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Sm–Nd garnet and U–Pb monazite dating of high-grade metamorphism and crustal melting in the West Uusimaa area, southern Finland

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Abstract: The 100 km wide late Svecofennian granite-migmatite zone in southern Finland contains the Sulkava, the Turku and the West Uusimaa low-pressure, high-temperature granulite areas. In the West Uusimaa area the peak metamorphic conditions are estimated at T = 750–800°C and P = 4–5 kbars. Detailed isotopic dating of different parts of migmatites (mesosomes and leucosomes) as well garnet-orthopyroxene gneisses was undertaken by conventional analysis of U–Pb on monazite and Sm–Nd on garnet. U–Pb monazite ages show that the West Uusimaa area underwent a granulite facies metamorphism at peak conditions between 1832±2 Ma and 1816±2 Ma. The area was then cooled down to 700–600°C at 1.81–1.79 Ga according to Sm–Nd garnet-whole rock data. These results together with previous data show that all the three granulite areas in southern Finland share a coeval thermal event probably stemming from common or similar heat sources.

Keywords: Palaeoproterozoic, Svecofennian, granulite, migmatite.

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Introduction and geological background

The Svecofennian orogen

The Svecofennian orogen was created semi-continuously (Gorbatschev & Bogdanova 1993) or episodically (Nironen et al. 2002) by successive accretions of volcanic arc complexes onto and against the Archaean craton between c. 1.92–1.83 Ga (Lahtinen 1994; Mansfeld 1996; Nironen 1997; Korsman et al. 1999; Vaasjoki et al. 2003). Successive intraplate deformation lasted at least to c. 1.77 Ga. Arc accretion took place diachronously and at present at least three different terranes can be identified in the Finnish part of the Svecofennian orogen. These are the Primitive Arc Complex, the Central Svecofennian Arc Complex (CSAC) and the Southern Svecofennian Arc Complex (SSAC) (Rämö et al. 2001, nomenclature after Väisänen et al. 2002). The c. 1.84–1.83 Ga volcanic rocks in southeastern Sweden might represent a younger, fourth terrane (Mansfeld 1996).

The SSAC was clearly subjected to different tectono-metamorphic events compared to the CSAC. In the CSAC, deformation, main magmatism and metamorphism took place at around 1.88 Ga (Nironen 1989; Lahtinen 1994; Kilpeläinen 1998; Mouri et al. 1999) and post-kinematic magmatism took place at 1.87 Ga (Nironen et al. 2000). In the SSAC the orogeny continued longer and lasted to c. 1.77 Ga (Vaasjoki & Sakko 1988; Ehlers et al. 1993; Ehlers & Skiöld 2001). According to Nironen et al. (2002) this younger stage of orogeny was actually caused by a continental collision between Sarmatia and Fennoscandia at 1.85–1.80 Ga followed by an orogenic collapse at 1.79–1.77 Ga.

Within the SSAC, an approximately 100 km wide east–west striking zone of migmatites associated to extensive outcrops of granites, so-called the late Svecofennian Granite-Migmatite zone (LSGM; Ehlers et al. 1993), runs across southern Finland. This zone is also characterised by c. 1.80 Ga post-collisional (Eklund et al. 1998) and c. 1.60 Ga anorogenic granitoids (Vaasjoki 1977). Within the LSGM, there are three areas consisting of low-pressure, high-temperature granulite facies rocks (Fig. 1). These are the Sulkava area in the eastern part (Korsman et al. 1984), the Turku area in the west (Väisänen & Hölttä 1999) and the West Uusimaa area in the central part of the belt (Schreurs & Westra 1986).

Low-pressure, high-temperature metamorphism in southern Finland and the problem of the heat source

The heat source that caused the low-pressure, high-temperature metamorphism in different areas of the LSGM is still a matter of debate. Several hypothesis were suggested, amongst: (i) crustal thickening (Korsman 1977), (ii) presence of a mafic layer at a depth of 30 to 40 km and CO_2 flushing (Schreurs & Westra 1986),

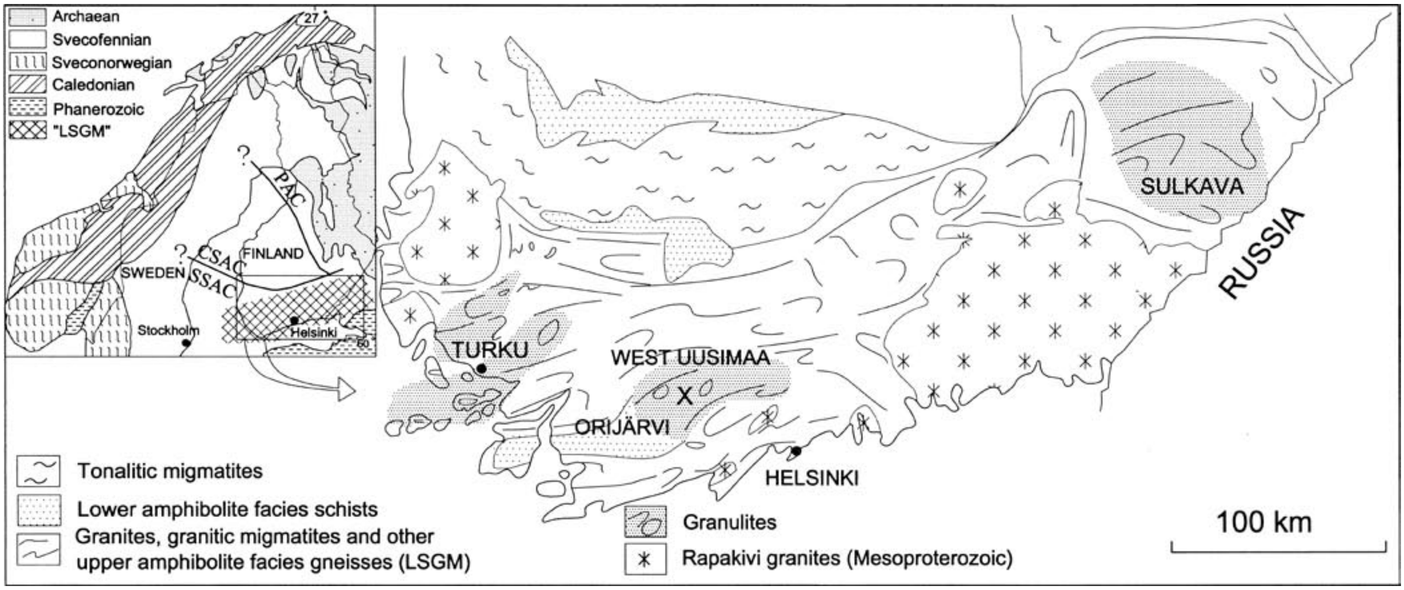

Fig. 1. Simplified geological map of southern Finland. Granulite areas (grey shade) drawn according to Korsman et al. (1997). Symbol X shows sampling locations. CSAC – Central Svecofennian Arc Complex, LSGM – Late Svecofennian granite–migmatite Zone, SSAC – Southern Svecofennian Arc Complex, PAC – Primitive Arc Complex.

(iii) post-collisional, mafic magmatism from the subcontinental lithospheric mantle (Väisänen et al. 2002), and (iv) hidden magmatic activity and regional contact metamorphism (Väisänen et al. 2004).

The granulite areas

Age determination of the high-temperature, low-pressure granulite facies metamorphism in southern Finland was undertaken mainly on rocks occurring in the Sulkava and Turku areas. In the Sulkava area conventional U–Pb dating of zircons from mesosome and leucosome of garnet-cordierite gneiss yielded ages of c. 1.81–1.83 Ga. Conventional monazite dating from the same rock types yielded ages of 1843±3 to 1816±3 Ma (Korsman et al. 1984).

In the Turku area, ion microprobe (SIMS) dating of zircons from leucosome of a metapelite, an enderbite and a leucosome from a metatonalite yielded ages of 1824±5 Ma, c. 1820 Ma and 1804±14 Ma (including one 1810±4 Ma concordant analysis), respectively (Väisänen et al. 2002). These ages partly overlap with the 1830–1815 Ma U–Pb zircon ages obtained from anatectic granites in southwestern Finland (Huhma 1986; Suominen 1991; Väisänen et al. 2000). A causal link between the leucosomes and the anatectic granites is also suggested by their similarity in geochemical characteristics (Johannes et al. 2003).

In the West Uusimaa area no previous age determination of the high-temperature, low-pressure metamorphism has been carried out. Therefore, the purpose of this study is to attempt to determine the age of the metamorphic peak as well as the early cooling history by combining conventional U–Pb monazite and Sm–Nd garnet-whole rock age methods.

In the West Uusimaa area the peak metamorphic conditions are estimated at 750–800°C and c. 4–5 kbars under water-undersaturated conditions consistent with the previous data obtained by Schreurs & Westra (1986) and Touret & Hartel (1990).

Sample description and petrography

This study focuses on migmatites and a garnet-orthopyroxene gneiss from the West Uusimaa area in southern Finland (Fig. 1). The migmatites exhibit a stromatic-banded structure in which it is possible to distinguish thin dark mesosomes and concordant thick leucosomes. The leucosome/mesosome ratio in these migmatites is high (>50%) and it is difficult to distinguish the different leucosome generations. The compositions of leucosomes are granitic and consist of K-feldspar together with quartz, plagioclase, and large euhedral crystals of garnet (about 2 cm in diameter) in addition to accessory monazite and biotite. Mesosomes are predominantly composed of quartz, plagioclase, sillimanite, garnet, biotite and K-feldspar as the peak metamorphic assemblage. Garnets are separated from sillimanite, biotite and quartz by coronas of cordierite with or without spinel. Monazite and zircon are accessory phases, they are observed either as inclusions in garnet or associated to the early biotite-sillimanite-quartz-plagioclase mineral assemblage forming the main foliation in the matrix. Textural analysis suggests that garnet was formed by the following dehydration melting reaction: Biotite + Sillimanite + Quartz ⇒ Garnet + K-feldspar + Melt. It is worth noting that the chemical composition of garnet does not show any distinct zoning pattern in terms of major elements, except a slight increase in the X_{Fe} towards the rim, which could be explained as late diffusion process. Peak metamorphic conditions were estimated to 750–800°C and 4–5 kbars using the average P–T calculation mode of THERMOCALC software (Holland & Powell 1990). These data are in accordance with the data obtained by Schreurs & Westra (1986) and Touret & Hartel (1990).

The garnet-orthopyroxene gneiss contains large garnet (6 cm in diameter) and orthopyroxene porphyroblasts.

The approach adopted here is to date monazite and garnet from mesosome-leucosome pairs using conventional dating of multi-grain samples (Table 1). Monazite and garnet were separated from two mesosome-leucosome pairs (HM-96-9a-c and HM-96-10a-b). In addition, the core and rim of a single porphyroblast of garnet from one leucosome (HM-96-10a) and from one garnet in garnet-orthopyroxene gneiss (HM-95-35) were dated. National coordinates of the samples are listed in the footnote of the Table 2.

Analytical procedures

About 2 kg of each sample was crushed and ground into particle size fractions. Samples were initially separated on a shaking table and further separated into magnetic and non-magnetic fractions with a Carpco magnetic separator. Subsequently monazite and garnet were separated by heavy liquids and by magnetic separation using a Frantz isodynamic separator. The final purification was achieved by handpicking under a binocular microscope. All laboratory work was performed at the Geological Survey of Finland.

U–Pb on monazite

The U–Pb analyses on monazites followed the procedures by Krogh (1973). The samples were washed in HNO_3 in an ultrasonic bath, rinsed several times with H_2O and dissolved in HF and HNO_3 at 200°C for a few days in steel jacketed teflon capsules. After evaporation of fluorides the sample in HCl solution was aliquoted and a mixed $^{208}Pb/^{235}U$ isotopic tracer was added. For isotopic measurements Pb was loaded on a single Re filament with Si-gel and H_3PO_4, and U on Ta-side filament using H_3PO_4. Measurements were made using a VG Sector 54 mass spectrometer. The performance of the ion counter was checked by repeated measurements of a NBS982 standard. The programs by Ludwig (1991, 2001) were used for age calculations.

Sm–Nd on garnet and whole rock

Recent studies have shown that the amount of Sm and Nd in garnet can be affected by the presence of microscopic inclusions of monazite. In order to avoid any such contamination problems, leaching of garnet fractions were performed following the step-wise dissolution method of DeWolf et al. (1996). This method involves powdering of about 300 mg of separated garnet in a boron carbide mortar for about 30 minutes and subsequent leaching in hot 6N HCl for about 6 hours, followed by rinsing with deionized water.

Samples were dissolved in HF-HNO_3 using Savillex screw-cap Teflon beakers (for garnet, 200–300 mg) or Teflon bombs (for whole rocks, 150 mg) for 48 h. After careful evaporation of fluorides (with $HClO_4$ and HNO_3) the residue was dissolved in 6 mol HCl and a clear solution was achieved. A mixed ^{149}Sm–^{150}Nd spike was added to the sample prior the dissolution. Measurements were made in a dynamic mode on a VG Sector 54 mass spectrometer using triple filaments or single Re-filament. Estimated error in $^{147}Sm/^{144}Nd$ is 0.4%. The $^{143}Nd/^{144}Nd$ ratio is normalized to $^{146}Nd/^{144}Nd$ = 0.7219. For the triple filament measurements the average value for La Jolla standard was $^{143}Nd/^{144}Nd$ = 0.511852±12 (SD, n= 23, errors in last significant digits). Compared to triple filaments measurements, the single Re-filament analyses on several samples and standard provided slightly lower (0.005%) $^{143}Nd/^{144}Nd$ ratios. The single filament measurements have been corrected accordingly, and should be compatible with La Jolla value of 0.51185. The measured Nd blank was 100 ng.

Results and discussion

U–Pb monazite

The monazite data are listed in Table 1 and the diagram of ages is shown in Fig. 2. Monazites from one mesosome (HM-10b) and two leucosomes (HM-10a and HM-9c) are concordant and provide $^{207}Pb/^{206}Pb$ ages of 1819±2 Ma, 1818±2 Ma and 1816±2 Ma. Monazites from the mesosome sample HM-96-9a is slightly older and yielded a concordant $^{207}Pb/^{206}Pb$ age of 1832±2 Ma (Table 1, Fig. 2).

Based on textural observations, monazites often occur in association with the peak metamorphic assemblages characterised by the coexistence of biotite-sillimanite in the main foliation or as inclusions in garnets. They are probably formed by peak or near peak metamorphic melting reaction simultaneously with the leucosome. Therefore, the obtained ages mark growth at the peak metamorphic stage. This requires that closure temperature for these monazites is slightly higher than the peak metamorphic conditions of 750–800°C in this area. According to Spear and Parrish (1996), Bingen & van Breemen (1998) and Parrish & Whitehouse (1999), monazites preserve older isotopic systematics, surviving high temperature overprint of 800°C or higher and may even record prograde growth ages (Vry et al. 1996). Since the peak temperature in the West Uusimaa area is in a range of 750–800°C, we infer that the obtained ages reflect the peak conditions, because monazites rarely undergo severe lead loss during subsequent geological events (e.g. Foster et al. 2002). The same conclusion was made for the Archaean granulites in central Finland by Hölttä et al. (2000).

The older mesosome age of 1832±2 Ma might reflect the episodic or continuous growth of monazites during a single pro-

Table 1. U–Pb data on monazite.

Analysed mineral/fraction	Sample weight (mg)	U ppm	Pb ppm	$^{206}Pb/^{204}Pb$ meas.	$^{208}Pb/^{206}Pb$ radiogenic	Isotopic ratios[a] $^{206}Pb/^{238}U$	$2\sigma_m$%	$^{207}Pb/^{235}U$	$2\sigma_m$%	$^{207}Pb/^{206}Pb$	$2\sigma_m$%	Rho[b]	Apparent ages (Ma) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
HM-96-9a, mesosome +200 mesh	1.3	7491	5602	15255	1.5	0.32637	1	5.0389	1	0.11198	0.12	0.99	1820	1825	1832±2
HM-96-9c, leucosome +100 mesh	1.6	7748	9683	5250	3.3	0.32726	2	5.0131	2	0.11111	0.12	1.00	1825	1821	1818±2
HM-96-10a, leucosome +200 mesh	1.2	5964	7017	35000	3	0.32739	1	5.0099	1	0.11099	0.12	0.99	1825	1820	1816±2
HM-96-10b, mesosome +200 mesh	1.2	3265	4861	21200	4.1	0.33116	1.5	5.0757	1.5	0.11117	0.12	1.00	1844	1832	1819±2

[a] Corrected for mass fractionation (0.1%/a.m.u.), blank (0.2 ng Pb) and common lead (Stacey & Kramers 1975).
[b] Error correlation

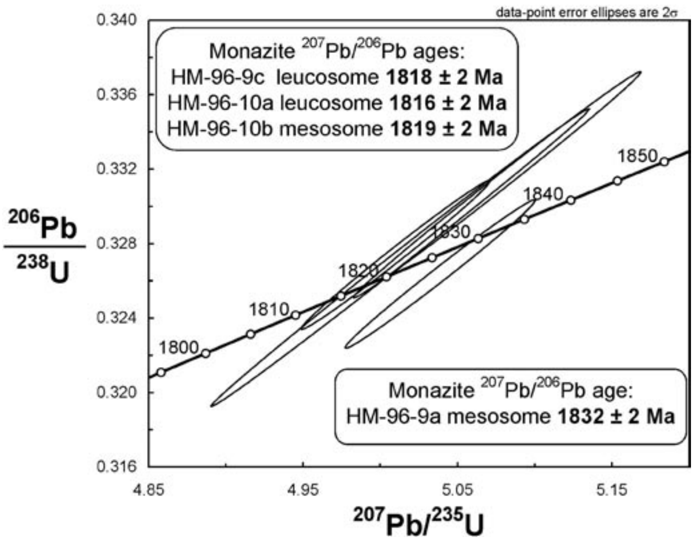

Fig. 2. U–Pb concordia diagram for monazite data.

longed metamorphic event. Another alternative is that this age reflects a mixed age of an older component inherited from an earlier thermal stage and a younger 1819–1816 Ma age, since it is possible that monazites preserve an inherited component (Foster et al. 2002). It is difficult to separate the different alternatives with the conventional methods that we used in this study. However, the monazites lack optical zoning patterns such as cores and overgrowths. In addition, the obtained ages are consistent with the previous data from similar rocks from the Sulkava and the Turku areas (Korsman et al. 1984; Väisänen et al. 2002). Therefore, mixed ages are not probable and the obtained ages between 1832±2 Ma and 1816±2 Ma are interpreted to reflect a single, prolonged metamorphic event.

Sm–Nd garnet-whole rock

The garnet-whole rock data are listed in Table 2 and the age diagrams are shown in Fig. 3A–C. Most of the data are technically correct and due to relatively high $^{147}Sm/^{144}Nd$ in garnet (1.81–2.43) the errors in ages are fairly small. An exception is the garnet from the mesosome (HM-96-9a), which has a low $^{147}Sm/^{144}Nd$ ratio of 0.19, and thus a large error in age.

The ages of the other seven samples range between 1810±6 Ma and 1791±9 Ma. The average Sm–Nd age for the garnet-whole rock leucosome-mesosome sample pairs is 1803±6 Ma. The core and the rim of the garnet from the leucosome do not show a difference in the age within errors (1800±8 Ma and 1791±9 Ma). The age of the garnet from the garnet-orthopyroxene gneiss is slightly older (1810±6 Ma). There is no difference in age between the core and the rim of the large garnets from the garnet-orthopyroxene gneiss.

The average mesosome-leucosome garnet ages are 5–17 Ma younger than the youngest U–Pb monazite age (1816±2 Ma). However, considering the error limits, the Sm–Nd age of the garnet from the garnet-orthopyroxene gneiss can be the same as the U–Pb age of the youngest monazite in migmatites.

The peak metamorphism at c. 750–800°C took place at 1834–1816 Ma as indicated by the monazite ages. This age range is supported by abundant granites throughout the LSGM zone in SW Finland, which also typically provide U–Pb monazite ages of ca. 1.83 Ga (Huhma 1986; Suominen 1991). Subsequent Sm–Nd garnet ages around 1.80 Ga might reflect either a cooling to the closure temperature of garnet or a new garnet growth episode at that time. New garnet growth does not seem very likely since textural relationships show clearly that garnets were formed during the peak metamorphism together with the leucosomes, i.e. ca. 15 m.y. earlier. Therefore, cooling model seems readily applicable to the Sm–Nd garnet ages.

The closure temperature of the Sm–Nd system in garnet cannot be precisely determined because it depends on many factors such as composition, grain size, existing fluids, peak metamorphic temperature, diffusion and cooling rates (Metzger et al. 1992; Ganguly et al. 1998). Anyway, it is lower than that in the U–Pb system in monazite (e.g. Jung & Mezger 2003). A closure temperature between 600°C (e.g. Metzger et al. 1992) and 700°C (e.g. Hensen & Zhou 1995) are often applied in recent literature, which are consistent with the experimental data for slowly cooling garnet (Ganguly et al. 1998).

Our Sm–Nd garnet ages apparently fall in two groups, the c. 1.80–1.79 Ga ages from migmatites and a marginally older 1.81 Ga age from garnet-orthopyroxene gneiss.

Conclusions

We conclude that the West Uusimaa low-pressure, high-temperature granulite area reached the peak metamorphic conditions (4–5 kbar and 750–800°C) between 1832±2 Ma and 1816±2 Ma. The granulites then cooled down to the closure temperature of the

Table 2. Sm–Nd garnet-whole rock data.

Sample/ anal#	Rock type/ mineral	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$ (±0.4%)	$^{143}Nd/^{144}Nd$	$2\sigma_m$	ε(1900)	T-grt-wr (Ma)
HM-96-9a	mesosome	5.84	32.16	0.1098	0.511470	0.000010	–1.7	
9a-grt	garnet	0.88	2.78	0.1902	0.512464	0.000060		1879±100
HM-96-9c	leucosome	7.23	29.65	0.1474	0.511985	0.000011	–0.8	
9c-grt	garnet	2.49	0.69	2.2040	0.536363	0.000021		1802±6
HM-96-10a	leucosome	1.33	7.44	0.1084	0.511499	0.000011	–0.7	
10a-grt	garnet	1.78	0.59	1.8180	0.531777	0.000070		1803±10
10a-grtcore	garnet core	1.18	0.38	1.9100	0.532835	0.000022		1800±8
10a-grtrim2	garnet rim	2.11	0.58	2.2000	0.536138	0.000063		1791±9
HM-96-10b	mesosome	7.27	40.77	0.1078	0.511460	0.000010	–1.4	
10b-grt	garnet	1.32	1.66	0.4796	0.515858	0.000013		1798±10
HM-95-35	opx-grl	4.06	20.77	0.1183	0.511689	0.000010	0.5	
35-grtrim	garnet rim	1.42	0.36	2.4320	0.539243	0.000043		1810±7
35-grtcore	garnet core	1.84	0.56	1.9880	0.533958	0.000051		1810±7

Grid coordinates: HM-96-9 – 6686.25/2488.10; HM-96-10 – 6687.35/2497.00; HM-95-35 – 6683.44/2499.00.
$^{143}Nd/^{144}Nd$ ratio is normalized to $^{146}Nd/^{144}Nd$ = 0.7219.

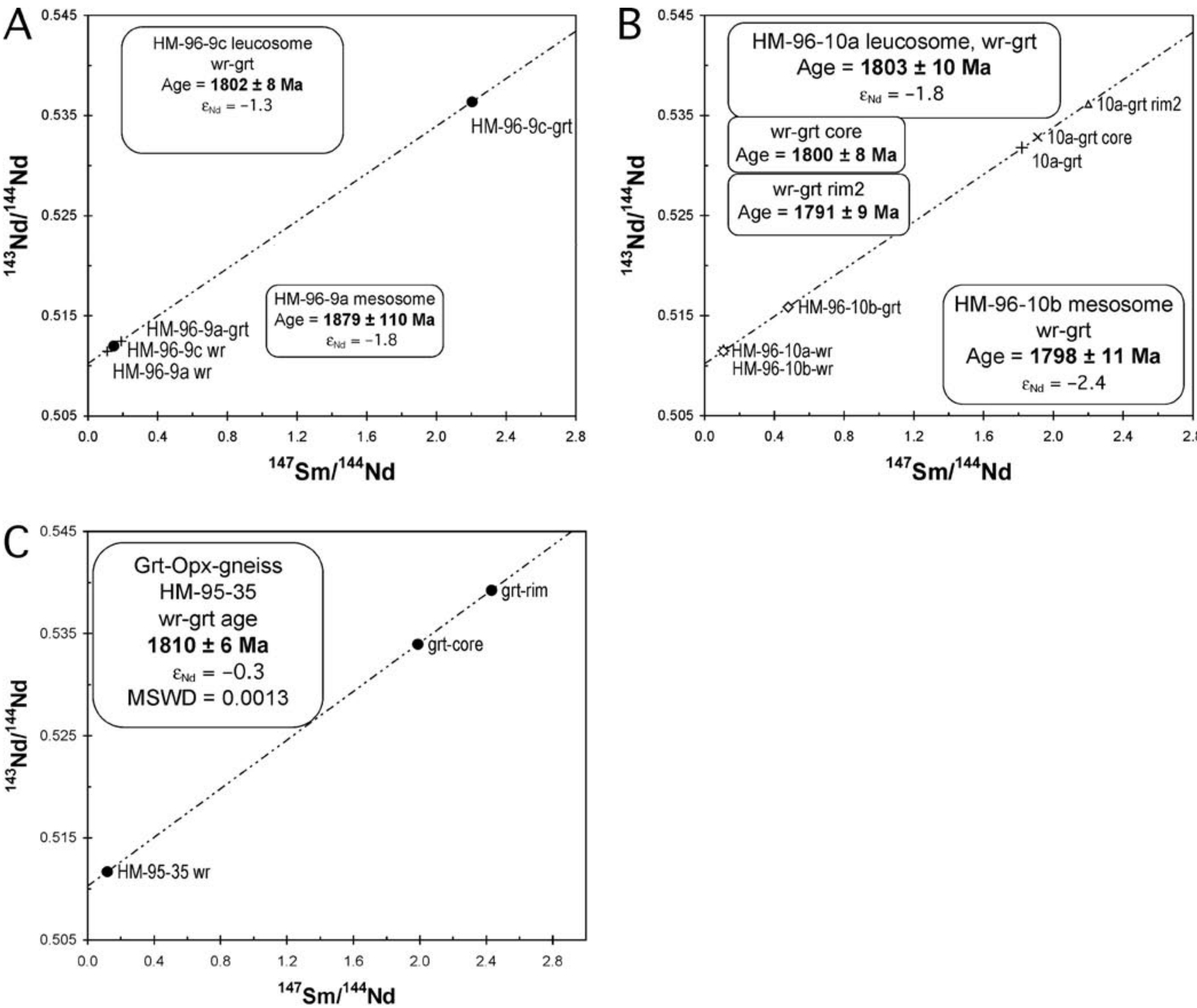

Fig. 3. **A.** Sm–Nd isochron diagram for garnet data, sample HM-96-9. **B.** Sm–Nd isochron diagram for garnet data, sample HM-96-10. **C.** Sm–Nd isochron diagram for garnet data, sample HM-95-35.

Sm–Nd system in garnet at c. 1.81–1.79 Ga. These data together with the previous work on the LSGM low-pressure, high-temperature granulites, show that the West Uusimaa, the Sulkava, and the Turku areas all attained the peak metamorphic conditions contemporaneously. This conclusion strongly suggests that these three areas were subjected to the same tectonic event and they share a common heat source. The source of the heat at the origin of the low-pressure, high-temperature metamorphism in the West Uusimaa area remains however uncertain and it is beyond the scope of this paper. Further detailed investigations including the Sulkava granulites is needed in order to explain the heat flow responsible for the regional low-pressure, high-temperature metamorphism in southern Finland.

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