066	0.7169	0.0186	12.72	211.67	0.717
Svecofennian Domain, Intrusions post-dating main stage of crustal thickening (SvGr), overlaps SvA, SvB, SvC	260	0.7628	0.0764	6.79	60.63	0.752
Rapakivi intrusions (Rap)	154	0.7617	0.0445	8.29	77.72	0.762
Karelian Domain, Archean rocks (KrAr)	1118	0.7236	0.0285	4.63	31.10	0.726
Karelian Domain, post-Archaean rocks (KrPr)	1464	0.7424	0.1188	17.58	436.39	0.742
Lapland Granulite Belt and Inari Complex, post-Archaean rocks (Grl)	301	0.7209	0.0255	14.13	221.97	0.719
Lapland Granulite Belt and Inari Complex, Archaean rocks (Ina)	67	0.7476	0.0865	1.51	4.68	0.755
Caledonian Domain (Kal)	12	0.7189	0.0250	0.67	2.18	0.714
Other units	180	0.7135	0.0339	9.21	97.47	0.725

Abbreviations used for the units in the text are in parentheses. The unit names are from Korsman et al. (1997). For their locations, see Figure 1.
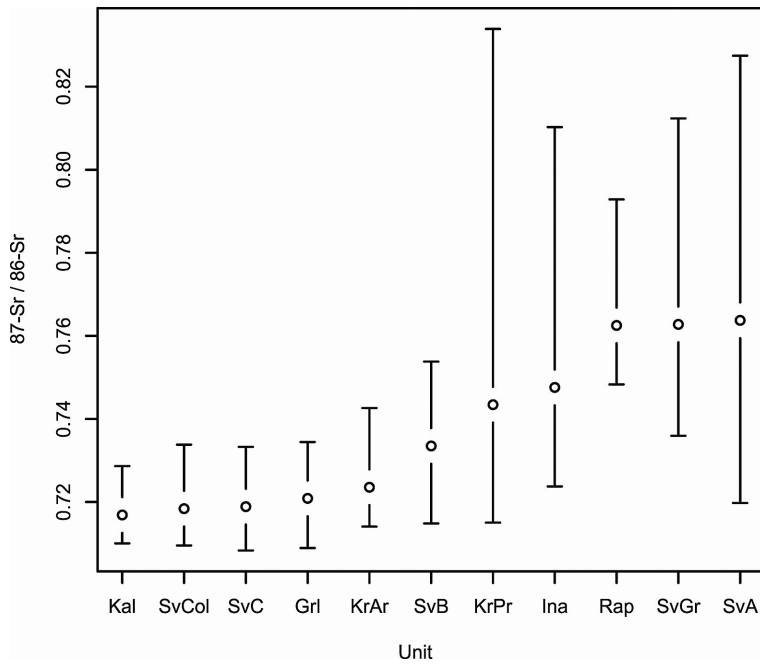
Fig. 2. The medians and first and third quartiles of the ^{87}Sr/^{86}Sr estimates by bedrock unit. (For abbreviations, see Table 2.)

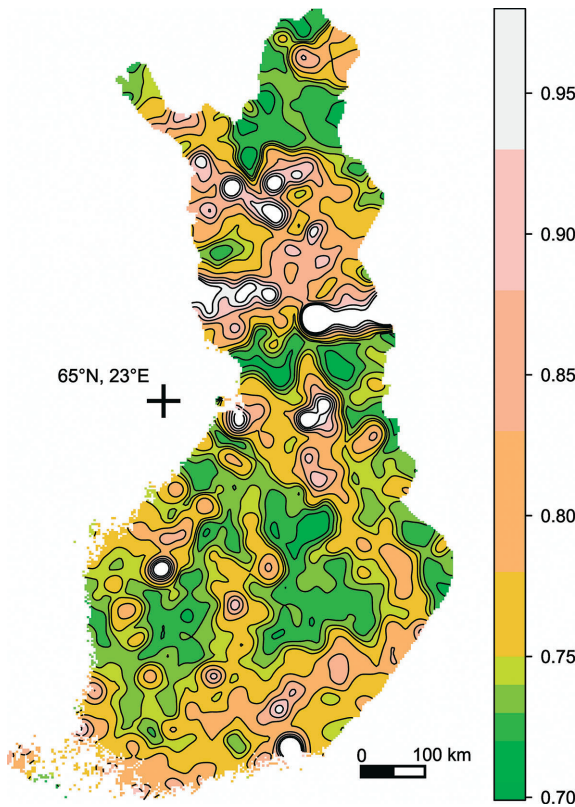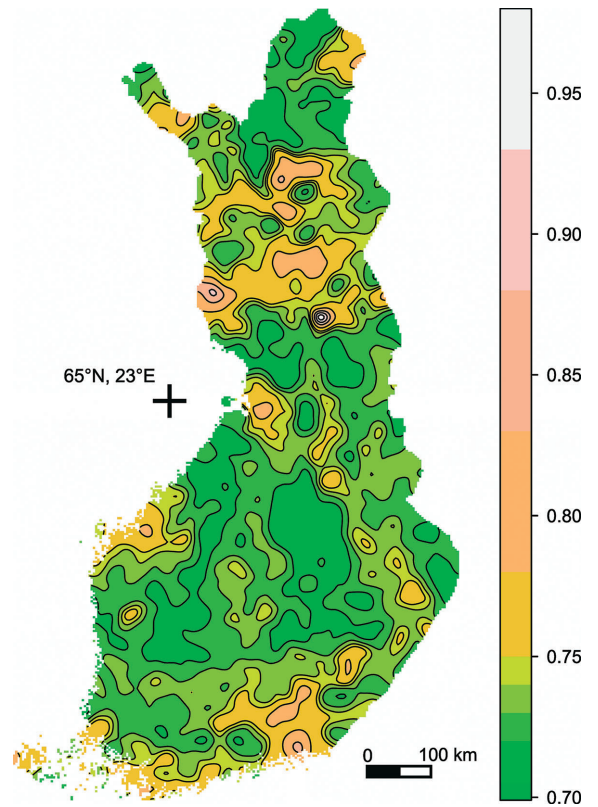**Fig. 3.** The smoothed estimation for the ^{87}Sr/^{86}Sr ratio of the Finnish bedrock. σ = 10 km.

Fig. 4. The smoothed and Sr-concentration-weighted estimation for the ^{87}Sr/^{86}Sr ratio of the Finnish bedrock. σ = 10 km.

4.2 Evaluation of the method using published Rb-Sr isotope analyses

A total of 138 published Rb-Sr isotope analyses from the Finnish Precambrian has been collected (Table 1). The absolute errors of the estimates calculated on the grounds of reported Rb/Sr ratios and ages variate between -0.335 and 0.040 when compared with the $^{87}Sr/^{86}Sr$ ratios measured in the analyses. The relative errors are less than 4.92 %. Yet, most (129) of the relative estimation errors are less than 1.00 %, with an average of 0.32 %. The estimates for which the relative errors exceed 1.00 % (9) are from granitic (*sensu stricto*) samples, granitic samples numbering 35 in total.

The relative error correlates to some extent with the Rb/Sr ratio of the rock. The average error of the estimates for the samples with Rb/Sr > 1 (24 samples, all except one granitic) is 1.49 %, and for the other samples 0.29 %.

For samples with Rb/Sr < 1 (114) the root mean square of errors is (RMS) 0.0028 and the coefficient of determination R^2 = 0.9842 (Fig. 5). For all the 138 analyses and for their estimates corresponding values are RMS = 0.0351 and R^2 = 0.9990.

The measured Rb/Sr ratio correlates well (R^2 = 0.9415; RMS = 0.0053) with measured $^{87}Sr/^{86}Sr$ ratio when Rb/Sr < 1 (Fig. 6), but less well when all the samples are considered (R^2 = 0.8546; RMS = 0.4171).

5. Discussion

When applied to the gathered strontium isotope analyses for which Rb/Sr < 1, and also when applied to all gathered isotope analyses, the method described above has a better coefficient of determination (R^2) and smaller standard residual error than the linear correlation of $^{87}Sr/^{86}Sr$ to Rb/Sr alone (Fig. 6). The errors for some granitic rocks are notable. They are larger than the errors of their initial isoto-

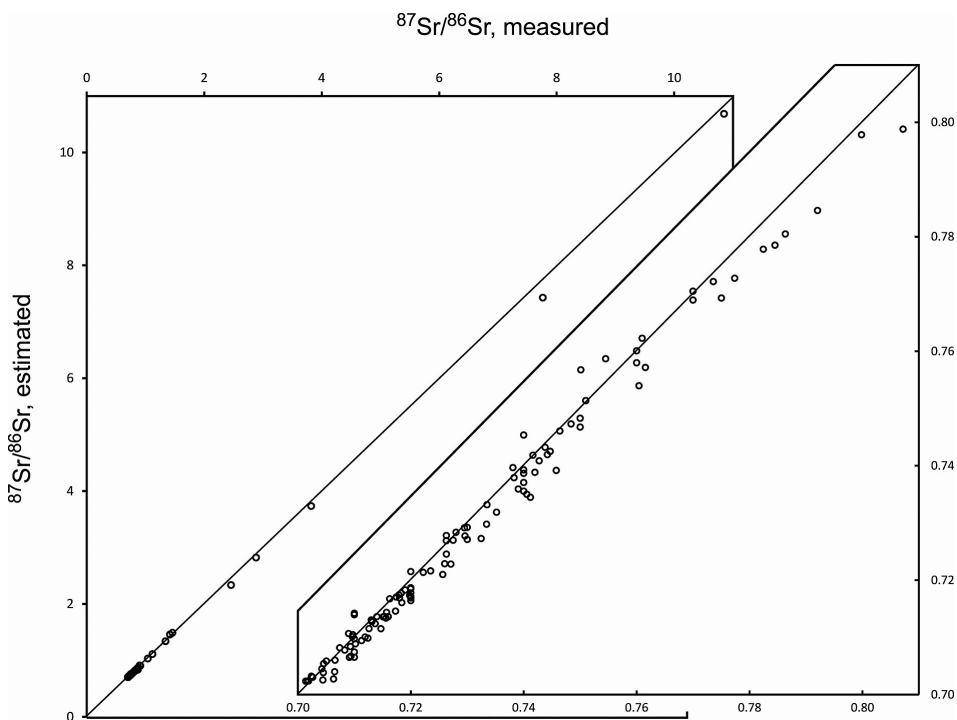**Fig. 5**. The measured $^{87}Sr/^{86}Sr$ ratios from published analyses vs. estimated ratios calculated from Rb and Sr concentrations and age data from the analyses. The equation of the line is y = x.
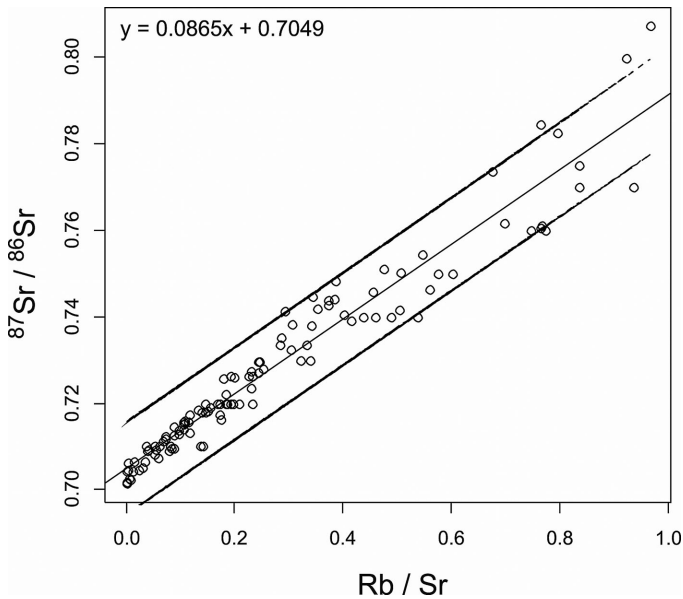
Fig. 6. The 95 % confidence intervals and the regression line fitted for the measured Rb/Sr and ^{87}Sr/^{86}Sr ratios of the published isotope analysis samples (Rb/Sr < 1.0).

pe ratio approximations, suggesting that the errors do not derive from a faulty initial isotope approximation. Typical for these granites are also high Rb/Sr ratios. The low precision of the ages given in RGDB account to some degree for the error of every estimate, except of those aged between 1800 and 2000 Ma.

In the evaluation of the method, the ages used in the Sr isotope ratio estimation are from the Rb-Sr isotope analyses. Generally, Rb-Sr method has given younger ages in the Finnish Precambrian than U-Pb and Pb-Pb methods. If this trend is due to erroneous Rb-Sr ages (cf. Vaasjoki, 1988; Martin & Parbey, 1988), the estimated Sr isotope ratios in the evaluation of the method will have a tendency to lower values, and the absolute error to more negative values from actual. These erroneous Rb-Sr ages may arise out of late fluid related Rb-Sr fractionation which certainly is a reason for the errors in high Rb/Sr samples. Largest absolute errors among high Rb/Sr samples are indeed negative. The nine granitic samples with large relative errors (> 1 %) are a case in point: They have low Sr concentrations (< 150 ppm), a possible indication of Rb and Sr leaching, and thus of possibly biased Rb-Sr ages. In his study of Rapakivi granite batholiths, Rämö (1999) considers young Rb-Sr ages as a result of subsolidus migration of Rb and Sr between mineral grains. Regardless of the exact process the Rb-Sr ages already include the effects of Rb and Sr mobility, and thus are better source material for ^{87}Sr/^{86}Sr estimation than ages from other dating methods. This being the case, the evaluation may give a too optimistic judgement of the estimation method if the method is used together with non-Rb-Sr ages. However, the inexact ages given in RGDB presumably override errors caused by differences in dating methods.

The evaluation of the method shows no clear correlation between errors in initial isotope ratio approximation and today's isotope ratio estimations. However, in larger datasets a major cause for errors in the initial isotope ratio approximations may be the contamination of the magma by crustal material. A plot of estimated ^{87}Sr/^{86}Sr *versus* 1/Sr (Fig. 7) suggests that bedrock units KrPr, KrAr and SvCol have been contaminated quite heavily whereas units Rap, SvGr and SvB only in small amounts.

5.1 The smoothed isotope ratio estimate

The smoothed values at the locations of the estimation points differ from the estimated values. Smoothed values are an estimate of the isotope ratios of the material weathered onto the bedrock. In this case the weathered material is assumed to had spread evenly to every direction following normal distribution in distance. It is not, however, either sensible to fit a parametric function to the estimation points, for it would require an assumption that the Sr isotope ratios are continuous between bedrock units.

The strontium concentration weighted smoothing (Fig. 4) gives clearly lower values for ^{87}Sr/^{86}Sr than the non-weighted smoothing (Fig. 3). This is an expected result, for without weighting by Sr concentration the areas of high Rb/Sr ratio (and thus generally high ^{87}Sr/^{86}Sr ratio but low Sr concentration) would have a too large effect on the

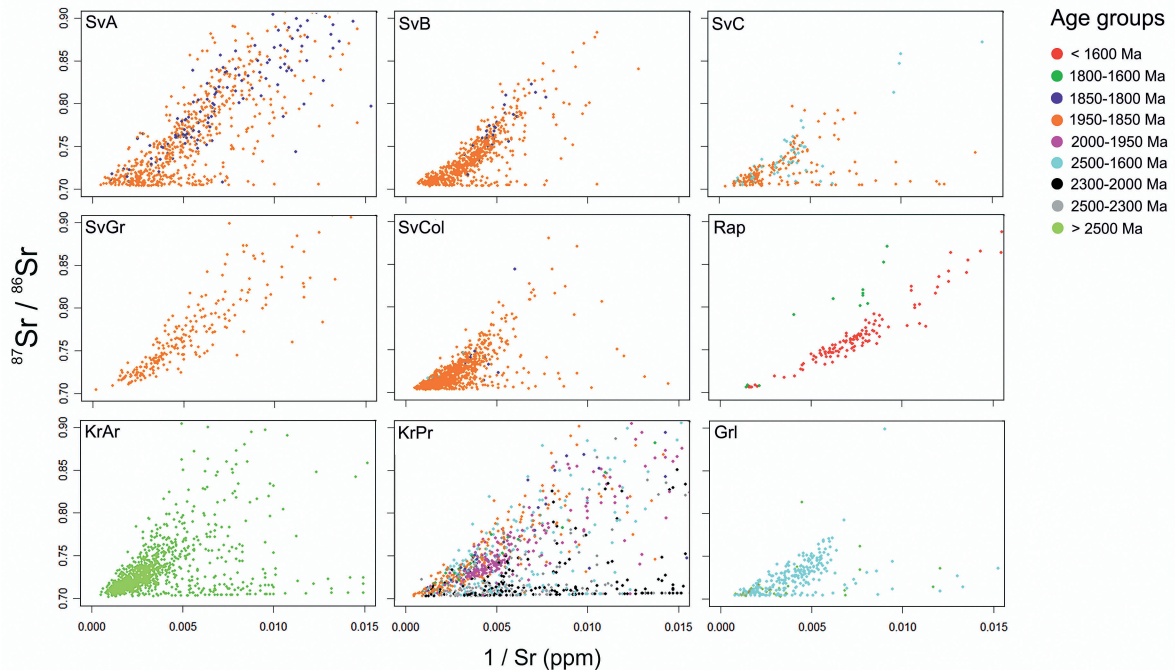**Fig. 7.** ^{87}Sr/^{86}Sr (estimated) *versus* 1/Sr mixing plots for samples from the major bedrock units. Note that samples are of different ages even inside one age group. KrPr shows probably complex mixing of different sources whereas Rap plots straight lines within age groups. Others fall between these two end members. The major bedrock units consist of number of smaller units inside large geographical regions, which means that straight lines are probably due to correlation within age groups (variable age groups plotting on separate lines) and degrees of differentiation. Pure binary mixing of these major units to explain the apparent mixing lines is unlikely. Scattering of the points would thus present smaller scale mixing and general heterogeneity within the bedrock unit.

isotope ratios of the surrounding. Smoothing using Sr concentration requires an assumption that Sr weathers at equal rates from different types of rocks.

The non-weighted smoothing follows well the medians and variations of the isotope ratios calculated by bedrock units. However, the values are probably too high because of the effect of Sr concentration variations. The Sr concentration weighted values are presumably realistic by the order of magnitude: Åberg (1995) has reported ^{87}Sr/^{86}Sr values of 0.71–0.8 from lakes, rivers, soil, and trees of Finland and Sweden. The average ^{87}Sr/^{86}Sr ratio of the strontium in the rivers on the Precambrian shield of Fennoscandia are estimated to be 0.730 (Löfvendahl et al., 1990), which is very close to the Sr concentration weighted average (0.7293) of the estimated values.

5.2 The estimate by bedrock units

There is distinct variation in isotope ratios (Table 2, Fig. 2) between bedrock units, but no systematic difference between the Archaean and Proterozoic areas. This could be explained by relatively similar Rb/Sr ratios of the rocks in these areas, concealing the effect of different age. The internal variation in many units (KrPr, Ina, SvA) is too big to distinct them clearly from the other units, whereas the units with lower medians (Kal, SvCol, SvC, Grl) have smaller internal variation.

On large scale, six areas of different Sr isotope ratios, partly corresponding to major bedrock units, can be distinguished from the smoothed Sr isotope estimate maps:

1) The southern and south-eastern Finland (Rap and SvA, approximately), consisting mainly of Rapakivi intrusions and Uusimaa, Häme and Tampere schist belts (including some Svecofennian late-orogenic granites), is dominated by high values of Sr isotope ratios. These high values in Rapakivi areas are expected because of the high Rb/Sr ratios (> 1) of Rapakivi rocks, due to fractionation during melting of existing crust.

2) Central Finland (SvB, approximately) has mostly low values, but has somewhat large deviation.

3) Three Archaean complexes of Central Karelian, Iisalmi and Pudasjärvi, which form the two southern KrAr units, have low values.

4) Areas 2 and 3 are separated by a zone of higher values from Oulu to south-east, which seems to intersect with early Proterozoic schist belts North Karelia, Kainuu and northern Bothnian (belonging to KrPr) and Svecofennian late-orogenic granites (belonging to SvC and SvA). The southern side of this zone follows the Raahe-Ladoga subduction zone and has a sharp border to lower values.

5) High values dominate also the Proterozoic part of Karelian Domain (KrPr) in central Lapland (consisting of schists of Lapponia and Karelia supergroups: Peräpohja and Kuusamo schist belts, Kittilä allochthon).

6) In northernmost Finland the Lapland granulite belt (Grl) together with western (Proterozoic) Inari area (Ina) has distinctly low Sr isotope ratios.

5.3 Issues to be considered in utilisation of results

The assumption that weathered material spreads evenly to its surrounds is hardly ever perfectly valid. In addition, the spatial accuracy of the estimate is affected by the value of the standard deviation σ used in smoothing. With small values of σ an spatially precise estimate with high resolution is acqui-

red, but with possibly low accuracy. However, in that case the differences between various areas are hard to detect as the number of areas with same isotope ratio is large and the areas are small.

As a mobile element Rb may have traveled long distances with fluids in the faults and joints of the bedrock. Thus the sampling convention of the RGDB causes uncertainty to the estimate, for the samples have been taken from "a distinct and homogeneous lithologic unit" (Rasilainen et al., 2007) and discontinuities may not be well represented in the sample points.

The basic assumption of the method is that the rocks are mantle derived. The validity of this assumption should not be taken as granted. If the method is applied to a specific area or bedrock unit, the Nd isotope studies (or other available indicators for mantle derivation) for this area/unit should be checked to see, if major discrepancies from this assumption exist.

Based on the results, it is not possible to position a single Sr isotope analysed sediment or organism sample to an exact area or corresponding bedrock unit of Finland. However, some of the units or areas can be ruled out from possible provenance alternatives and large scale approximations of provenance can be made. In archaeology/palaeontology the results are probably most easily exploitable in a case of migrating animals or animals with wide living areas, for the Sr isotope ratios of their tissues reflect the average strontium isotope composition of the living area (Feranec et al., 2007). For such cases a large value for σ in smoothing would be appropriate, minimizing the errors deriving from single estimation points with anomalously high error and from faulty assumption of the spreading of weathered material. Smaller values of σ are appropriate when evaluating the estimated isotope ratios to real values in a restricted region using bones and teeth from small animals inside this area.

6. Conclusions

The presented method to estimate the [87]Sr/[86]Sr ratio of the Precambrian of Finland on the basis of age data and Rb/Sr elemental analyses yields an ac-

curate result on most rock types showing very good correlation when evaluated against actual Rb-Sr isotope analyses. Possibly large errors can occur in areas where bedrock has undergone Sr redistribution, e.g. due to fluid activity or subsolidus Rb/Sr migration in granitic plutons. The method can be used together with the data from the Rock Geochemical Database of Finland to derive a large-scale generalization of $^{87}Sr/^{86}Sr$ ratios for the Precambrian of Finland. Distinct areas of high and low $^{87}Sr/^{86}Sr$ ratios are distinguishable in the resulted estimate and approximately six major areas can be outlined. No systematic difference between Archaean and younger rocks due to age difference can be seen in the estimated isotope ratios, and $^{87}Sr/^{86}Sr$ ratio differences are more likely to be due to rock type and Rb/Sr concentration differences. For utilization in sedimentological, archaeological or palaeontological studies the estimation method can bring about a preliminary approximation about the possible provenance areas. Erosional processes and the transportation of Rb and Sr by fluids in rocks need still to be considered and sampling of soil or sediments must be done in more exact provenance studies.

7. Acknowledgements

References

Åberg, G., 1995. The use of natural strontium isotopes as tracers in environmental studies. Water, Air and Soil Pollution 79, 309–322.

Beard, B.L. & Johnson, C.M., 2000. Strontium isotope composition of skeletal material can determine the birth place and geographic mobility of humans and animals. Journal of Forensic Sciences 45, 1049–1061.

Bernard-Griffiths, J., Peucat, J.J., Postaire, B., Vidal, P., Convert, J. & Moreau, B., 1984. Isotopic data (U-Pb, Rb-Sr, Pb-Pb and Sm-Nd) on mafic granulites from Finnish Lapland. Precambrian Research 23, 325–348.

Capo, R.C., Stewart, B.W. & Chadwick, O.A., 1998. Strontium isotopes as tracers of ecosystem processes: theory and methods. Geoderma 82, 197–225.

Curran, J., Meighan, I., Simpson, D., Rogers, G. & Fallick, A., 2001. $^{87}Sr/^{86}Sr$: a new discriminant for provenancing neolithic porcellanite artifacts from Ireland. Journal of Archaeological Science 28, 713–720.

English, N.B., Betancourt, J.L., Dean, J.S. & Quade, J., 2001. Strontium isotopes reveal distant sources of architectural timber in Chaco Canyon, New Mexico. Proceedings of the National Academy of Sciences 98, 11891–11896.

Faure, G. & Mensing, T.M., 2005. Isotopes: Principles and applications. 3rd ed. John Wiley and Sons, Hoboken, New Jersey. 897 p.

Faure, G. & Powell, J.L., 1972. Strontium Isotope Geology. No. 5 in Monograph Series of Theoretical and Experimental Studies. Berlin. 188 p.

Feranec, R.S., Hadly, E.A. & Paytan, A., 2007. Landscape use of Holocene mammals using strontium isotopes. Oecologia 153, 943–950.

Gosz, J.R. & Moore, D.I., 1989. Strontium isotope studies of atmospheric inputs to forested watersheds in New Mexico. Biogeochemistry 8, 115–134.

Halicz, L., Segal, I., Fruchter, N., Stein, M. & Lazar, B., 2008. Strontium stable isotopes fractionate in the soil environments? Earth and Planetary Science Letters 272, 406–411.

Halliday, A., Luukkonen, E.J. & Bowes, D.R., 1988. Rb-Sr whole-rock isotopic study of late Archaean and early Proterozoic granitoid intrusions, Kainuu, Eastern Finland. Bulletin of the Geological Society of Finland 60, 107–113.

Hodell, D.A., Quinn, R.L., Brenner, M. & Kamenov, G., 2004. Spatial variation of strontium isotopes ($^{87}Sr/^{86}Sr$) in the Maya region: a tool for tracking ancient human migration. Journal of Archaeological Science 31, 585–601.

Korsman, K., Koistinen, T., Kohonen, J., Wennerström, M., Ekdahl, E., Honkamo, M., Idman, H. & Pekkala, Y. (toim.), 1997. Suomen kallioperäkartta – Berggrundskarta över Finland – Bedrock map of Finland 1:1 000 000. Geological Survey of Finland, Espoo, Finland.

Krom, M.D., Cli, R.A., Eijsink, L.M., Herut, B. & Chester, R., 1999. The characterisation of Saharan dusts and Nile particulate matter in surface sediments from the Levantine basin using Sr isotopes. Marine Geology 155, 319–330.

Kähkönen, Y., Huhma, H. & Aro, K., 1989. U-Pb zircon ages and Rb-Sr whole-rock isotope studies of early Proterozoic volcanic and plutonic rocks near Tampere, southern Finland. Precambrian Research 45, 27–43.

Löfvendahl, R., Åberg, G. & Hamilton, P.J., 1990. Strontium in the rivers of the Baltic Basin. Aquatic Sciences 52, 315–329.

Martin, H., 1989. Archaean chronology in the eastern part of the Baltic Shield: a synthesis. Precambrian Research 43, 63–77.

Martin, H. & Barbey, P., 1988. Zircon U-Pb versus Rb-Sr

whole-rock age data from eastern Finland. Precambrian Research 39, 221–226.

Martin, H. & Querré, G., 1984. A 2.5 G.a. reworked sialic crust: Rb-Sr ages and isotopic geochemistry of late archaen volcanic and plutonic rocks from E. Finland. Contributions to Mineralogy 85, 292–299.

Martin, H., Chauvel, C., Jahn, B.M. & Vidal, P., 1983. Rb-Sr and Sm-Nd ages and isotopic geochemistry of Archaean granodioritic gneisses from eastern Finland. Precambrian Research 20, 79–91.

Miller, E.K., Blum, J.D. & Friedland, A.J., 1993. Determination of soilexchangeable cation loss and weathering rates using Sr isotopes. Nature 362, 438–441.

Pebesma, E.J. & Bivand, R.S., 2005. Classes and methods for spatial data in R. R News 5 (2), http://cran.r-project.org/doc/Rnews/

Porder, S., Paytan, A. & Hadly, E. A., 2003. Mapping the origin of faunal assemblages using strontium isotopes. Paleobiology 29, 197–204.

Price, T.D., Connor, M. & Parsen, J.D., 1985. Bone chemistry and the reconstruction of diet: strontium discrimination in white-tailed deer. Journal of Archaeological Science 12, 419–442.

R Development Core Team, 2009. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org

Rämö, T., 1999. Sr isotopic composition of Finnish rapakivi granites: the Suomenniemi batolith. Bulletin of the Geological Society of Finland 71, 339–345.

Rämö, T., Vaasjoki, M., Mänttäri, I., Elliott, B.A. & Nironen, M., 2001. Petrogenesis of the post-kinematic magmatism of the Central Finland Granitoid Complex I; radiogenic isotope constraints and implications for crustal evolution. Journal of Petrology 42, 1971–1993.

Rasilainen, K., Lahtinen, R. & Bornhorst, T., 2007. The Rock Geochemical Database of Finland Manual. Geological Survey of Finland, Report of Investigation 164, 1–38.

Rock Geochemical Database of Finland (2008). Version 1.1. Geological Survey of Finland, Espoo, 25th April 2008. Online database accessed 15th June 2008, http://www.gtk.fi/publ/RGDB

Tichomirowa, M., Grosche, G., Götze, J., Belyatsky, B.V., Savva, E.V., Keller, J. & Todt, W., 2006. The mineral isotope composition of two Precambrian carbonatite complexes from the Kola Alkaline Province, alteration versus primary magmatic signatures. Lithos 91, 229–249.

Vaasjoki, M., 1988. Zircon U-Pb versus Rb-Sr whole-rock age data from eastern Finland: a critical comment on the papers of Barbey & Martin and Martin, Precambrian Research, vol. 35, 1987. Precambrian Research 39, 217–219.

Workman, R.K. & Hart, S.R., 2005. Major and trace element composition of the depleted MORB mantle (DMM). Earth and Planetary Science Letters 231, 53–72.