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Permo-Triassic pegmatites in the eo-Alpine eclogite-facies Koralpe complex, Austria: age and magma source constraints from mineral chemical, Rb–Sr and Sm–Nd isotope data

by *Martin Thöni*[1] and *Christine Miller*[2]

Abstract

Two distinct pegmatite groups are present in the Koralpe, Austria: spodumene-bearing pegmatites and spodumene-free pegmatites. The Rb–Sr and Sm–Nd systematics of the whole-rocks from both pegmatite types yield no valid age information; scatterchron regression, however, is in line with a presumed Permian emplacement age. The apparent age scatter is related to heterochronous emplacement and primary inhomogeneities (coarse grain size), as well as strong Alpine tectonometamorphic reworking of the pegmatites. Both pegmatite types exhibit strongly negative, crustal-type initial εNd values (–10.5 to –6.4). The spodumene-free pegmatites could have been formed *"in-situ"*, by partial mobilization of the metasedimentary host rocks during a Permo-Triassic high-T/low-P event. Although coeval, the metagranite of Wolfsberg, the only silicic meta-igneous body in the study area, is not parental to the pegmatites.

Garnets from spodumene-free pegmatites have high spessartine contents and high to very high Sm/Nd ratios (up to 11.9). In general, garnets have retained their primary element zonation as well as their primary, Permo-Triassic Sm–Nd age, despite the Alpine eclogite-facies overprint of the Koralpe crystalline. However, Rb–Sr and Sm–Nd mineral isochrons from *"aplitic border zone"* samples (= contact between pegmatite and wall rock) of the spodumene-bearing pegmatites at Weinebene, Koralpe, yield very young apparent ages between 87 and 65 Ma. These ages are interpreted to reflect local remobilization and recrystallization of the Permian protolith by fluid release and decompression during rapid exhumation of the high-P Koralpe complex in the Late Cretaceous.

Keywords: pegmatites, garnet Sm–Nd dating, REE fractionation, Permo-Triassic event, Cretaceous exhumation, Koralpe, Austria.

Introduction

Pegmatites are mostly taken as igneous rocks that crystallize during the last stages of magmatic differentiation and cooling. These fluid saturated, generally coarse-grained magmas are strongly enriched in the most incompatible elements and may contain rare, economically interesting mineral phases, in which trace elements such as Li become major constituents. Alternatively, pegmatitic rocks may also be generated by anatexis, if sufficient fluid is available. Anatectic pegmatites are generally peraluminous in composition and lack the unusual enrichment in very incompatible elements seen in the differentiates of granitic suites.

The study of pegmatites in metamorphic terrains can provide important geological and geochemical information: (1) Mutual cross-cutting relationships of pegmatite swarms and country rocks yield important constraints on the minimum age of the metamorphic fabric and on the tectono-metamorphic history of an area under study. (2) Initial isotopic compositions of pegmatites can provide information about magma sources of the melts. (3) In addition, these studies elucidate isotopic exchange processes in unusually coarse-grained systems.

Within the Austroalpine basement units of the Eastern Alps, pegmatites are wide-spread, although volumetrically subordinate. Available

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age-data indicate pegmatite emplacement during the early Palaeozoic (SCHWEIGL, 1995), sometimes during the Variscan cycle (THÖNI, 1986, and unpubl. data), but predominantly during the Permian to early Triassic (MORAUF, 1981; BORSI et al., 1980; JUNG, 1982; BOCKEMÜHL, 1988; SCHUSTER and THÖNI, 1996; HEEDE, 1997; HABLER and THÖNI, 1998).

In the case of the Koralpe area, there is no evidence for coeval silicic magmatic activity. The only intrusion exposed is the Wolfsberg metagranite, which differentiated from a mafic melt between 283 and 251 Ma (MORAUF, 1980).

This paper presents new Rb–Sr, Sm–Nd and mineral chemical data for pegmatites and their metasomatic "aplitic border zones" from Weinebene, Koralpe in order (1) to constrain the timing of their crystallization; (2) to obtain minimum ages of deformation; (3) to infer magma sources from initial isotopic ratios and (4) to study isotope exchange mechanisms in coarse grained systems. In addition, some new isotopic data are given for the Wolfsberg metagranite to investigate a possible genetic link with the pegmatite-forming event.

Regional Geology

The Koralpe complex in SE Austria forms part of the Austroalpine basement nappe system. Prior to 1980 the entire tectonometamorphic evolution of this polymetamorphic basement complex was interpreted as pre-Alpine, with only minor Alpine re-heating and structural re-working. Recent studies, however, indicate an eclogite facies metamorphic overprint during the Cretaceous, with minimum PT conditions of 1.8 GPa / 600 °C (e.g. MILLER, 1990; THÖNI and JAGOUTZ, 1992; STÜWE and POWELL, 1995; THÖNI and MILLER, 1996; MILLER and THÖNI, 1997; LICHEM et al., 1997). It is, therefore, essential to consider this younger metamorphic event when interpreting isotopic data from the "pre-Alpine basement".

In the Koralpe (Fig. 1), two distinct types of pegmatites have been distinguished: *spodumene-bearing pegmatites* and *spodumene-free pegmatites*. The two pegmatite types may be assigned to either the *muscovite class* or the *rare-element class* (CERNY, 1998). Spodumene-free pegmatites are volumetrically not very important, but are dispersed as small lenses and layers (up to some tens

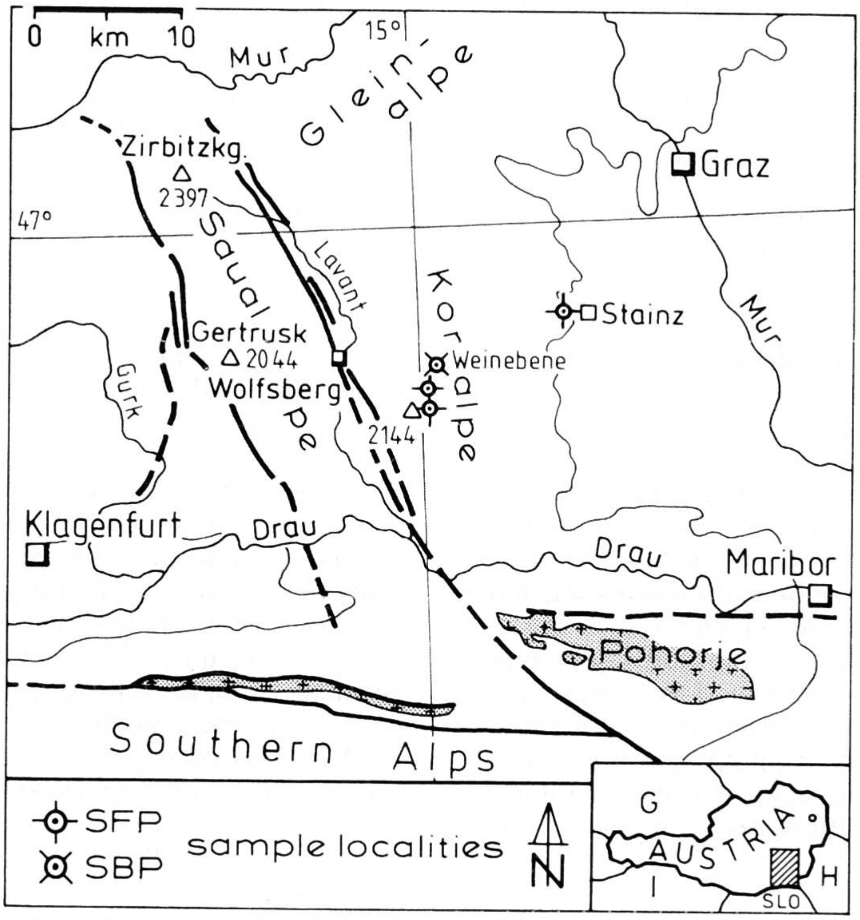


Fig. 1 Location of the Koralpe pegmatite samples investigated in the present study. Stippled areas with crosses represent young intrusive rocks. SFP = spodumene-free pegmatite, SBP = spodumene-bearing pegmatite.

of metres in thickness) over a large area which lacks associated granitoid plutons (BECK-MANNAGETTA, 1980).

Spodumene-bearing pegmatites are known from the central-northern (GÖD, 1989) and north-eastern part of the Koralpe complex (ESTERLUS, 1983, with references). Those from Weinebene, one of the largest known lithium deposits in Europe, have been described in detail by GÖD (1989). They are hosted by amphibolitized eclogites or by kyanite-garnet-mica schists of the Koralpe basement nappe (GÖD, 1989) and have been deformed to varying extents by the eo-Alpine (Cretaceous) event, which produced the main foliation in the host rocks. The contacts between pegmatites and country rocks are generally sharp, although often overprinted by ductile deformation. The amphibolite-hosted pegmatites are characterized by an aplitic border zone and a narrow aureole where biotite, tourmaline and holmquistite [$Li_2(Mg,Fe)_3(Fe,Al)_2Si_2O_{22}(OH, F, Cl)_2$] formed. In contrast, the mica schist-hosted pegmatites are extensively recrystallized, and lack aplitic border zones and other visible contact phenomena.

The only granite in the area is the Wolfsberg metagranite, which is part of the Wolfsberg window, an Austroalpine-internal window structure. This tectonically lower Muriden unit was overthrust by the Koriden nappe complex s. s. during Alpine nappe stacking and exhumation. MORAUF (1980) reported analyses on seven whole-rock samples of the Wolfsberg metagranite which define a Rb–Sr isochron with an age of 258 ± 11 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7046 ± 0.0028.

Analytical techniques

Except for micas, all minerals used for isotopic analysis were hand-picked under a binocular microscope from defined sieve (0.15, 0.3, 0.42 mm) and magnetic fractions. Concentrates were > 99.9% pure. Mica concentrates were repeatedly ground with alcohol in an agate mill, to remove inclusions and intergrowths.

Before decomposition, minerals were washed in acetone and deionised water. Garnets were additionally washed in warm 2.5n HCl, to remove dust and surface contaminations. Sample weights used for dissolution varied between 100 and 300 mg. Sample digestion and element separation for Sm and Nd closely followed the procedure described by THÖNI and JAGOUTZ (1992). Sr and Rb were determined from separate aliquots, using a HF/HNO_3 mixture for dissolution. Rb, Sr, Sm and Nd concentrations were determined from two separate sample aliquots by isotope dilution (ID), using a ^{87}Rb–^{84}Sr and a ^{147}Sm–^{150}Nd spike, respectively. Total procedural blanks were < 100 pg for Sm, < 300 pg for Nd and < 1 ng for Rb and Sr. Rb and Sr concentration (ID) and Sr isotope composition (IC) samples were loaded on a single Ta filament and measured on a MICROMASS M30 machine. Sm and Nd ID as well as Nd IC samples were measured as metals from a Re double filament, using a FINNIGAN MAT262 mass spectrometer. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios for the NBS987 (Sr) and the La Jolla (Nd) international standards during the course of this work were 0.71014 ± 3 and 0.51185 ± 1, respectively. Errors for the $^{87}Rb/^{86}Sr$ and the $^{147}Sm/^{144}Nd$ ratios are taken as ± 1%, or smaller, based on iterative sample analysis and spike recalibration. Isochron calculation follows LUDWIG (1992). Ages are based on decay constants of 1.42×10^{-11} a^{-1} for ^{87}Rb and 6.54×10^{-12} a^{-1} for ^{147}Sm. Uncertainties given for ages on figures 5–10 are based on internal errors. A linear evolution of Nd isotopes is assumed throughout geological time; the following DM (Depleted Mantle) parameters were used: $^{147}Sm/^{144}Nd = 0.222$, $^{143}Nd/^{144}Nd = 0.513114$ (MICHARD et al., 1985).

Mineral composition data were obtained with an ARL SEMQ electron microprobe by energy- and/or wavelength-dispersive spectrometry at the University of Innsbruck. The accelerating voltage was 15 kV and sample current 20 nA. Natural and synthetic standards were used for calibration.

Abbreviations apatite (Ap), biotite (Bt), garnet (Grt), K-feldspar (Kfs), kyanite (Kya), quartz (Qtz), plagioclase (Pl), spodumene (Spod), tourmaline (Tour), white mica (WM), whole-rock (WR).

Petrography of samples

The samples analyzed in the present paper include both spodumene-bearing and spodumene-free pegmatites. Petrographic details and mineral chemistry are given in the appendix and in table 1. Spodumene-free pegmatites are composed of plagioclase (Ab_{88-93}), quartz, K-feldspar, white mica, tourmaline, apatite and garnet. Spodumene-bearing pegmatites consist of K-feldspar, quartz, muscovite, plagioclase (Ab_{89-92}) and spodumene. Tour, WM, Spod and Ap may attain a size of several centimeters. The primary mineral assemblage of both spodumene-free and spodumene-bearing pegmatites has been overprinted to various degrees by deformation-induced recrystallization, as well as by the growth of new metamorphic minerals.

The contact zone between spodumene-bearing pegmatites and host rocks (amphibolite/amphibolitized eclogite), called "aplitic border zone" by GÖD (1989), is of special interest. The mineral assemblages of these aplitic border zones are quite variable and may contain, apart from plagioclase, quartz, K-feldspar, biotite and muscovite also holmquistite, scapolite, clinozoisite, garnet, tourmaline and green apatite. In the literature their age and origin are controversial. GÖD (1989) interprets the aplitic border zones of amphibolite-hosted, spodumene-bearing pegmatites as primary exomorphic aureoles. In contrast, NIEDERMAYR (in NIEDERMAYR and GÖD, 1992) emphasizes that the characteristic minerals of these zones, such as holmquistite, scapolite, clinozoisite and in part also garnet, tourmaline and apatite are the product of late metasomatic and metamorphic recrystallization processes. In addition, it is stated that primary pegmatitic features in mica schist-hosted pegmatites were almost completely obliterated by metamorphic overprinting.

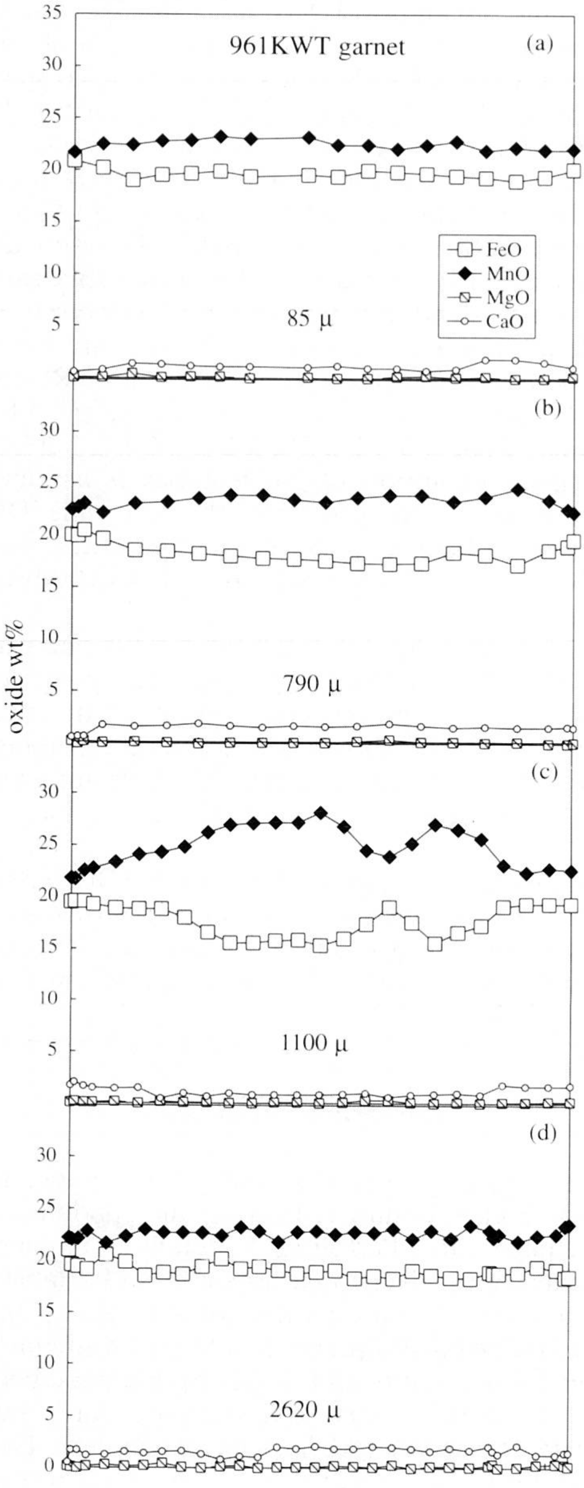


Fig. 2(a–d) Compositional profiles for MnO and FeO across four garnets of different size from "aplitic border zone" sample 961KWT. MgO contents are < 0.3 wt%, CaO contents range between 0.73 and 1.94 wt%.

Magmatic and metamorphic PT conditions

The bulk compositions of the Koralpe Li-pegmatites (GÖD, 1989) plot close to the minimum in the system quartz-albite-eucryptite-H_2O, suggesting that the Li-rich magma could have formed by partial melting of Li-bearing metasediments at low pressures and temperatures at least 75 °C below the minimum melting temperature of the haplogranitic system at the same pH_2O (STEWARD, 1978). In addition to coarse spodumene, sample 961KWT contains fine-grained symplectitic intergrowths of spodumene and quartz. These domains could represent pseudomorphs after primary petalite, possibly indicating a decrease in temperature and/or an increase in pressure postdating the primary pegmatite crystallization (LONDON and BURT, 1982) (Fig. 4). The chemical composition of the pegmatite garnets is restricted to the almandine-spessartine series, with low Mg and Ca contents (Tab. 1). GREEN (1977) concluded that garnets with spessartine contents of > 10 mol% are stable in silicic liquids at 0.5 GPa or less. The pegmatite garnets are distinctly different from the Mg-rich garnets in the surrounding country rocks (THÖNI and MILLER, 1996).

The garnets in the outermost biotite-rich selvage of aplitic border zone sample 87T12 are distinctly different from garnets in more internal parts: the compositional profiles across the former (Fig. 3a, b) reveal discontinuous spessartine-rich overgrowths on Mn-poor, but MgO-rich core domains, at the expense of MgO and FeO. In contrast, the latter (Fig. 3c) are characterized by very low MgO and distinctly higher spessartine contents. This could indicate open-system crystallization in the outermost zone induced by mineralizing fluids resulting in Mn-rich garnets mantling pre-existing MgO-rich host-rock garnets.

The metamorphic PT conditions, however, are difficult to assess owing to the lack of appropriate thermodynamic data for Li- and B-rich systems and the low number of phases. A temperature estimate based on the garnet-biotite Fe–Mg exchange equilibrium (KLEEMANN and REINHARDT, 1994) yields 545 °C (at a nominal pressure of 0.4 GPa) for the biotite selvage of aplitic border zone sample 87T12. Some garnets and tourmalines in the spodumene-free pegmatite 95T06K are surrounded by a narrow rim containing kyanite, muscovite and plagioclase. The intersection of the garnet-muscovite Fe–Mg exchange equilibrium (GREEN and HELLMAN, 1982) with the garnet-kyanite-plagioclase-quartz equilibrium yields 550 °C / 0.52 GPa (HODGES and SPEAR, 1982) and 560 °C / 0.71 GPa (KOZIOL, 1989) for this sample.

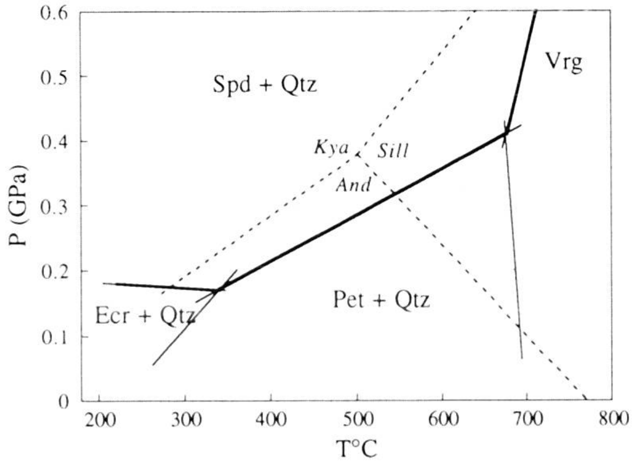
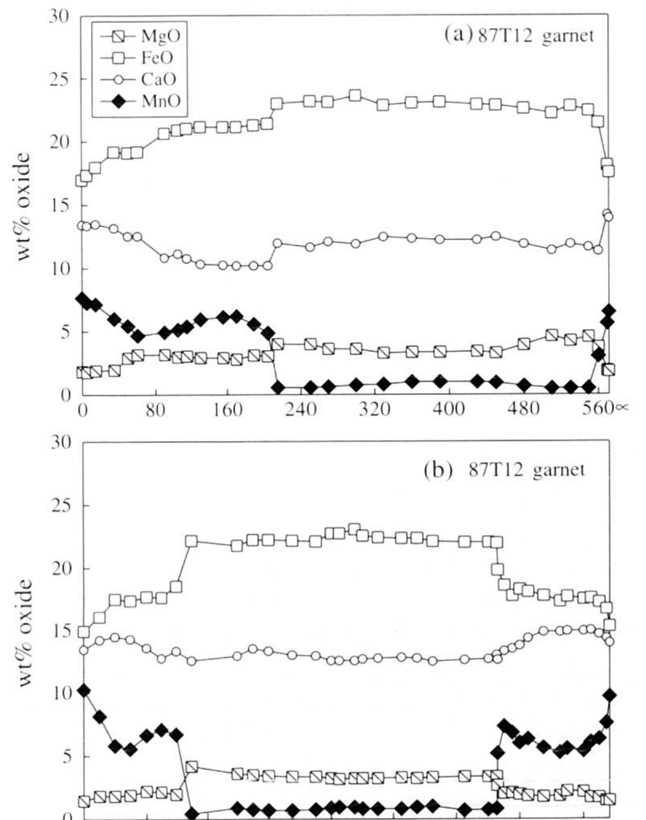


Fig. 4 Phase diagram (LONDON, 1984) involving eucryptite (Euc), petalite (Pet), spodumene (Spd), virgilite (Vrg) and quartz (Qtz), and the aluminium silicate triple point (HOLDAWAY, 1971).



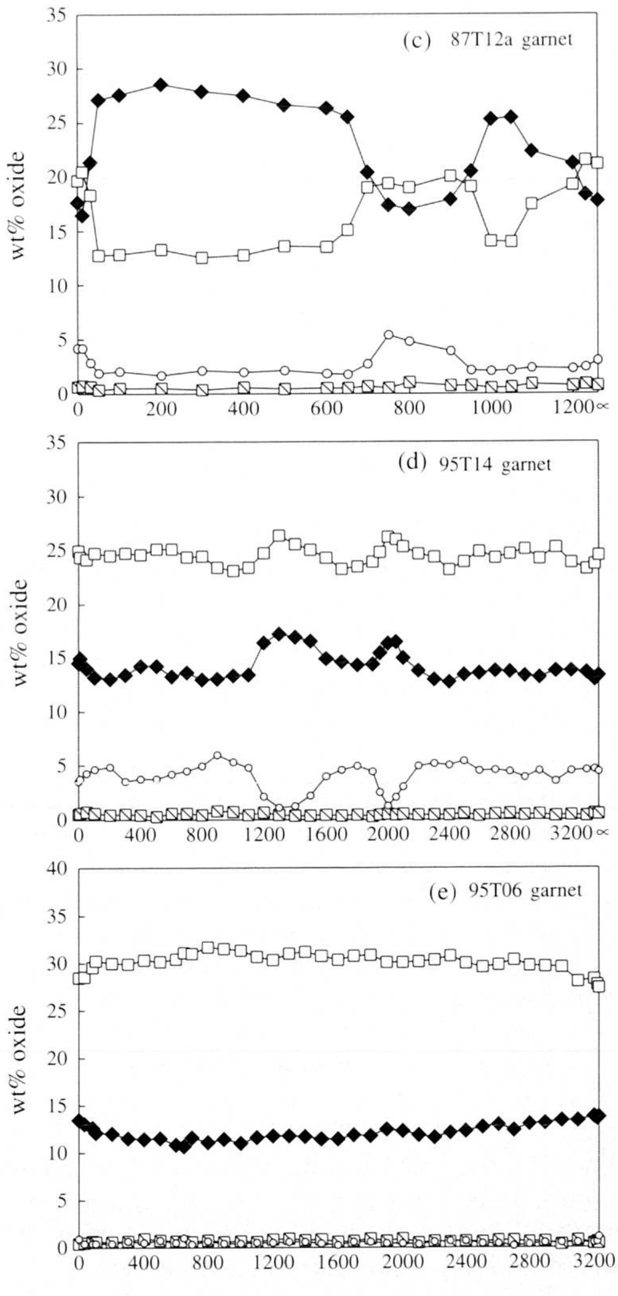


Fig. 3 Compositional profiles across garnets from Koralpe pegmatites. Note that the discontinuous Mn-rich overgrowths on garnet cores (a and b) are restricted to the biotite-rich selvage of the aplitic border zone and that these garnets differ from those (c) observed in more internal parts of sample 87T12. The latter are highly irregular in shape as are garnets (d) from spodumene-free pegmatite 95T14. Their zoning patterns could indicate composite grains.

Tab. 1 Selected microprobe analyses of garnets from Koralpe pegmatites.

Sample	87T12 SBP-ABZ core	87T12 SBP-ABZ overgrowth	87T12 SBP-ABZ core	87T12 SBP-ABZ rim	961KWT SBP-ABZ core	961KWT SBP-ABZ rim	95T06 SFP core	95T06 SFP rim	95T14 SFP core	95T14 SFP rim
SiO_2	38.28	37.98	36.55	36.50	36.38	36.11	36.32	36.42	36.36	36.78
TiO_2	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.04	0.00
Al_2O_3	21.54	21.47	20.62	20.65	20.49	20.25	20.54	20.60	20.60	20.74
Cr_2O_3	0.08	0.00	0.05	0.09	0.10	0.00	0.00	0.00	0.07	0.14
FeO	22.94	15.29	15.08	17.83	16.34	17.65	30.48	27.91	22.17	23.36
MnO	0.97	9.40	25.06	21.42	25.08	23.50	11.45	13.69	17.24	13.05
MgO	3.22	1.52	0.51	0.57	0.12	0.02	0.54	0.59	0.37	0.38
CaO	12.69	13.96	1.86	2.53	1.36	1.61	0.33	0.60	2.52	5.41
Total	99.72	99.62	99.81	99.59	99.87	99.14	99.66	99.81	99.37	99.86
Cations per 12 oxygens										
Si	2.999	3.000	2.997	2.995	2.996	2.997	2.999	2.999	2.995	2.994
Ti	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.000	0.002	0.000
Al	1.989	2.000	1.993	1.998	1.989	1.981	2.000	2.000	2.000	1.991
Cr	0.005	0.000	0.003	0.006	0.007	0.000	0.000	0.000	0.005	0.009
Fe^{3+}	0.007	0.000	0.001	0.002	0.008	0.021	0.001	0.001	0.000	0.006
Fe^{2+}	1.495	1.010	1.033	1.222	1.118	1.204	2.104	1.920	1.527	1.585
Mn	0.064	0.629	1.741	1.489	1.750	1.652	0.801	0.955	1.203	0.900
Mg	0.376	0.179	0.062	0.070	0.015	0.002	0.066	0.072	0.045	0.046
Ca	1.065	1.182	0.163	0.222	0.120	0.143	0.029	0.053	0.222	0.472
CAT	8.001	8.000	7.999	8.003	8.002	8.001	8.000	8.001	8.000	8.003
pyrope	12.54	5.97	2.01	2.07	0.30	0.00	2.22	2.41	1.50	1.26
almandine	49.87	33.67	34.46	40.79	37.30	40.16	70.15	64.04	50.95	52.92
grossular	34.90	39.38	5.07	7.05	3.29	3.64	0.88	1.63	7.07	15.02
spessartine	2.07	20.97	58.08	49.71	58.40	55.13	26.70	31.84	40.13	30.05
uvarovite	0.25	0.00	0.16	0.29	0.33	0.00	0.00	0.00	0.23	0.45
andradite	0.37	0.00	0.07	0.09	0.39	1.07	0.06	0.07	0.00	0.29

Isotopic data

Rb–Sr and Sm–Nd data for whole-rock powders and mineral concentrates of the different rock groups are listed on tables 2 and 3, respectively.

PEGMATITE WHOLE ROCK SAMPLES

Rb–Sr and Sm–Nd data from whole-rock samples are plotted in evolution diagrams (Figs 5a, b). The two pegmatite groups, *i.e.* spodumene-bearing and spodumene-free pegmatites, are characterized by clearly different element and isotopic ratios as well as trace element concentrations (Tabs 2, 3). In both Rb–Sr and Sm–Nd, spodumene-free pegmatites are much less evolved than spodumene-bearing pegmatites, with aplitic border zone samples being intermediate between the two groups. In accordance with this observation, present-day isotopic ratios of spodumene-free pegmatites are moderately radiogenic, whereas spodumene-bearing pegmatites and aplitic border zone samples are highly radiogenic, with respect to both Rb–Sr and Sm–Nd systematics.

In both Rb/Sr and Sm/Nd isochron diagrams (Figs 5a, b) the three rock groups do not show linear arrays, but form clusters with considerable scatters, well outside the analytical uncertainties of the individual samples. Thus, no valid age information can be gained from the whole-rock data. The regression ages quoted on figure 5, however, indicate that the data are roughly consistent with a Permian to Triassic age of emplacement. For the spodumene-bearing pegmatites at Weinebene, a zircon U–Pb (multigrain, upper intercept) age of 240 ± 1.5 Ma has recently been published (Heede, 1997).

Sm–Nd AND Rb–Sr ANALYSES ON MINERALS FROM PEGMATITES

Minerals analysed from spodumene-free and spodumene-bearing pegmatites include garnet, white mica, spodumene and tourmaline. Results are given in tables 2 and 3 and plotted on figures 6a–c.

Garnet Sm–Nd Grt-WR isochron ages for three spodumene-free pegmatites range from 264 ± 3 to 256 ± 3 Ma (Fig. 6a; sample 93T23Ka, see Thöni and Miller, 1996), 225 ± 3 and 222 ± 8 Ma

Tab. 2 Rb–Sr data from pegmatites and granite gneisses of the Koralpe.

Sample		Locality	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma m$	Isochron age (Ma)
a) spodumene-free pegmatites							
93T23Ka	WR	Stainz	44.7	24.3	5.336	0.72082 ± 8	
93T24K	WR	Stainz	117	216	1.567	0.71602 ± 5	
95T06K	WR	Koralmhaus	91.1	44.7	5.913	0.73126 ± 6	
	Grt					0.73836 ± 14	
95T14K	WR	Grillitschhütte	247	52.4	13.68	0.75747 ± 9	
	Grt					0.85659 ± 9	
	Tour					0.73724 ± 1	
95T16K	WR	near Grillitschhütte	92.6	138	1.945	0.72450 ± 8	
b) spodumene-bearing pegmatites							
SPPCM	WR	Weinebene	1035	9.79	349.0	2.15008 ± 42	
	Spod 1 (xx)		83.5	1.73	143.3	0.98355 ± 35	112.6 ± 2.2 (Spod1-Spod2)
	Spod 2 (xx)		41.2	0.398	315.1	1.25842 ± 6	
87T14	WR	Weinebene	2918	15.6	657.2	2.92900 ± 41	
	Spod (xx)		32.2	1.54	61.80	0.90915 ± 1	238.5 ± 2.6 (WR-Spod)
965KWT	WR 1	Weinebene	1244	9.50	436.0	2.22832 ± 18	
	WR 2		1240	9.51	434.0	2.22740 ± 15	
	WM (.3-.4)		4403	3.11	21863.0	45.078 ± 70	140.7 ± 2.6 (WM-WR)
	Spod (xx)		14.8	4.13	10.50	0.76185 ± 1	242.8 ± 1.7 (WR1, 2-Spod)
c) aplitic border zone to spodumene-bearing pegmatites							
87T12	WR	Weinebene	656	138	14.10	0.95447 ± 5	
	WM (>.25)		3931	14.8	849.9	1.79901 ± 21	71.1 ± 0.7 (WM-WR)
	Ap (green)		47.0	602	0.233	1.01875 ± 10	64.6 ± 1 (Ap-WM)
	Bt (contact)		6974	7.02	4196.0	5.39509 ± 66	74.8 ± 0.7
87T13	WR		326	40.2	24.12	0.97568 ± 28	
961KWT	WR	Weinebene	535	17.2	95.20	1.25313 ± 23	
	Ms (.4-.45)		4815	5.52	3419.0	4.33722 ± 80	65.3 ± 0.7
	Grt					2.51587 ± 15	
d) Wolfsberg granite gneiss							
WAP623	WR	Wolfsberg	395	24.6	47.17	0.87842 ± 10	
90T126	WR	Wolfsberg	334	27.4	35.68	0.83441 ± 9	
WAP624	WR	Wolfsberg	641	8.95	222.3	1.44875 ± 18	
Zr, 1st leach						0.78123 ± 3	
Zr, 2nd leach						0.7494 ± 12	
WAP625	WR	Wolfsberg	335	31.7	30.92	0.81209 ± 6	
94T55KW	WR	Wolfsberg	24.2	88.5	0.792	0.71173 ± 7	
94T19KG	WR	Schwanberg	47.6	236	0.583	0.71578 ± 8	

(xx) central part of cm-sized crystals

(Fig. 6b; sample 95T06K; Tab. 3) and 183 ± 3 Ma (Fig. 6c; sample 95T14K). In this latter sample a younger garnet generation has overgrown older garnet grains. Tourmaline analyzed from this sample yields a Tour-Grt age of 182 ± 3 Ma, which is identical with the 183 ± 3 Ma Grt-WR result. All analyzed garnets have high Sm/Nd ratios. The composition of the coarse-grained garnet from sample 95T06K with a $^{147}Sm/^{144}Nd$ ratio of 7.21 (chemical Sm/Nd ratio: 11.9), however, is extreme, pointing to exceptional fractionation of REE in Grt of some pegmatite "melts" (Tab. 3).

Spodumene Three spodumene concentrates taken from the centre of cm-sized porphyroclasts were analyzed. LREE concentrations in Spod were too low to be analyzed precisely for the Nd isotopic composition. Nd concentrations are clearly below the 10 ppb level (Tab. 3). Sr concentrations in this mineral are also relatively low. Given the coarse primary grain size, as well as the polyphase nature of the mineral assemblages, isotopic disequilibrium is likely. Therefore, the Rb–Sr data are not expected to give concordant geochronological information. Nevertheless, it is striking that two out of three Spod-WR pairs (Tab. 2) give age results close to 240 Ma, similar to the U–Pb age of HEEDE (1997).

White mica An extremely radiogenic coarse-grained white mica separated from the spodumene-bearing sample 965KWT yields a Rb–Sr WM-WR age of 140.7 ± 2.6 Ma.

"APLITIC BORDER ZONE" OF SPODUMENE-BEARING PEGMATITES

The isotopic results obtained on minerals from the "aplitic border zone" samples 961KWT and

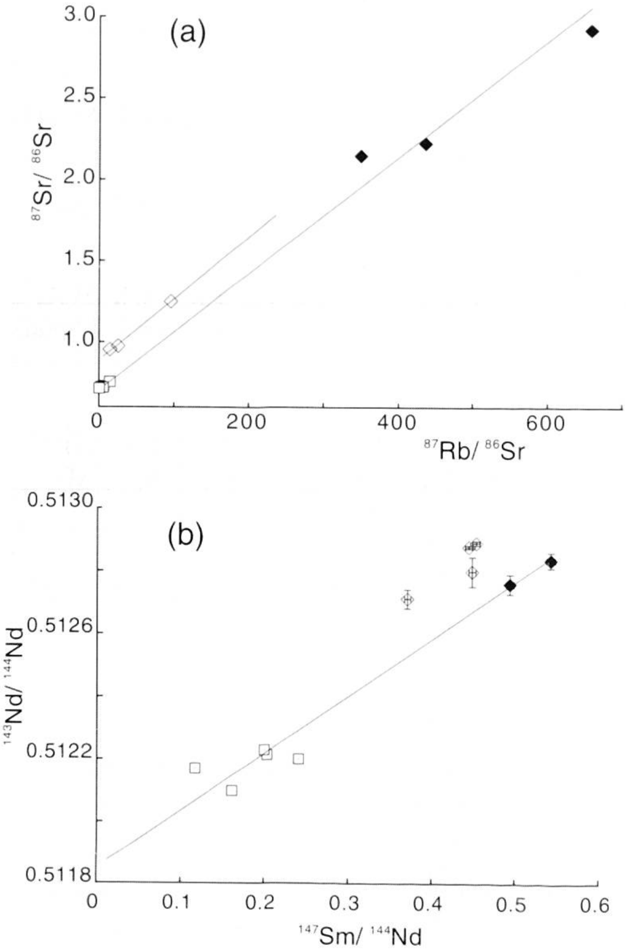


Fig. 5 (a) Rb–Sr evolution diagram showing results of whole-rock analyses for spodumene-free pegmatites (open squares), spodumene-bearing pegmatites (full diamonds) and "aplitic border zone" samples (open diamonds). Trend lines yield 245 ± 20 Ma (I.R. = 0.727 ± 0.038, MSWD = 3430) for the first two groups and 265 ± 170 Ma (I.R. = 0.893 ± 0.01, MSWD = 848) for the three aplitic border zone samples. Symbol size exceeds internal errors. (b) Sm–Nd evolution diagram showing results of whole-rock analyses for spodumene-free pegmatites, spodumene-bearing pegmatites and "aplitic border zone" samples. A trend line through the data scatter of spodumene-free and spodumene-bearing pegmatites and excluding the aplitic border zones yields 270.5 ± 64.2 Ma (ε(t) = –8.36 ± 1.02; MSWD = 199). Symbols as in figure 5a. Note that symbol size is mostly larger than internal errors given on table 3.

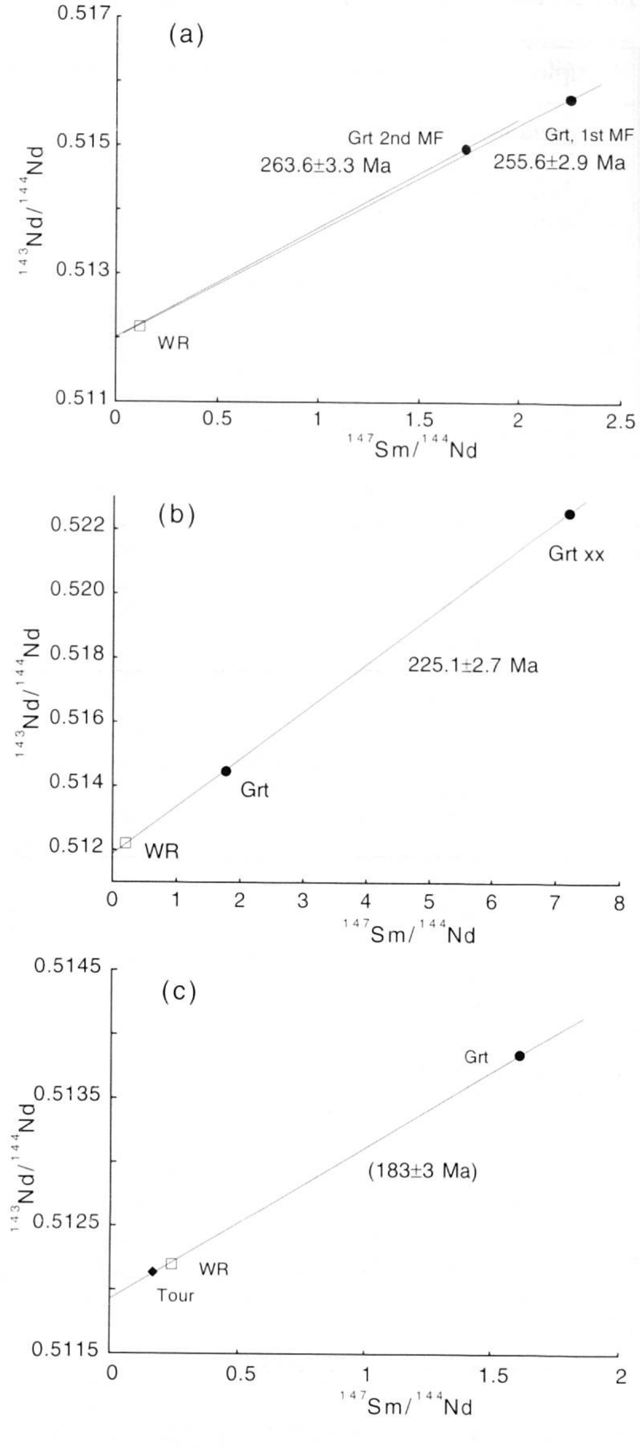


Fig. 6 Sm–Nd mineral isochron plots for three spodumene-free pegmatites. (a) Garnet porphyroclasts from the strongly mylonitized sample 93T23Ka (platten gneiss) show a perfectly preserved, flat major element profile; the two magnetic fractions give WR-Grt ages of 263.6 ± 2.9 and 255.6 ± 3.3 Ma, respectively. (b) Two grain mounts of the chemically homogeneous garnet 95T06K yield ages of 222.4 ± 7.7 and 225.4 ± 2.9 Ma. Including the WR, the three-point isochron age is 225.4 ± 0.8 Ma (MSWD = 1.28). Grt xx is a grain mount separated from the core part of three cm-sized Grt grains. (c) Garnet 95T14K is overgrown by a Cretaceous rim, thus producing a "mixed" (meaningless) age of 183.4 ± 2.9 Ma.

Tab. 3 Sm–Nd data from pegmatites and granite gneisses of the Koralpe.

Sample		Locality	Lithology/Structure	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm 2\sigma m$	Isochron age (Ma)	ε t (Nd)[+]	ε 240 (Nd)[+]
a) spodumene-free pegmatites										
93T23Ka	WR	Stainz	platten gneiss (mylonite)	2.473	12.780	0.11700	0.512174 ± 9		–6.41	
	Grt, 1st MF			0.993	0.267	2.25520	0.515750 ± 16	255.6 ± 2.9		
	Grt, 2nd MF			0.965	0.337	1.73250	0.514962 ± 16	263.6 ± 3.3		
93T24	WR	Stainz	platten gneiss (mylonite)	5.850	28.217	0.12532	0.512098 ± 9		–10.53	
95T06K	WR	Koralmhaus	coarse-grained	3.750	11.135	0.20359	0.512214 ± 11		–8.49	
	Grt			1.614	0.557	1.75215	0.514468 ± 75	222.4 ± 7.7		
	Grt xx			1.393	0.117	7.21423	0.522557 ± 82	225.4 ± 2.9		
95T14K	WR	Grillitschhütte	fine-grained, recrystallized	2.268	5.703	0.24038	0.512201 ± 7		–9.98	
	Grt			1.700	0.637	1.61358	0.513849 ± 16	(183.4 ± 2.9)		
	Tour			0.579	2.107	0.16617	0.512138 ± 13	(180.7 ± 2.9)		
b) spodumene-bearing pegmatites										
SPPCM	WR	Weinebene	massive to mylonitic	0.119	0.133	0.54211	0.512834 ± 25			–6.76
	Spod			0.034	<0.01*		n.d.			
87T14	WR	Weinebene	massive to mylonitic	0.016	0.021		n.d.			
965KWT	WR	Weinebene	massive to mylonitic	0.162	0.199	0.49356	0.512759 ± 31			–6.73
c) aplitic border zone to spodumene-bearing pegmatites										
87T12	WR 1	Weinebene	"aplite", contact to wall rock	7.233	9.654	0.45300	0.512887 ± 7			(–2.99)
	WR 2			7.375	10.044	0.44392	0.512878 ± 5			(–2.89)
	WM 1						0.512636 ± 20			
	WM 2			0.067	0.095	0.42482	0.512670 ± 20			
	Grt 1			0.449	0.077	3.78710	0.514322 ± 50	75.1 ± 2.5 (WM2)		
	Grt 2			0.585	0.074	4.79600	0.514721 ± 38	71.7 ± 1.7 (WM2)		
	Ap (green)			37.433	45.574	0.49740	0.512880 ± 8	65.9 ± 1.3 (Grt1-Grt2)		
	LF (Fsp+Qtz)			0.515	0.682	0.45710	0.512830 ± 16			
87T13	WR			0.132	0.212	0.37740	0.512721 ± 30			(–3.92)
961KWT	WR	Weinebene	"aplitic", spodumene-bearing	0.377	0.508	0.44820	0.512799 ± 47			(–4.56)
	Grt			0.262	0.024	6.59500	n.d.			
	Grt2			0.563	0.054	6.36050	0.516184 ± 196	87.5 ± 5.2		
d) Wolfsberg granite gneiss										
WAP623	WR	Wolfsberg	granite gneiss	7.848	33.153	0.14311	0.512561 ± 8		0.28	
90T126	WR	Wolfsberg	augen gneiss	6.326	29.485	0.12972	0.512600 ± 12		1.58	
WAP624	WR	Wolfsberg	granite gneiss	5.515	20.884	0.15965	0.512622 ± 3		0.92	
Zr, 1st leach				47.304	61.173	0.46752	0.512799 ± 10	87.9 ± 4.7		
Zr, 2nd leach				0.356	0.431	0.49914	0.512947 ± 60	(146.3 ± 24)		
94T55KW	WR	Wolfsberg	contact to wall rock	4.149	21.479	0.11676	0.51210 ± 7		–7.79	
94T19KG	WR	Schwanberg	augen gneiss	1.665	5.673	0.17740	0.512216 ± 5		–7.60	

* concentration outside analytical precision limits. [+] ages and ε values given in parenthesis are suggested to have been strongly influenced by Alpine overprint.

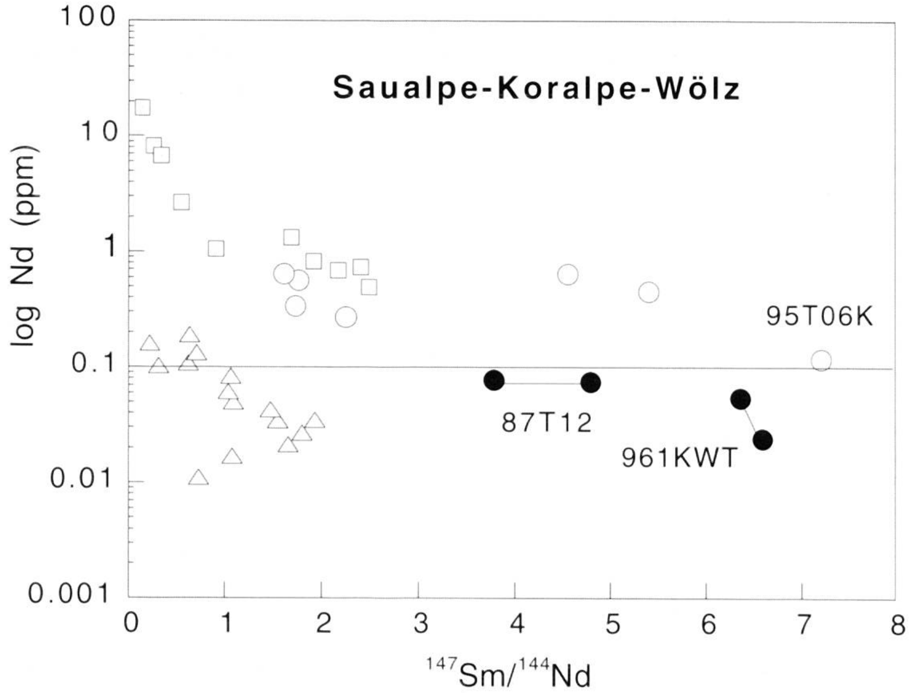
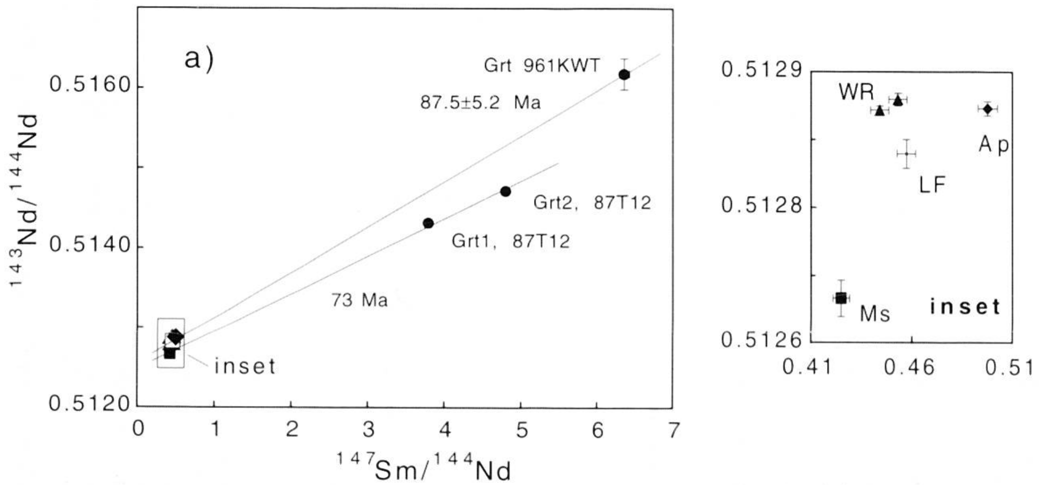


Fig. 7 Isotope dilution analyses for garnets of different lithologies from the SE Austroalpine units in a log Nd (ppm) vs $^{147}Sm/^{144}Nd$ plot. Note the unusually high Sm/Nd ratios of some pegmatite garnets and the "aplitic border zone" garnets analyzed in the present study. Symbols: open squares = Grt from metapelites; open triangles = Grt from metabasites; open circles = Grt from spodumene-free pegmatites; full dots = garnets from "aplitic border zone" to spodumene-bearing pegmatites (samples 87T12 and 961KWT). Data from: THÖNI and JAGOUTZ (1992), THÖNI and MILLER (1996), SCHUSTER and THÖNI (1996), MILLER and THÖNI (1997), HABLER and THÖNI (1998), and data from the present study.



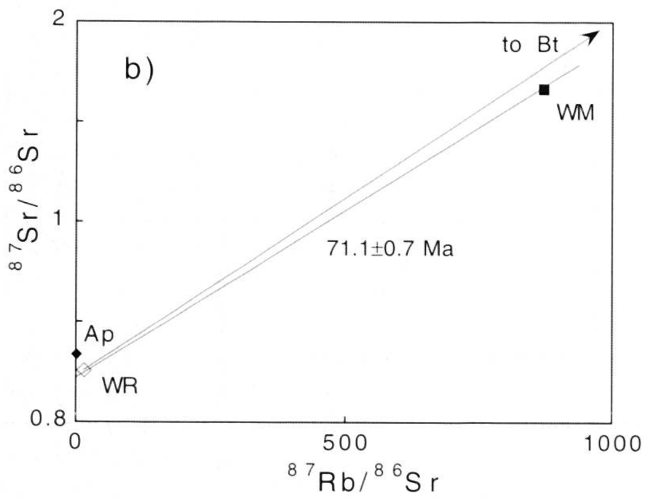


Fig. 8 (a) Sm–Nd isochron plot for minerals and whole-rocks from "aplitic border zone" samples 961KWT and 87T12 at Weinebene. The Grt-WR regression age for sample 961KWT is 87.5 ± 5.2 Ma. Rectangle marks inset shown to the right of main plot, with error bars and exact position of the different components with lower Sm/Nd ratios, demonstrating isotopic disequilibrium in sample 87T12. The 73 Ma trend line shown on figure 8a refers to WM-Grt1-Grt2 (low probability fit), where WM-Grt1 yields 75.1 ± 2.5 Ma and WM-Grt2 yields 71.7 ± 1.7 Ma. Ap-Grt1-Grt2 yields 65.9 ± 1.3 Ma (MSWD = 1.1). LF = light fraction (quartz + feldspar). (b) Rb–Sr isochron plot for minerals and whole-rock of the aplitic border zone sample 87T12. WM-WR yields 71.1 ± 0.7 Ma, Ap-WR 64.6 ± 1.4 Ma, Ap-Grt 64.6 ± 1 Ma and Bt-WR 74.8 ± 0.7 Ma.

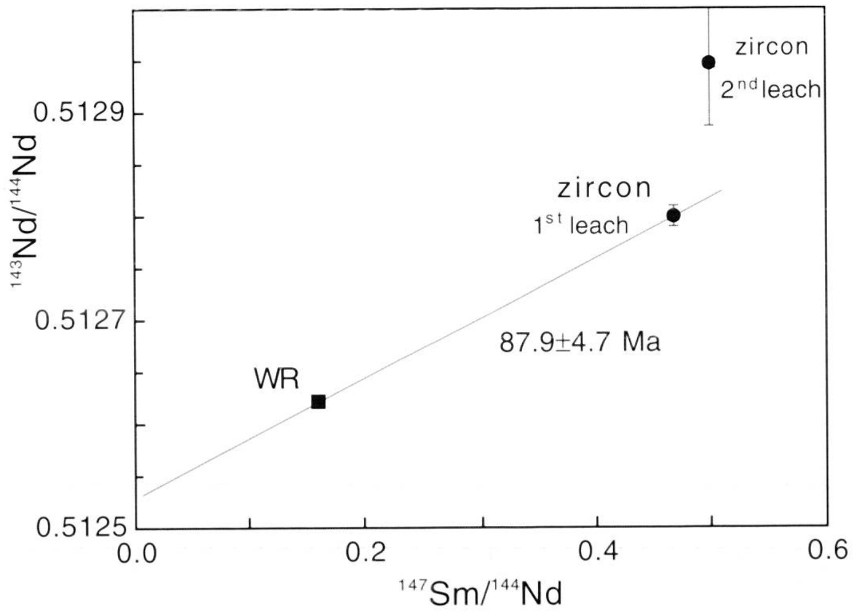


Fig. 9 Sm–Nd isochron plot for whole rock and two leachates of a zircon fraction from the Wolfsberg metagranite sample WAP624. WR calculated with the 1st zircon leach yields 87.9 ± 4.7 Ma.

87T12 are especially interesting, since they differ from all other data.

Figure 7 shows different garnet magnetic fractions from these two samples, together with garnet analyses from spodumene-free pegmatites and other lithologies of the study area, in a log Nd (ppm) vs $^{147}Sm/^{144}Nd$ plot (see THÖNI et al., 1997). It is evident that these "aplitic border zone" garnets are characterized by fairly low Nd concentrations (below 100 ppb), but unusually high Sm/Nd ratios (Tab. 3).

For some of the metapelite garnets, the inverse relationship between Nd concentration and Sm/Nd ratio (Fig. 7) may partly reflect the quality of the separated grain mount (i.e., whether the garnet concentrate is really clean with respect to Nd-rich solid inclusions, such as apatite, clinozoisite-epidote, sphene, zircon, monazite, etc.). However, the Sm/Nd ratios should also be a product of the reacting assemblage and therefore depend on garnet major element chemistry and the chemical composition of the protolith (SCHWANDT et al., 1996; MAWBY et al., 1999).

Grt from 961KWT has a very high $^{147}Sm/^{144}Nd$ ratio of 6.4–6.6 (chemical Sm/Nd = 10.9; Tab. 3). This sample represents a layered transition to the inner and coarser grained spodumene-pegmatite and contains fine-grained, recrystallized spodumene. 87T12, on the other hand, represents the outermost spodumene-free contact (c. 10 cm wide), next to the wall rock.

Grt-WR from 961KWT yield a Sm–Nd age of 87.5 ± 5.2 Ma (Fig. 8a). The WM-WR Rb–Sr age for this sample is 65.3 ± 0.7 Ma (Tab. 2).

The isotopic results for 87T12 are plotted in isochron diagrams (Fig. 8a, b). It is striking that all age results are relatively young, but internally fairly consistent, if both the Rb–Sr and Sm–Nd data are compared. Ap and WM define a Rb–Sr age of 64.6 ± 1 Ma. This number is identical with the Sm–Nd age of 65.9 ± 1.3 Ma, calculated for Ap and the two Grt fractions. WM and WR, on the other hand, define a Rb–Sr age of 71.1 ± 0.7 Ma. This number is, again, close to or identical with the ages calculated between WM and either the two Grt fractions in the Sm–Nd system (75.1 ± 2.5 Ma for WM–Grt1 and 71.7 ± 1.7 Ma for WM–Grt2). Biotite from the very biotite-rich contact (c. 0.5 cm wide zone) between the "aplitic" part and wall rock gives a Rb–Sr age of 74.8 ± 0.7 Ma. In spite of the clear disequilibrium for both isotopic systems between the different components of this sample (Fig. 8a, b), it is argued that the regression ages still give rough time brackets for the last pervasive event in this assemblage.

WOLFSBERG METAGRANITE

Samples from the small Permian intrusive stock near Wolfsberg, the only silicic meta-igneous outcrop in the Koralpe, were analysed in order to elucidate a possible genetic relationship with the pegmatites.

Three whole-rock samples from the central part of the Wolfsberg metagranite gave positive initial (260 Ma; cf. MORAUF, 1980) εNd values in the range of +0.3 to +1.6. In contrast, sample

94T55K, from the border zone of the intrusion, as well as an augen gneiss sample (94T19K) collected some 20 km to the SE of Wolfsberg gave strongly negative initial εNd values of –7.6 and –7.8 (Tab. 3), respectively.

A zircon fraction from metagranite sample WAP624 (initial εNd value of +0.92; see Tab. 3) was leached in two steps, using a $HF/HClO_4$ mixture. The leachates were then analyzed by the Sm–Nd method. If calculated with the WR data point, the first zircon leachate (1st leach) yields an age of 87.9 ± 4.7 Ma, whereas the second leachate (2nd leach) gives a badly defined age at 146 Ma (Fig. 9).

Discussion

The Rb–Sr and Sm–Nd scatterchrons in figure 5, the Sm–Nd garnet-WR ages (Fig. 6a, b) and the spodumene-WR Rb–Sr ages for two out of three spodumene-bearing samples (Tab. 3) indicate a Permo-Triassic pegmatite-forming event in the Kor-alpe and surrounding areas. This is in agreement with pegmatite ages based on Rb–Sr dating of core domains from cm-dm sized muscovite books, which are mostly in the range 240–280 Ma (MORAUF, 1981; JUNG, 1982). Published Sm–Nd ages from Mn-rich, highly radiogenic primary garnets of spodumene-free pegmatites range between 269 ± 3 and 249 ± 3 Ma (SCHUSTER and THÖNI, 1996; THÖNI and MILLER, 1996; HABLER and THÖNI, 1998). Rb–Sr whole rock ages close to 270 Ma have also been determined for several spodumene-free pegmatites from the Austroalpine basement to the S and W of the Tauern window (see BOCKEMÜHL, 1988, for review). These ages have been interpreted as (minimum) formation/emplacement ages of the pegmatite melts. Permo-Triassic age results compiled from the literature are given in figure 10.

It is evident, however, that the pegmatite age data scatter widely and that even internal data sets may be strongly discordant. Three possibilities could explain the observed scatter: (i) heterochronous crystallisation/emplacement, extending over a long period; (ii) primary isotope disequilibrium between the generally coarse grained pegmatite minerals; (iii) post-emplacement open system behaviour.

An intense tectonometamorphic overprint with PT conditions in the range of 2 GPa / 650 °C

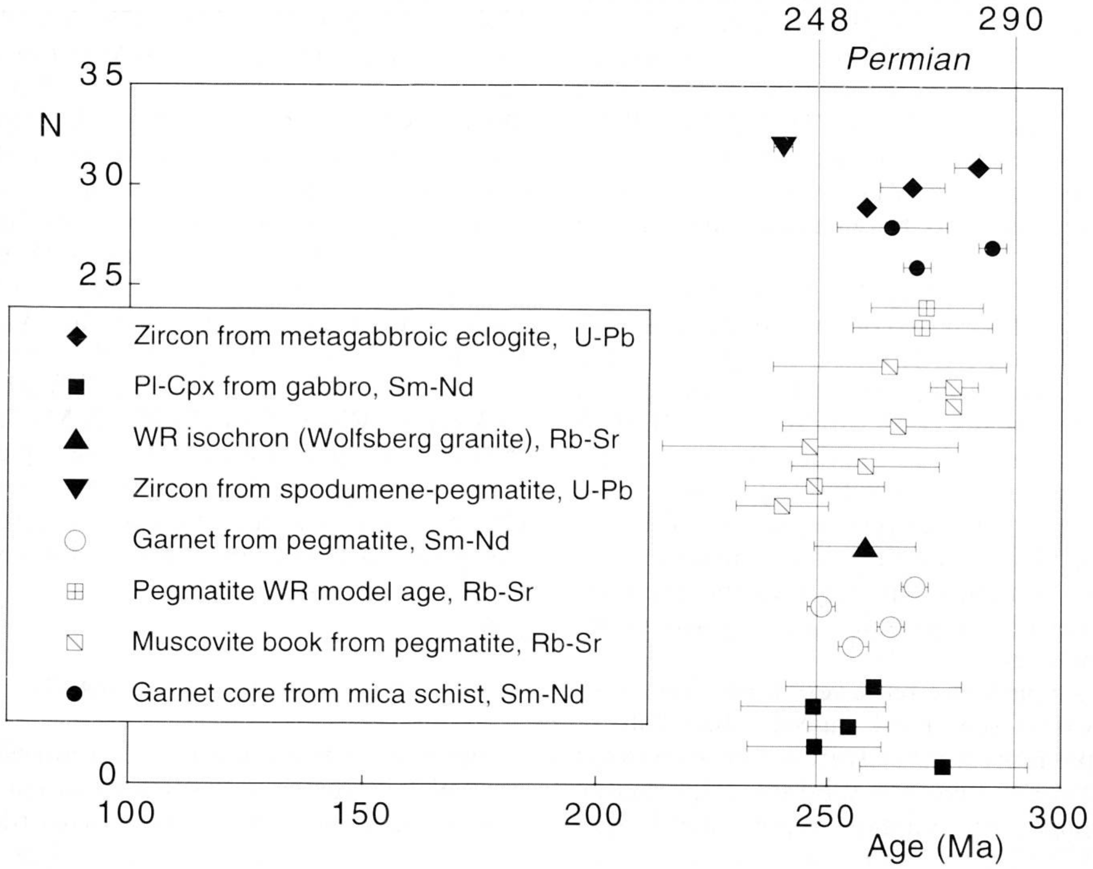


Fig. 10 Compilation of Permo-Triassic ages of the wider area of investigation (Koralpe-Saualpe-Wölz crystalline). Note that, with the exception of metapelite garnet cores, all ages are interpreted as magmatic ages. Data from: MORAUF (1980; 1981), JUNG (1982), THÖNI and JAGOUTZ (1992), THÖNI and MILLER (1996), SCHUSTER and THÖNI (1996), MILLER and THÖNI (1997), LICHEM et al. (1997), HEEDE (1997), HABLER and THÖNI (1998), and unpubl. data (THÖNI, 1999).

(e.g. MILLER and THÖNI, 1997) affected the central-southern Koralpe and adjoining areas during the Cretaceous (see THÖNI, 1999, for review). Metamorphic mineral ages in metapelites and metabasites are almost exclusively Cretaceous (110–65 Ma). In contrast, primary coarse grained rocks like the pegmatites could have escaped or do not show clear evidence of the eclogite-facies Cretaceous overprint recorded by mafic and pelitic lithologies. Also, the two isotopic systems applied (Sm–Nd and Rb–Sr) behaved fairly different during this event. Sr loss in muscovite was variable, but still incomplete (e.g. sample 965KWT, Tab. 2). As shown by the internal concordance of ages, thermally induced Nd diffusion in primary pegmatite Grt by Alpine re-heating has obviously not taken place (samples 93T23Ka and 95T06K, Fig. 6a, b). This observation is consistent with the undisturbed textural and chemical zonation of major elements (Fig. 3d and THÖNI and MILLER, 1996, Figs 3d and 7a). However, meaningless ages could be produced by using growth domains of primary cores and Cretaceous (metamorphic) rims for analysis: the result of 95T14K (Tab. 1) is probably a "mixed" age, resulting from the intergrowth of primary pegmatitic and Alpine metamorphic garnet.

The results concerning the isotopic characterization of the source are not easy to interpret. The wide scatter of data points in figures 5a, b could indicate that the whole rock systems have been disturbed during the Alpine tectonometamorphic processes. On the other hand, the high-precision Grt Sm–Nd age data (Figs 6a, b and 10) clearly document that crystallization/emplacement of the spodumene-free pegmatites extended over a time span of at least 30–40 Ma, precluding a colinear array of the whole rock data points in the isotope evolution diagram and concordant initial ratios. Therefore, initial ratios from the present work should be viewed with caution, at least as far the Rb–Sr system is concerned. The calculation of εNd(t) in spodumene-bearing pegmatites is based on an emplacement age of 240 Ma (HEEDE, 1997). The εNd (240 Ma) values are –6.7 for two samples (Tab. 3). For spodumene-free pegmatites, initial εNd values scatter more widely (–10.5 to –6.4). For simplicity, a mean emplacement age of 260 Ma is used for three out of four samples (Tab. 3), based on Grt from sample 93T23Ka with its perfectly preserved, homogeneous major element profile (THÖNI and MILLER, 1996). ε (t) for sample 95T06K, however, is calculated for a time of 225 Ma (Fig. 6b). The strongly negative initial εNd values for both pegmatite types indicate that the pegmatite protolith material was derived from a LILE-enriched, crustal-type source, similar to the present-day metasedimentary pegmatite wall rock.

The mechanisms of the pegmatite genesis and emplacement are difficult to assess. There is ambiguity in the literature about a strictly magmatic vs metamorphic origin of the pegmatites. WEISSENBACH (1965) used the term "pegmatoids" for the spodumene-free pegmatites and interpreted these rocks as "exsudates" of their country rocks in the high-grade metamorphic part of the Saualpe. Based on a more recent geodynamic interpretation, the spodumene-free pegmatites could represent metamorphic-anatectic mobilisates, formed essentially *in situ* by partial melting of the metasedimentary host rocks during the Permo-Triassic low-P/high-T metamorphism (HABLER and THÖNI, 1998). The strongly negative εNd(t) values of these pegmatites are well within range of the paragneiss/mica schist country rocks (their calculated mean for t = 260 Ma ranges at –8.5 ε; see e.g. MILLER and THÖNI, 1997) and would be consistent with this interpretation.

In contrast, the spodumene-bearing metapegmatites at Weinebene have been interpreted as products of igneous differentiation (GÖD, 1989). Our data show that both, spodumene-free as well as spodumene-bearing pegmatites, are derived from crustal sources. They could even represent products of partial melting of metasedimentary sequences and/or metasomatic processes s.l. during prograde metamorphism. If the Li-pegmatites are related to a granite and had intruded at great distances from their source, this must have been an S-type and quite unlike that of the Wolfsberg intrusion.

The positive εNd(t) and low initial $^{87}Sr/^{86}Sr$ ratios of the Permian Wolfsberg granite clearly preclude any genetic relationship with the pegmatites. Instead, the isotopic signatures indicate a mantle source for the meta-granite of Wolfsberg and generation of silicic melts by fractionation processes of a mantle melt (MORAUF, 1980). Mantle-derived metabasites documenting Permian rifting are well known from the Koralpe (MILLER and THÖNI, 1997). In addition, the 87.9 ± 4.7 Ma WR-zircon Sm–Nd age (Fig. 9) documents an intense Alpine metamorphic overprint even within the deeper parts of the Koralpe section (MORAUF, 1980).

Results from the "aplitic border zones" of spodumene-bearing pegmatites (see appendix) are of special interest. At the contacts between spodumene-bearing pegmatites and country rocks (metapelites or metabasites) strong geochemical gradients exist for trace elements and the concentration of radiogenic isotopes. The fact that "aplitic border zone" whole-rock samples are characterized by high Sm/Nd ratios similar to those observed in spodumene-bearing pegmatites, but quite different from those observed in the spodumene-free pegmatites, could indicate that these contact zones represent a primary, integral part of the pegmatite. This is especially true for sample 961KWT which contains spodumene and represents the outermost, fine-grained aplitic rim of a massive spodumene-bearing layer.

Garnet from the "aplitic border zone" is characterized by unusually high Sm/Nd ratios (Tab. 3; Fig. 8a) and by high spessartine contents (Tab. 1). As high spessartine contents are characteristic for garnets in rocks of granitic composition (e.g. NABELEK et al., 1992; see also BOCKEMÜHL, 1988; GLODNY and GRAUERT, 1996; KRUGER et al., 1998) this could indicate magmatic crystallization for the aplitic border zone garnets as well. The high Sm/Nd ratios might then be explained by fractionation of accessory minerals enriched in LREE. All pegmatite garnets analysed in the present study have high to very high spessartine contents (see Figs 2, 3 and 7; THÖNI et al., 1997).

Aplitic border zone samples 961KWT and 87T12 yielded surprisingly young mineral ages. The 87.5 ± 5.2 Ma Grt-WR Sm–Nd age of sample 961KWT is within the range of metamorphic ages observed in the study area (see also Fig. 9). This age is therefore interpreted as dating pervasive recrystallization and neoformation of Grt and Spod, close to the peak of eo-Alpine metamorphism. In addition, the low grossular-content in this garnet points to a formation at rather low pressures, i.e., after the pressure peak and during rapid exhumation. This would agree with the interpretation that the time span of 90–80 Ma records a drastic pressure drop in the Koralpe (see THÖNI, 1999, for review). As the age of the chemically homogeneous Grt of sample 961KWT (Fig. 2a–d) is interpreted as metamorphic rather than as primary magmatic, its chemical composition should mimic that of the primary (Permian) magmatic assemblage.

The results of Grt 87T12 are more complex. Garnet compositions and element zonation patterns (Figs 3a–c) suggest a two-phase history. The isotopic data (Figs 8 a, b) clearly indicate isotopic disequilibrium between the different minerals (Ap, Bt, WM and Grt). Despite this disequilibrium, the internal concordance of ages (including iterative analyses) from the Rb–Sr and Sm–Nd isotopic systems is remarkable (Tabs 2, 3; Fig. 8). For instance, the Ap-WM Rb–Sr age (64.6 ± 1 Ma) is identical with the Sm–Nd Ap-Grt age (65.9 ± 1.3 Ma; Tab. 3). In a strict sense, however, these ages may represent "mixed" ages, resulting from an earlier and a later eo-Alpine component. This is inferred from figure 3b, where chemically distinct core and rim domains in garnet are clearly discernible. The isotopic data also imply that apatite (a mineral of great interest for both the Sr and the Nd and Sm budget) was open for isotopic exchange in this sample, if not crystallizing, until 70–65 Ma. Moderately high temperatures at this time are indeed indicated for the central and southern Koralpe by biotite Rb–Sr ages from metapelites, which range between 67 and 63 Ma (3 data; THÖNI and JAGOUTZ, 1992; MILLER and THÖNI, 1997).

The chemically distinct aplitic border zones could have formed by metasomatic processes between the pegmatite and host rocks in Permo-Triassic time, but the pervasive late eo-Alpine overprint nearly obliterated older textures and reset mineral chemical and radiogenic isotope characteristics. Fluids released during a rapid Cretaceous pressure drop may have strongly enhanced element mobilisation in these Li-rich zones, producing late crystallization of new minerals, among them spassartine-rich garnet and green apatite (NIEDERMAYR and GÖD, 1992). Pervasive postkinematic recrystallization of the "aplitic border zones" is well documented by textures, which show randomly oriented mineral assemblages completely lacking alteration and internal deformation, comparable to unaltered magmatic rocks. This scenario requires complete remobilisation of the pre-Cretaceous aplitic border zone material, possibly even decompression melting, during the eo-Alpine exhumation. Recent U–Pb dating of zircon has indeed shown that some of the eclogite-related pegmatoids in the Saualpe were generated during later stages of the Cretaceous metamorphic event (HEEDE, 1997).

The Bt Rb–Sr age of sample 87T12 is another interesting and rather unusual result. The age of 74.8 ± 0.7 Ma fits well into the regional mica cooling pattern for the eo-Alpine event (e.g. MORAUF, 1980). However, it is, outside analytical uncertainties, older than the age calculated for WM and WR (71.1 ± 0.7 Ma; Tab. 2), and thus in clear conflict with a simple cooling age model, as predicted by the blocking temperature concept. Since Bt 87T12 was separated from a cm thin layer consisting almost exclusively of biotite, at the very contact between the "aplitic border zone" and wall rock, it is suggested that the mica age is essentially controlled by the modal composition of the rock (JENKIN, 1997). The results from sample 87T12 indicate significant isotope exchange and recrystallization, probably under special fluid and low-grade conditions, which were effective at Weinebene until 70–65 Ma ago.

Regional geologic implications

Permian to Triassic magmatism is documented in the Austroalpine basement by tholeiitic gabbros and basalts, granites and pegmatites (Fig. 10). The new εNd data for the Wolfsberg meta-granite show a major mantle component for this granite, supporting the earlier interpretation that this magma differentiated from a mantle melt in Permian times (MORAUF, 1980). In contrast, the wide-spread pegmatites were derived from old crustal sources.

Recent field and analytical work indicates that the Permian magmatic pulses were accompanied by a low-P/high-T metamorphic event in the polymetamorphic basement rocks (e.g. HABLER and THÖNI, 1998). Sm–Nd data obtained from core domains in polyphase, cm-sized metapelite garnet confirm such a Permian metamorphic event (SCHUSTER and THÖNI, 1996; LICHEM et al., 1997; THÖNI, 1999, unpubl. data). There is increasing evidence that this low-P metamorphism affected large areas of the southern Austroalpine basement units, from the Lake Como area in the W to the Koralpe in the E (SCHUSTER et al., 1998), implying a thermal event of regional importance. From a geodynamic point of view, the high Permo-Triassic thermal gradient in the crust is not related to the Variscan cycle. Instead, this event (formerly called "Late Variscan event") is interpreted to reflect lithospheric thinning and mantle upwelling, initiating crustal extension, rifting and the opening of new oceanic branches, like the Meliata domain, at the western end of the Paleo-to Neotethyan realm (STAMPFLI and MOSAR, 1999). Available age data on magmatic and metamorphic rocks related to this Late Palaeozoic–Early Mesozoic event (Fig. 10) document a long-lasting process of crustal-scale dimension.

In the course of the Late Mesozoic convergence of Africa and Europe, the Koralpe and adjoining southeastern Austroalpine units were subducted to depths of 60–70 km. Related intense deformation and recrystallization, with peak PT conditions at approximately 2 GPa / 650 °C, induced variable resetting of the isotopic systems of pre-Cretaceous assemblages. Following peak pressures at c. 100 ± 10 Ma and subsequent rapid exhumation, recrystallization processes continued. This stage is documented by metamorphic mineral ages in the range 90–80 Ma. In addition, pegmatoids were generated locally during isothermal decompression. Element mobilization by fluid-enhanced metasomatic processes was responsible for the crystallization of even younger mineral assemblages, until c. 75–65 Ma. Regional cooling below 300 °C was completed in the central-southern Koralpe at c. 65 ± 5 Ma.

Conclusions

The results presented in this paper lead to the following conclusions: (1) Rb–Sr and Sm–Nd whole-rock and mineral data support a Permian to Triassic protolith age for both spodumene-bearing as well as spodumene-free pegmatites in the Koralpe. (2) The pegmatite-forming event extended over a time span of at least 40 Ma. (3) During the Cretaceous high-P tectonothermal event, the pegmatites were variously mylonitized and recrystallized, leaving coarse-grained minerals, like WM, Tour, Grt or Spod in part as relics (porphyroclasts) of the Permo-Triassic pegmatite-forming stage. (4) The observed age scatter for whole rock systems can be explained by (i) heterochronous emplacement; (ii) primary inhomogeneity and/or coarse grain size; (iii) intense, but variable Cretaceous tectonometamorphic overprinting of the pegmatites. (5) During eo-Alpine overprinting and intense deformation, the Rb–Sr system in cm-sized white mica was variously reset. In contrast, most coarse-grained spodumene (cm-size) as well as mm-cm-sized garnet crystals were able to retain their primary Rb–Sr and Sm–Nd ages, respectively. (6) εNd values are consistent with formation of the spodumene-free pegmatites by partial melting of their metasedimentary host rocks in the course of the Permo-Triassic high-T/low-P event. (7) Within "aplitic border zones" (probably generated by mineralizing fluids at the contacts between spodumene-bearing pegmatites and host rocks) mineral isochrons document pervasive late eo-Alpine recrystallization during the final stages of Cretaceous exhumation and decompression (75–65 Ma). (8) Garnet from spodumene-free pegmatites and from the aplitic border zone of spodumene-bearing pegmatites is spessartine-rich with unusually high Sm/Nd ratios (chemical ratio up to 11.9), and thus exceptionally well suited for Sm–Nd dating. (9) Alpine overprinting conditions of approximately 2 GPa / 650 °C in the Koralpe constrain the blocking temperature for Nd diffusion in Mn-Fe-rich garnet to about 650 °C, or higher.

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Appendix

PETROGRAPHY AND MINERAL CHEMISTRY OF STUDIED SAMPLES

961KWT aplitic border zone to spodumene-bearing pegmatite – Garnets are highly variable in grain-size (0.1–3 mm) and always irregular, even skeletal in shape, with numerous inclusions of Qtz. The chemical composition is restricted to the spessartine-almandine series, with minor Ca and Mg contents (Tab. 1). Many individual garnet grains are essentially unzoned (Tab. 1), but zoned grains are also present (Fig. 2). Compositions between different grains vary in the range of ($Pyr_{0-0.8}Alm_{37.1-46.8}Grs_{0-4.8}Sps_{49.4-63.8}Adr_{0-1.9}$). Other mineral phases are spodumene, quartz, plagioclase (Ab_{98}), muscovite, tourmaline and apatite. In addition, fine-grained symplectite domains consisting of spodumene and Qtz are present.

87T12 aplitic border zone to spodumene-bearing pegmatite, outermost zone – The narrow biotite-rich selvage also contains plagioclase, quartz, sphene, apatite and garnets that are rounded in shape and up to 0.7 mm in diameter. They frequently contain inclusions of Bt, Qtz and sphene. As shown on table 1 and figures 3a, b these garnets are zoned, consisting of a relatively homogenous core rich in Mg and Fe and poor in Mn ($Pyr_{12.6}Alm_{49.8}Grs_{34.7}Sps_{2.1}$) and a discontinuous and zoned overgrowth distinctly richer in Mn and somewhat richer in Ca at the expense of Fe and Mg. Outer rim compositions are $Pyr_{5.8}Alm_{32.9}Grs_{37.8}Sps_{23.0}$.

87T12 aplitic border zone, interior zone – Garnets are highly irregular with inclusions of WM, Ap, Tour and Qtz and grain sizes up to 2.5 mm. The garnets are rich in MnO and always low in MgO (< 1 wt%). The irregular shape and complex zoning with respect to Mn, Fe and Ca (Fig. 3c) could indicate a composite grain. Rim compositions are $Pyr_{2-3}Alm_{45-50}Grs_{7-12}Sps_{39-49}$, core compositions are variable, containing up to 64 mol% spessartine (Tab. 1). Additional phases are quartz, plagioclase (Ab82), microcline, muscovite, tourmaline, apatite and spodumene.

95T06K spodumene-free pegmatite – 3 to 20 mm garnets are oblong or rounded and poor in inclusions (Qtz, Tour). The small garnet shown in Fig. 3e is slightly zoned with respect to Mn and Fe (Tab. 1), with rim compositions ($Pyr_{2-3}Alm_{64-65}$ Grs_1Sps_{32-33}) somewhat enriched in Mn relative to the core ($Pyr_{2-3}Alm_{69-70}Grs_1Sps_{26-27}$). The chemical data for a large garnet (12–16 mm in diameter) indicate similar concentrations, without regular zoning. Some garnets and tourmalines are partly surrounded by a narrow rim containing fine-grained Kya, Ms, Pl and Qtz. The plagioclase in these rims is slightly more Ab-rich (Ab_{95}) compared with the coarse-grained plagioclase (Ab_{92}) in the matrix.

95T14K spodumene-free pegmatite – Garnets are very irregular in shape and contain numerous inclusions of Qtz, Tour and Ms. The garnets are up to 4 mm in diameter, poor in Mg and zoned with respect to Mn, Fe and Ca. The zoning pattern across a 3 mm garnet shown in figure 3d suggests coalescent garnet growth. Compositions vary in the range of $Pyr_{1-2}Alm_{51-57}Grs_{7-15}Sps_{30-40}$ (Tab. 1). In addition to garnet, plagioclase (Ab_{88}), K-feldspar (Or_{94}), quartz, muscovite, tourmaline and apatite are present.

93T23Ka spodumene-free pegmatite – This sample is a highly deformed pegmatite layer within the plattengneiss-mylonite. The garnets have preserved a completely undisturbed primary chemistry and Sm–Nd age (Tab. 3), despite the high-grade Cretaceous mylonitization. The garnets form porphyroclasts that are Ca-poor, with spessartine contents of c. 15 mol%, distinctly different from pyrope-rich and spessartine-poor (< 1%) garnets in the adjacent country rocks (data in THÖNI and MILLER, 1996).