Contrib Mineral Petrol (2005) 150: 70–84
DOI 10.1007/s00410-005-0004-0

ORIGINAL PAPER

**Christine Miller · Roland Mundil · Martin Thöni
Jürgen Konzett**

Refining the timing of eclogite metamorphism: a geochemical, petrological, Sm-Nd and U-Pb case study from the Pohorje Mountains, Slovenia (Eastern Alps)

Received: 20 December 2004 / Accepted: 13 May 2005 / Published online: 22 June 2005

Abstract High-pressure metamorphism in the Pohorje Mountains of Slovenia (Austroalpine unit, Eastern Alps) affected N-MORB type metabasic and metapelitic lithologies. Thermodynamic calculations and equilibrium phase diagrams of kyanite–phengite-bearing eclogites reveal PT conditions of >2.1 GPa at $T<750°C$, but within the stability field of quartz. Metapelitic eclogite country rocks contain the assemblage garnet + phengite + kyanite + quartz, for which calculated peak pressure conditions are in good agreement with results obtained from eclogite samples. The eclogites contain a single population of spherical zircon with a low Th/U ratio. Combined constraints on the age of metamorphism come from U/Pb zircon as well as garnet–whole rock and mineral–mineral Sm-Nd analyses from eclogites. A coherent cluster of single zircon analyses yields a $^{206}Pb/^{238}U$ age of 90.7 ± 1.0 Ma that is in good agreement with results from Sm-Nd garnet–whole rock regression of 90.7 ± 3.9 and 90.1 ± 2.0 Ma (ϵNd: $+8$) for two eclogite samples. The agreement between U-Pb and Sm-Nd age data strongly suggests an age of approximately 90 Ma for the pressure peak of the eclogites in the Pohorje Mountains. The presence of garnet, omphacite and quartz inclusions in unfractured zircon indicates high-pressure rather than ultrahigh pressure conditions. The analysed metapelite sample yields a Sm-Nd garnet–whole rock scatterchron age of 97 ± 15 Ma. These data probably support a single P-T loop for mafic and pelitic lithologies of the Pohorje area and a late Cretaceous high-pressure event that affected the entire easternmost Austroalpine basement including the Koralpe and Saualpe eclogite type locality in the course of the complex collision of the Apulian microplate and Europe.

Communicated by V. Trommsdorff

C. Miller (✉) · J. Konzett
Institut für Mineralogie und Petrographie,
University of Innsbruck, Innrain 52,
A-6020 Innsbruck, Austria
E-mail: Christine.Miller@uibk.ac.at

R. Mundil
Berkeley Geochronology Center, 2455 Ridge Road,
Berkeley, CA 94709 USA

M. Thöni
Institut für Geologische Wissenschaften, University of Vienna,
Althanstrasse 14, A-1090 Wien, Austria

Introduction

Eclogites may record subduction/continental collision and subsequent exhumation events and thus provide important information on the geodynamics of mountain chains. Constraining the timing of high-pressure metamorphism, however, is known to be difficult. Rb-Sr and U-Pb zircon dating is often impossible in mafic eclogites because of low Rb/Sr ratios of phases suitable for dating (e.g. phengite) and the scarce occurrence of zircon due to low whole-rock Zr concentrations. In addition, although zircon, if present, may yield precise metamorphic ages in eclogite parageneses (e.g. Rubatto and Hermann 2003), a close link of the timing of zircon formation with a specific evolutionary stage along the metamorphic P-T path remains a major challenge of data interpretation (Rubatto et al. 1999; Thöni et al. 2001). In contrast, the rare-earth elements (REE) represent essential trace elements of the major eclogite minerals garnet and omphacite, and it has been demonstrated that the Sm-Nd isotope system has a great potential for high-precision age dating in metabasic high-pressure assemblages (Griffin and Brueckner 1985; Jagoutz 1988; Stosch and Lugmair 1990; Becker 1993; Schmädicke et al. 1995; Miller and Thöni 1995; 1997), and for garnet-bearing rocks in general (e.g. Mezger et al. 1992; Vance and O'Nions 1990; 1992). However, there are a number of problems with the interpretation of Sm-Nd data, especially in eclogites, since Sm-Nd garnet ages appear to be strongly dependent on the cooling history (e.g. Mezger et al. 1992; Burton et al. 1995) and also because of variably inherited isotopic signatures in metagabbroic high-pressure assemblages (e.g. Mørk and Mearns 1986; Thöni and Jagoutz 1992; Jagoutz 1995). In addition, LREE-rich inclusions such as zoisite, apatite and zircon in garnet and isotopic disequilibrium between garnet and inclusions (e.g. Prince et al. 2000) or between garnet and other eclogite mineral phases may present problems in using the Sm-Nd method to date high-pressure metamorphism in eclogite.

The main objective of this paper is to provide combined U-Pb and Sm-Nd isotope and geochronological information on the timing of the high-pressure metamorphism in the Pohorje Mountains, which is essential for constraining the geodynamic evolution of the easternmost segment of the Alpine orogen. We also address the question of whether high-pressure metamorphism affected both, mafic and pelitic lithologies, and discuss the isotope characteristics of the eclogite protoliths.

Geological setting

The Pohorje massif is the south-easternmost part of the Eastern Alps (Fig. 1a). According to Hinterlechner-Ravnik and Moine (1977) it is dominated by ortho- and paragneisses with intercalations of micaschists, marbles and amphibolites that were intruded by a tonalite/granodiorite during Oligocene and by dacitic dikes during Miocene times (Faninger 1970). Eclogites and ultramafic rocks within the Pohorje basement sequence were first described by Ippen (1892). The size of individual eclogite bodies varies from a few metres up to some hundreds of metres, but exposure is very poor. Despite detailed petrological work by Hinterlechner-Ravnik and Moine (1977), Visonà et al. (1991, with references), Janák et al. (2004) and Sassi et al. (2004), the age of the high-pressure eclogites is unknown so far.

The Pohorje massif and the basement complexes of the Koralpe and Saualpe to the North are a part of the Austroalpine nappe system (Fig. 1) and can be considered as displaced terranes from the former southern margin of the Alpine Tethys. Plate tectonic reconstructions (e.g. Stampfli and Mosar 1997) indicate that there was no simple, single-stage collision in the Mediterranean region but rather a series of rifting, subduction and collisional events involving different microcontinents and oceanic basins (Rubatto and Gebauer 1999). The Austroalpine domain was dissected and accreted to

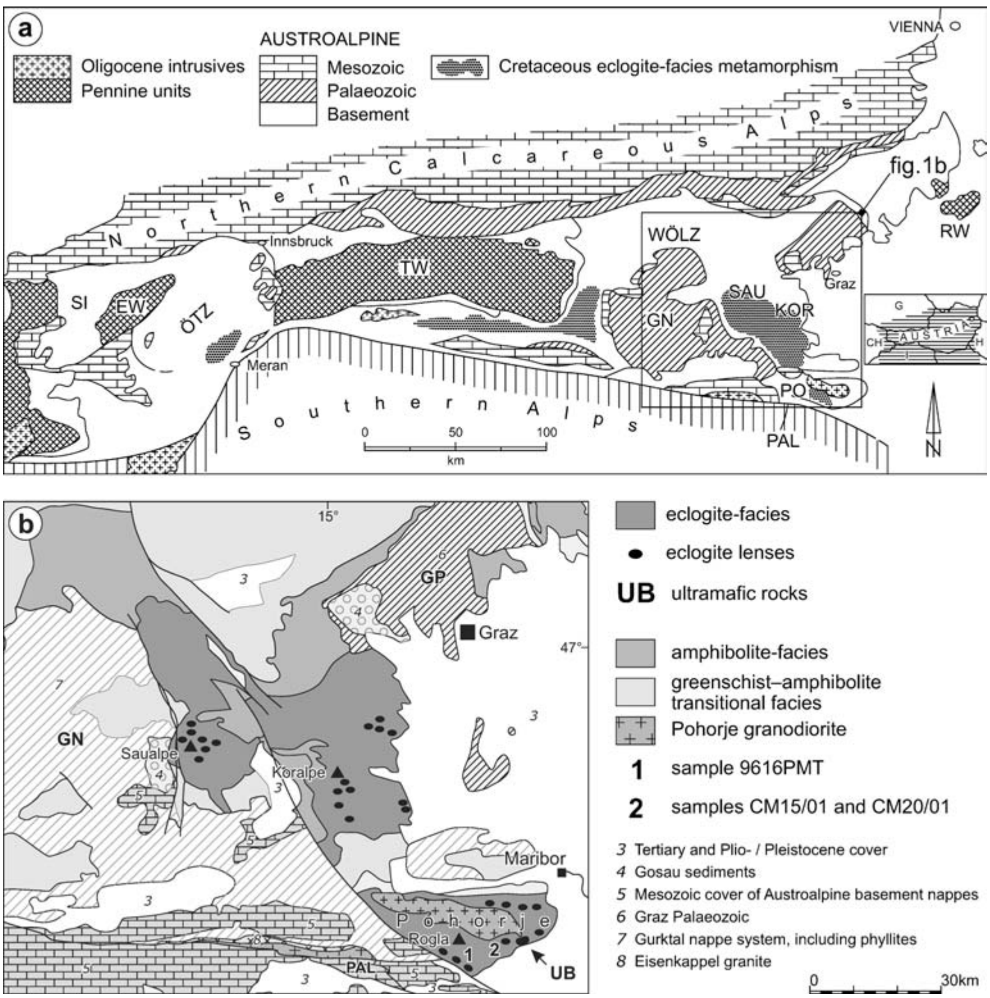

Fig. 1 **a** Simplified geological map of the Eastern Alps, showing different segments of the Austroalpine basement units and the distribution of Cretaceous eclogite-facies metamorphism (modified from Thöni 2002). *PO* Pohorje, *KOR* Koralpe, *SAU* Saualpe, *ÖTZ* Ötztal, *SI* Silvretta, *GN* Gurktal nappe, *TW* Tauern window, *EF* Engadine window, *RW* Rechnitz window, *PAL* Periadriatic lineament. **b** General geology of the easternmost Austroalpine units, including Saualpe, Koralpe and Pohorje high-pressure domains, major eclogite outcrops and sample locations in Slovenia

Europe as the Meliata and Vardar oceans closed, and the Apulian microplate collided with Europe. In the easternmost Austroalpine basement units, subduction-related high-pressure metamorphism is recorded in metabasic and metapelitic lithologies (Miller 1990; Thöni and Jagoutz 1992; Thöni and Miller 1996; Miller and Thöni 1997). The majority of metamorphic mineral Sm-Nd ages from the high-pressure domains in the Koralpe and Saualpe are in the range of approximately 100 ± 10 Ma, followed by isothermal decompression and rapid tectonic exhumation in the upper Cretaceous (Thöni 1999).

Sample preparation and analytical techniques

Mineral separates for Sm-Nd analysis were obtained by standard methods (crushing, sieving), followed by handpicking under a binocular microscope from $>0.125<0.5$ mm sieve fractions in which garnet and omphacite were pre-enriched with a Frantz magnetic separator. Before decomposition, the handpicked mineral separates were washed in warm (50°C) HCl (2.5 M for garnet, and 0.2 M for omphacite and apatite) and then rinsed repeatedly in distilled water to remove surface contamination. Samples for Sm-Nd analysis were digested in screwed Savillex beakers using an ultrapure 5:1 mixture of HF and $HClO_4$ at 100°C on a hot plate. After evaporating the acids, repeated treatment of the residue using 5.8 N HCl resulted in clear solutions for all samples. Upon cooling, approximately 10–20% of the sample solution was diluted with a mixed REE (^{147}Sm$-^{150}$Nd) spike for Sm and Nd concentration determination. The whole rock powders for Rb-Sr analysis were spiked before dissolution, using a ^{87}Rb$-^{84}$Sr tracer, and then dissolved in a HF:HNO_3 ultrapure mixture 4:1. Rb, Sr and the REE fractions were extracted using AG® 50 W-X8 (200–400 mesh, Bio-Rad) resin and 1.0 N, 2.5 N and 4.0 N HCl, respectively. Nd and Sm were separated from the REE fraction using Teflon®-coated HdEHP, and 0.24 N and 0.8 N HCl, respectively, as elution media. To avoid any isobaric interference, Nd IC samples for all mineral concentrates were separated twice. Maximum total procedural blanks were <50 pg for Sm, <100 pg for Nd, and <1 ng for Rb and Sr. Rb, Sm and Nd ID, as well as the Nd IC fractions from sample 9616PMT were measured as metal species from a Re double filament in the static mode, using a multicollector FINNIGAN® MAT262 TIMS. Nd and Sr IC and Sr ID samples for the eclogites were loaded as nitrates or chlorides, and run on a ThermoFinnigan Triton TI® machine, and the same sample preparation/evaporation procedure was applied. A ^{143}Nd/^{144}Nd ratio of 0.511857 ± 0.000013 (MAT262; $n=25$) and 0.511850 ± 0.000004 (Triton TI; $n=8$), respectively, was determined for the La Jolla (Nd) international standard during the period of investigation, while the ^{87}Sr/^{86}Sr ratio determined for the NBS987 (Sr) standard was 0.710240 ± 6 (Triton TI). All analytical work for Sm-Nd and Rb-Sr was performed at the Laboratory for Geochronology, Institute of Geological Sciences, University of Vienna. Errors on the ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr ratios are given as 2σ error of the mean for individual runs (2σ_m internal). Considering replicate analyses, spike recalibration and blank contribution, maximum errors on the ^{147}Sm/^{144}Nd and ^{87}Rb/^{86}Sr ratios are given as ±1.0%; regression calculation is based on these uncertainties. Isochron calculation follows Ludwig's (1999) isoplot. Ages are based on a decay constant of 6.54×10^{-12} a^{-1} for ^{147}Sm (Lugmair and Marti 1978), age errors are given at the 2σ level. A linear depletion of the mantle is assumed throughout geological time (Goldstein et al. 1984); the following Depleted Mantle parameters were used: ^{147}Sm/^{144}Nd = 0.222, ^{143}Nd/^{144}Nd = 0.513114 (Michard et al. 1985).

Zircon U/Pb IDTIMS analyses were performed at the Berkeley Geochronology Center. Zircon crystals were examined by transmitted light microscopy in order to avoid grains with optically recognisable cores. Prior to dissolution the crystals were (1) rinsed several times in conc. HNO_3, (2) cleaned in ultrasonically agitated aqua regia (HCl conc./HNO_3 conc. = 3: 1) followed by clean HNO_3. Zircons were then transferred to perforated miniature PTFE capsules and spiked with ^{205}Pb$-^{233}$U$-^{235}$U tracer solution. The capsules were placed on an elevated rack in a 125 ml digestion vessel, allowing vapour transfer dissolution in a mixture of 50%HF/conc. HNO_3 (30/1) at 220°C for 6 days. After complete dissolution, the dried sample/tracer mixture was taken up in 20 µl 3 M HCl + 5 µl 0.25 M H_3PO_4, dried down, and loaded together with silica gel + H_3PO_4 on outgassed Re filaments. Isotope ratios were determined on a Micromass Sector 54 mass spectrometer using a Daly-type ion counter positioned behind a WARP filter. Pb (as Pb^+) and U (as UO^{2+}) were run sequentially on the same filament. The ^{205}Pb$-^{233}$U$-^{235}$U tracer solution used in this study was calibrated repeatedly against solutions derived from certified standards of isotopically pure ^{206}Pb and natural U (NIST SRM-991and CRM-145, respectively; see Mundil et al. 2001 for details), yielding an uncertainty of 0.15% (insignificant for this study) for the Pb/U of the tracer. Repeat measurements (from 2001 to 2004) of the total procedural blank averaged 0.8 ± 0.3 pg Pb (U blanks were indistinguishable from zero), with ^{206}Pb/^{204}Pb = 18.55 ± 0.63, ^{207}Pb/^{204}Pb = 15.50 ± 0.55, ^{208}Pb/^{204}Pb = 38.07 ± 1.56 (all 2 of population), and a ^{206}Pb/^{204}Pb$-^{207}$Pb/^{204}Pb correlation of +0.9. These ratios and uncertainties were propagated into the age and age error calculations (Ludwig 1980). Common Pb in excess of the analytical blank was assumed to be a result of surface contamination with the same composition as given above. The impact on the final result using 90 Ma model Pb isotopic composition (Stacey and Kramers 1975) is insignificant (resulting in a ca. 0.1 Ma bias). Mass fractionation of U during the analysis was controlled by U double-spike techniques, whereas Pb mass fractionation was corrected by 1.5 ± 0.9 permil/AMU (based on multiple analyses of NBS 981). A detailed description of analytical procedures and tracer calibration for U/Pb analyses is given in Mundil et al. (2004).

In situ trace element analyses of individual mineral phases were carried out using laser ablation inductively coupled plasma spectrometry at the CNR-IGG, Section of Pavia, Italy. The laser probe consists of a Q-switched Nd: YAG laser, model Quantel (Brilliant), whose fundamental emission in the near-IR region (1,064 nm) is converted to 266 or 213 nm by harmonic generators. The ablated material was analysed by a double focussing sector-field analyser Element I (ThermoFinnigan MAT), in which the standard field regulator power stage of the magnet and the ICP torch were upgraded to those of the Element II model. Helium was used as carrier gas and mixed with Ar downstream of the ablation cell. NIST SRM 612 was used as an external standard, with ^{29}Si as an internal standard. Precision (< 7%) and accuracy (better than ± 12%) were assessed from repeated analyses of SRN NIST 612 reference standard. A detailed description of instrumental parameters and quantification procedure are given in Tiepolo et al. (2003).

The composition of mineral phases was determined using a JEOL JXA microprobe and energy-dispersive analytical modes with 15 kV and 20 nA sample current on a benitoite standard. Whole-rock major element XRF analyses were performed using standard methods. Mineral abbreviations follow Kretz (1983), wr, whole rock.

Sample geochemistry and petrology

Eclogites

On the basis of whole rock and mineral chemical data quartz-rich and kyanite-rich eclogite types can be distinguished in the Pohorje Mountains (Sassi et al. 2004). As in the adjacent Koralpe and Saualpe (Miller 1990), the kyanite-rich eclogites are derived from plagioclase-rich gabbroic cumulates, whereas the quartz-rich eclogites represent less-fractionated "basaltic" compositions. In addition to low TiO_2 and variable Al_2O_3 contents, meta-cumulate samples display high Cr contents, low rare earth element (REE) contents and positive Eu anomalies (Sassi et al. 2004). Trace element and REE signatures of quartz-rich eclogites are similar to those of N-MOR basalts, whereas kyanite-rich eclogites resemble cumulate gabbros from mid-ocean ridges (Sassi et al. 2004). Both varieties are depleted in light REE (LREE) with $La_N/Yb_N = 0.35–0.69$ and characterised by present-day $^{143}Nd/^{144}Nd$ values ranging from 0.513050 to 0.513141 and $^{87}Sr/^{86}Sr$ values between 0.702606 and 0.704801 (Table 1). When calculated for a hypothetical magmatic age of 250 Ma (i.e. crystallisation age of MORB-type eclogite protoliths in the Koralpe; Thöni and Jagoutz 1992; Miller and Thöni 1997), the isotopic data points plot on the Mantle array or close to it and within the field of eclogites and their gabbroic protoliths from the Koralpe and Saualpe (Fig. 2).

Eclogite samples CM15/01 and CM20/01

Sample location: N46°24.87′E15°27.473′ near Kebelj

Samples CM15/01 and CM20/01 are quartz-rich eclogites containing the high-pressure assemblage garnet-omphacite-quartz-rutile in addition to accessory phengite, kyanite, apatite, zircon and pyrite. Minor Ca-amphibole and associated clinozoisite form poikiloblastic and texturally late grains. Both samples show only very limited retrograde alteration, appearing as narrow symplectite rims around omphacite and phengite. Subhedral garnet consists essentially of almandine (44–52 mol%), pyrope (22–30 mol%) and grossular (22–27 mol%) components with only minor spessartine and andradite (< 1 mol%). Compositional maps and profiles reveal a weak zoning with low X_{Mg} in the core surrounded by a high X_{Mg} mantle and an outer rim with decreasing X_{Mg} in sample CM15/01 (Fig. 3a, b), and a high X_{Ca} in the core surrounded by a lower X_{Ca} mantle and increasing X_{Ca} at the rim of sample CM20/01. Garnet may contain inclusions of quartz, rutile, apatite, omphacite and zircon. In order to check to which extent REE-rich micro-inclusions could have affected the bulk Sm-Nd budget of the garnet separates obtained by ID, a few LA-ICP-MS analyses were performed on garnet from eclogite CM15/01. Although the results (Table 2) show rather large variations, the broad concentration ranges are consistent with those obtained by ID, indicating that the isotope analyses presented in Table 1 are largely free of the effect of inclusions. Omphacite is unzoned with 37–40 mol% Jd and 1–2 mol% Acm. Phengite has 3.30–3.34 Si apfu.

Despite the absence of coesite and microdiamond, Janák et al. (2004) claimed an ultrahigh-pressure origin for the Pohorje eclogites based on mineral compositions and quartz inclusions in garnet, omphacite and kyanite that are surrounded by radial fractures. Sassi et al. (2004), however, challenged this conclusion and estimated peak metamorphic conditions within the high-pressure eclogite facies field instead. A new argument in favour of high-pressure eclogite metamorphism is the fact that quartz was identified by Raman spectroscopy as an inclusion within an unfractured zircon in a Pohorje eclogite (Miller and Konzett 2005).

Figure 4 displays the equilibrium phase diagram for a simplified bulk composition of sample CM20/01 calculated with the DOMINO program of De Capitani (1994). The database is an updated version of Berman (1988) and the following solution models were used: garnet (Berman 1990), phengite (Massonne and Szpurka 1997), omphacite and amphibole (Meyre et al. 1997). The stability field of the peak-pressure assemblage Omp + Grt + Qtz + Phe + Ky + H_2O (Fig. 4) ranges from about 600°C to 740°C and 1.9 to 2.6 GPa. This agrees

Table 1 Rb-Sr and Sm-Nd analytical data of eclogites and metapelites from the Pohorje Mountains, Eastern Alps

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$\pm 2\sigma m$	Weight (mg)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\pm 2\sigma m$	Age rel. to wr	ϵ (t)	Age rel. to pure Grt
Qtz-rich eclogites														
CM15/01 wr	0.96	63.6	0.044	0.704801	0.000008	139	2.99	8.45	0.210	0.513055	0.000006			90.7 ± 3.9
Grt dirty						134	0.583	0.111	3.171	0.514968	0.000044	98.7 ± 2.5	8.0	
Omp						112	0.610	0.683	0.540	0.513267	0.000009	98.0 ± 5.1	8.0	89.9 ± 4.3
Grt (pure)						110	0.585	0.100	3.522	0.515020	0.000082	90.7 ± 3.9	8.0	
Ap						12	8.98	12.32	0.441	0.513245	0.000006	125.6 ± 6.6	8.0	88.1 ± 4.1
CM20/01 wr	0.69	63.0	0.032	0.703863	0.000006	162	3.43	9.61	0.216	0.513050	0.000018			90.1 ± 2.0
Grt/1						116	0.742	0.294	1.525	0.513900	0.000018	99.3 ± 3.1	7.8	80.4 ± 4.2
Omp/1						113	0.835	0.900	0.561	0.513296	0.000005	109.1 ± 8.3	7.8	87.1 ± 2.0
Grt/2						118	0.765	0.436	1.061	0.513577	0.000023	95.4 ± 5.3	7.8	87.5 ± 3.3
Omp/2						86	0.828	0.853	0.586	0.513284	0.000012	96.7 ± 8.9	7.8	89.0 ± 2.2
Grt/3 (H2SO4 leached)						109	0.543	0.119	2.754	0.514546	0.000024	90.1 ± 2.0	7.9	
Grt dirty						111	0.595	0.139	2.594	0.514411	0.000043	87.5 ± 3.1	7.9	
Ap						30	24.01	35.52	0.409	0.513199	0.000004	118.6 ± 14	7.8	87.8 ± 1.9
Ky-rich eclogites														
CM42/01 wr	1.64	130	0.037	0.703054	0.000005	196	0.516	1.15	0.271	0.513141	0.000006		7.4[a]	
CM48/01 wr	0.07	140	0.002	0.702606	0.000006	173	1.22	3.04	0.242	0.513120	0.000010		7.9[a]	
Metapelite														
9616PMT wr						114	6.82	39.8	0.104	0.512070	0.000003			
Grt/1 (1 MF)						113	3.24	4.36	0.450	0.512260	0.000005	83.8 ± 2.7	−10.0	
Grt/2-1 (2MF)						41	3.14	2.71	0.702	0.512452	0.000006	97.7 ± 2.1	−9.9	
Grt/2-2 (2MF, HCl leached)						67	3.13	3.43	0.552	0.512335	0.000007	90.1 ± 2.6	−10.0	
" HCl leachate							9.36	45.4	0.125	0.512061	0.000005	97.9 ± 3.1(R-L)		
Grt/2-3 (2MF, R H2SO4)						73	3.31	4.54	0.442	0.512244	0.000008	78.7 ± 4.7	−10.1	

R residual (leached) fraction; *L* leachate; *MF* magnetic fraction

[a] ϵ-values calculated for an assumed protolith age of 250 Ma

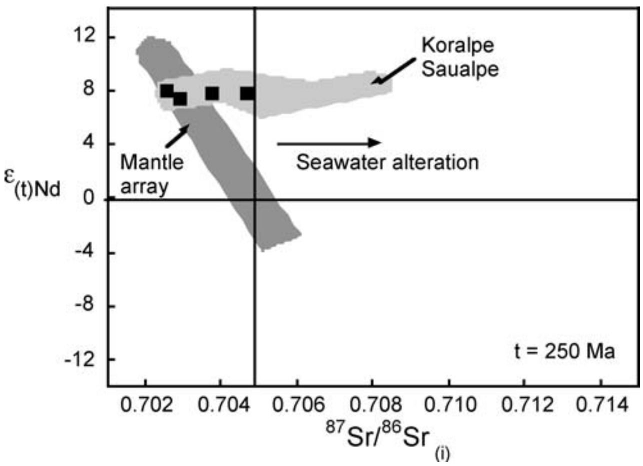

Fig. 2 Nd versus Sr isotope correlation diagram for Pohorje Ky- and Qtz-rich eclogites, showing that they plot in the field defined by Ky- and Qtz-rich eclogites and their gabbroic protoliths from the Koralpe and Saualpe (data from Thöni and Jagoutz 1992; Miller and Thöni 1997). Whereas the Ky-rich Pohorje eclogites plot on the Mantle array, the Sr isotopic composition of the quartz-rich eclogites could have been altered by reactions with seawater (e.g. Muehlenbachs 1986)

well with the results obtained by different thermometers and barometers listed in Table 3. The phase diagram also shows that in the investigated compositions amphibole and zoisite should form during early decompression on the retrograde path, in agreement with microtextural observation.

Metapelites

Major and trace element compositions of two analysed kyanite-garnet-micaschists suggest that these eclogite country rocks derive from a clay-rich sedimentary protolith. Considering Nd-isotopic compositions, the samples (Table 1; Thöni 2002) are within the range reported for metapelites from the Koralpe and Saualpe (Thöni and Jagoutz 1992; Thöni and Miller 1996). Their Nd model age of 1.3 Ga is similar to the model ages from other Austroalpine basement units (Thöni 1999) and indicates a Proterozoic mean crustal residence age for the protolith material.

Garnet–kyanite micaschist 9616PMT

Sample location: N46°25.886′E15°22.174′, on the road from Zrece to Rogla

This eclogite country-rock shows evidence of an intense polyphase ductile to ductile-brittle deformation. Garnet crystals, up to 8 mm in diameter, in addition to kyanite, phengite and quartz, are major phases. Accessory minerals are rutile, apatite, graphite, pyrrhotite, zircon and monazite. Staurolite appears as small anhedral grains along the rims of kyanite and phengite. Minor plagioclase, K-feldspar, biotite, chlorite and ilmenite document incipient replacement of phengite, kyanite, garnet and rutile. Garnet is anhedral and essentially unzoned with a composition of approximately 26 mol% Prp, 11 mol% Grs, 62 mol% Alm and 1 mol% Sps. It is only at the outermost rims, along cracks or in small (<300 μm) grains, that Prp and Grs contents drop significantly with a concomitant increase in Alm and Sps (Fig. 5). Garnets may contain inclusions of quartz, rutile, apatite, graphite, pyrrhotite, zircon and monazite (Fig. 5). Phengite is present in two generations (phengite I and II) that can be distinguished by their composition. Large phengite I is deformed and zoned with respect to the Tschermak exchange component, with values up to Si = 3.3 apfu in the cores decreasing to Si = 3.1 apfu near the rims. Phengite I has often partially reacted to an intergrowth of plagioclase, K-feldspar, quartz, biotite and chlorite. Small phengite II flakes overgrowing the foliation defined by phengite I are unzoned with low Tschermak's component and Si apfu <3.1.

Stable assemblages for metapelite 96T16PMT were calculated with DOMINO (De Capitani 1994) in the sodium-free CKFMASH system and with excess H_2O.

Fig. 3 Compositional map (*light and dark grey* represent high and low concentrations, respectively) for Mg and major element zoning of garnet from Pohorje quartz-rich eclogite CM15/01

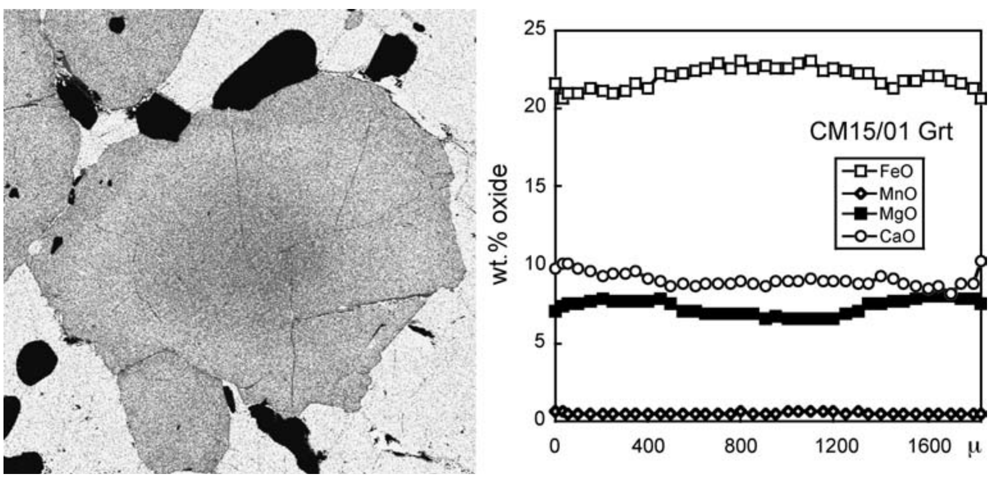

Table 2 Rare earth elements of Pohorje eclogite garnet CM15/01

(ppm)	Grt 1.2	Grt 1.4	Grt 3.1	Grt 3.2	Grt 3.3
La	< 0.002	< 0.002	< 0.003	< 0.002	0.009
Ce	0.023	< 0.002	0.004	0.003	0.003
Pr	0.002	0.001	0.01	< 0.002	< 0.002
Nd	0.10	0.04	0.21	0.01	0.14
Sm	1.17	0.76	1.09	0.05	0.62
Eu	0.78	0.77	1.01	0.06	0.72
Gd	8.31	7.71	7.75	0.42	6.11
Tb	3.50	2.84	2.25	0.32	2.56
Dy	33.31	20.73	16.28	5.03	19.55
Ho	8.31	4.52	3.51	1.93	4.06
Er	19.91	11.30	9.32	6.20	10.63
Tm	2.56	1.66	1.30	0.91	1.46
Yb	14.78	11.46	9.67	5.33	10.44
Lu	1.95	1.65	1.41	0.77	1.61

The solution model of Berman (1990) was used for garnet. Phengite activity was computed with the solution model of Massonne and Szpurka (1997). The equilibrium phase diagram (Fig. 6) displays a large stability field for the assemblage Grt + Phe + Ky + Qtz + H_2O with an upper pressure limit represented by the quartz–coesite transition. Above 1.45 GPa, a lower temperature limit of 580–614°C is given for this bulk composition by the appearance of chloritoid as an additional phase. Below 1.45 GPa, staurolite is stable up to 670°C in addition to the peak pressure assemblage. Biotite appears below ~1.1 GPa at 630°C, and plagioclase is stable at pressures below 0.6–0.7 GPa in the temperature range 560–680°C. Application of the garnet-rutile-kyanite-ilmenite-quartz (GRAIL) barometer (Bohlen et al.

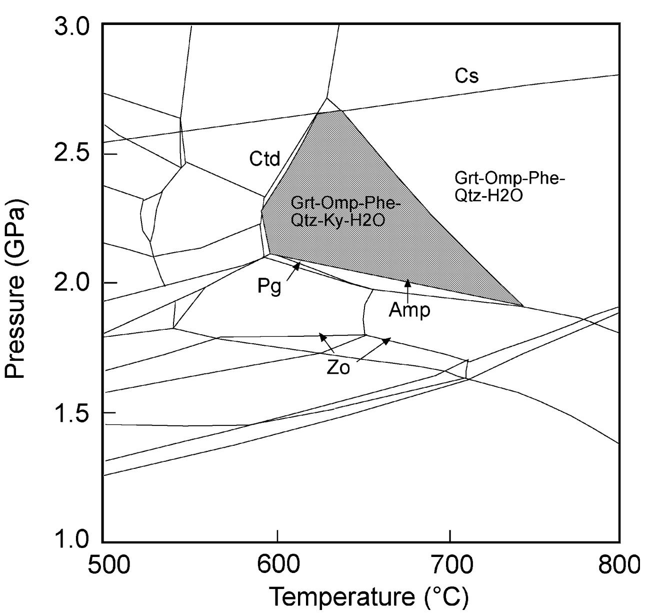

Fig. 4 Simplified pseudosection in the KNCFMASH system for phengite-bearing quartz-rich eclogite CM20/01 calculated with the DOMINO program (De Capitani 1994). The peak-pressure assemblage Grt-Omp-Phe-Ky-Qtz is marked in *grey*, abbreviations according to Kretz 1983. *Arrows* indicate out-reactions

1983) suggests that rutile was stable above pressures between 0.87 and 0.92 GPa for an assumed temperature range of 550–650°C. Thermobarometric constraints during decompression of approximately 580°C/0.8 GPa have also been obtained by using the garnet–biotite Fe–Mg exchange thermometer calibrated by Kleemann and Reinhardt (1994), the garnet-kyanite-quartz-plagioclase (GASP) geobarometer (calibration of Koziol and Newton 1988) and compositions of texturally late garnet, biotite and plagioclase. Calculated P-T conditions are thus in good agreement with those obtained from eclogite samples and clearly document that the Pohorje metapelites were affected by the high-pressure event as well.

Zircon textures and mineral chemistry

The zircon grains from eclogite CM15/01 analysed for U/Pb were separated from crushed bulk rock and thus their precise petrographic environment is unknown. In thin section, zircon is found as an inclusion in garnet (dominant), omphacite, rutile and in the matrix. Grain size is highly variable, with longest dimensions ranging from approximately 10 to 135 μm in eclogites CM15/01 and CM20/01. In cross section, zircon grains have ovoid or rounded shapes, irrespective of size. Very rarely, zircon contains inclusions of rutile, omphacite (Fig. 7), garnet, apatite and quartz, suggesting zircon growth under eclogite-facies conditions. Cathodoluminescence (CL) images reveal the presence of irregularly shaped bright domains in most, otherwise faintly zoned grains, regardless of their petrographic position (Fig. 7).

LA-ICP-MS analyses (Table 4) of bright-CL zircon cores and low-CL grains or rims show that both domains have very low Th (0.01–1.14 ppm) and U (0.80–6.68 ppm) contents with an average Th/U ratio of 0.05, along with very low $\sum$REE abundances, ranging from 11 to 109 ppm. The chondrite-normalised REE plot for zircon and adjacent garnet (Fig. 8) shows that garnet exhibits steeply positive profiles from Nd to Tb, and negatively sloping profiles for the heavy REE (HREE). Chondrite-normalised REE patterns of zircon grains also reveal differences between bright-CL and low-CL domains (Fig. 8). Bright-CL cores exhibit profiles with a pronounced fractionation in HREE (Yb_N/Dy_N = 16.7–33.3), whereas low-CL domains are less enriched in HREE (Yb_N/Dy_N = 1.1–1.7). Another interesting observation is the reduction or obliteration of the positive Ce anomaly present in bright-CL domains (Fig. 8), possibly documenting a change in redox conditions in the course of zircon growth. Low-CL domains are distinctly richer in Hf (1.3–1.5%) but contain less Y (34–48 ppm) when compared with bright-CL domains with 0.93–0.95% Hf and 54–106 ppm Y. Both domains have high contents of Sc in the range 840–1,000 ppm that is far in excess of values < 250 ppm reported from igneous zircons (Hoskin and Schaltegger 2003), small amounts of Nb (1.44–1.64 ppm) and Ta (0.12–0.23 ppm),

Table 3 Summary of estimated P-T conditions of Pohorje eclogites

Sample	T1	T2	P1	P2/T	P3/T	P4/T
CM15/01	644°C	703°C	2.07 GPa	707°C/2.47	651°C/2.29	640°C/2.21
CM20/01	657°C	722°C	2.18 GPa	696°C/2.38	635°C/2.26	666°C/2.19

T1: Grt-Cpx (Krogh Ravna 2000); T2: (Powell 1985); calculated for a pressure of 2 GPa
P1: estimated at the calculated T1 (Waters and Martin 1993)
P2/T: (Krogh Ravna and Terry 2004);
P3/T: (Coggon and Holland 2002) using Thermocalc v.3.1
P4/T: (Brandelik and Massonne 2004)

whereas large ion lithophile elements (LILE) are below detection limits.

The external morphology, metamorphic mineral inclusions, CL patterns and extremely low Th/U ratios of the zircon grains strongly suggest a metamorphic origin (e.g. Hoskin and Schaltegger 2003; Rubatto 2002; Rubatto and Hermann 2003). This is further supported by $\sum$REE, Th, U contents that are much lower than typical magmatic values (Hoskin and Schaltegger 2003 and references therein), and by the normalised REE patterns that do not show the pronounced positive Ce and negative Eu anomalies characteristic for igneous zircon (e.g. Hoskin and Schaltegger 2003). The absence of negative Eu anomalies suggests that zircon formed after the high-pressure breakdown of plagioclase. In addition, zircon/garnet REE distribution coefficients calculated using average compositions of zircon and garnet in sample CM15/01 increase from 0.27 for Sm to 2.0 for Yb. These partition coefficients are remarkably similar to those determined by Rubatto (2002) for metamorphic zircon rims formed in equilibrium with garnet in an eclogitic micaschist from the Sesia-Lanzo Zone. The form of the REE patterns and the distribution coefficients are consistent with contemporaneous growth of zircon and garnet (Rubatto 2002; Rubatto and Hermann 2003; Whitehouse and Platt 2003), suggesting that zircon formation occurred at the high-pressure peak.

Isotope systematics

For Sm-Nd mineral dating of eclogites, kyanite-poor lithologies were preferred since kyanite-rich metagabbroic eclogites often show incomplete Nd isotope equilibration between the high-pressure minerals in addition to very low Nd concentrations in garnet (cf. Thöni 2002, with references). LA-ICP-MS trace element mineral data of the Pohorje eclogites indeed document that garnets from quartz-rich lithologies have distinctly higher Nd contents than those from kyanite-rich eclogites (Miller et al. in preparation). The Sm-Nd isotope analytical results for minerals and whole-rock splits of two quartz-rich eclogites (CM15/01, CM20/01) and of metapelite (9616PMT) are presented in Table 1, the data are plotted on isochron diagrams, Fig. 9a-c. In addition, whole-rock Sm-Nd and Rb-Sr analyses for two Ky-bearing eclogites are also given in Table 1. U/Pb single zircon data are presented in Table 5 as well as in a concordia diagram (Fig. 10).

Eclogite sample CM15/01

From this sample, garnet (Grt, pure), omphacite (Omp), apatite (Ap), a second garnet fraction containing (mostly dark) inclusions (Grt dirty), and the whole rock (wr) were analysed. Garnet shows a high $^{147}Sm/^{144}Nd$ ratio of 3.52 and a concomitant low Nd concentration of 0.1 ppm (Table 1), indicating high sample purity. Two-point regression of Grt-wr and of Grt-Omp yields within error the identical ages of 90.7 ± 3.9 Ma (ϵNd = + 8.0) and 89.9 ± 4.3 Ma (ϵNd = + 8.4), respectively. If lumped together, the three data points yield a result of 91 ± 26 Ma (ϵNd = + 8.2; MSWD = 9), indicating some excess scatter between these components. If the data point for Ap is added, a scatterchron age of 90 ± 11 Ma (ϵNd = + 8.5; MSWD = 47) is obtained. Thus, imperfect Nd isotopic equilibration and/or variable disturbance of the system during the final stages of metamorphism is

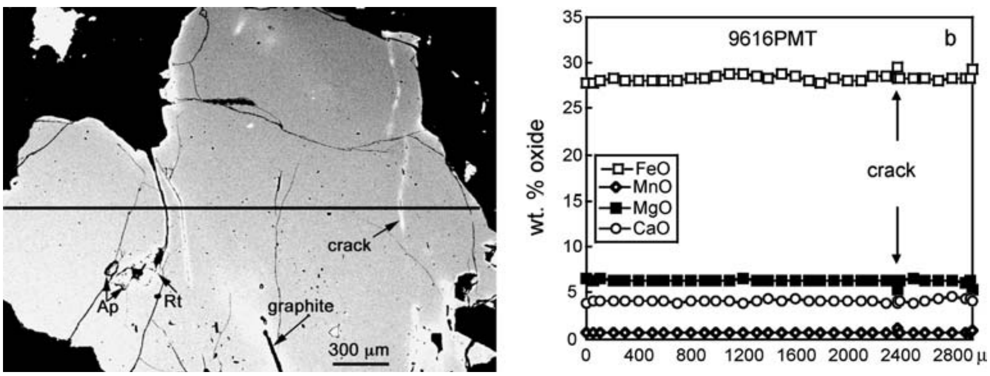

Fig. 5 Backscattered electron image and major element zoning profile of garnet from metapelite sample 9616PMT, Pohorje Mountains. *Lighter shades of grey* at the outermost rims and along cracks indicate strongly decreasing pyrope and grossular coupled with increasing almandine and spessartine contents

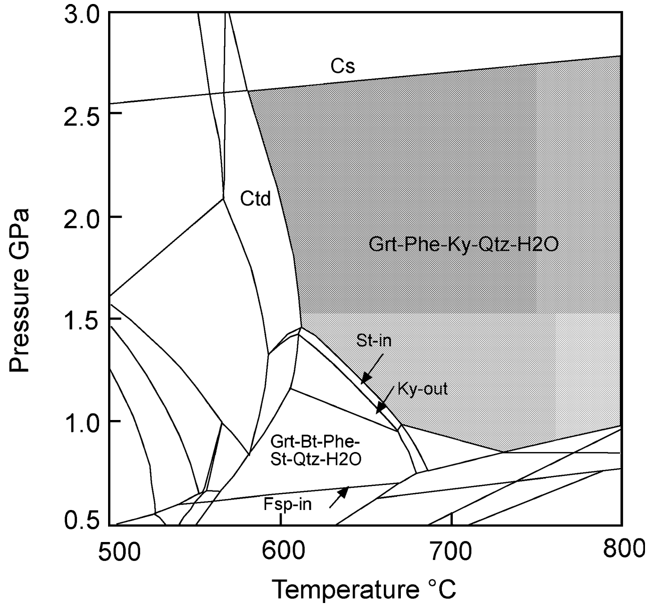

Fig. 6 Equilibrium phase diagram of Pohorje metapelite sample 9616PMT in the KCFMASH system calculated with the DOMINO program (De Capitani 1994). The peak-pressure assemblage Grt-Phe-Ky-Qtz (*grey area*) is overprinted by staurolite, biotite and feldspar (abbreviations according to Kretz 1983) with decreasing pressure

confirmed by the data points for Ap and the impure garnet fraction (Grt dirty) that deviate significantly from the Grt-wr reference line (Fig. 9a).

U/Pb isotopic analyses were applied to nine individual zircon grains from sample CM15/01. All crystals are characterised by low U (16–32 ppm) and extremely low Th concentrations, with $^{208}Pb/^{204}Pb$ ratios of all analyses being smaller than 39 indicating an extremely low abundance (or even absence) of Th in the crystallisation environment and by low Th/U ratios. Zircons with similar features have been described as metamorphically formed in eclogite-facies rocks by Rubatto and Gebauer (2000), suggesting that the obtained age can be associated with the metamorphic event (Rubatto et al. 1999; Thöni et al. 2001). Small sample size in combination with low U concentrations results in very small amounts of both U and Pb and therefore elevated uncertainties on individual analyses (with most of the age information coming from $^{206}Pb/^{238}U$ since $^{207}Pb_{sample} < ^{207}Pb_{blank}$). All analyses show $^{206}Pb_{sample}/^{206}Pb_{common} > 1.4$ (see Table 5). Despite low U and Pb concentrations, the use of larger samples (multi-crystal analyses) aimed at achieving lower uncertainties was deemed unsuitable as unrecognised age bias due to averaging effects imposed by unrecognised inheritance and/or Pb loss may result (Mundil et al. 2001). All nine analyses form a coherent, concordant cluster with a weighted $^{206}Pb/^{238}U$ age of 90.7 ± 1.0 Ma (MSWD = 0.7) whereas the $^{207}Pb/^{235}U$ as well as the $^{207}Pb/^{206}Pb$ age are associated with large uncertainties due to low U and Pb concentrations and the effect of blank corrections. For example, the $^{207}Pb/^{235}U$ age calculates to an age of 93 ± 18 Ma but an extremely low MSWD indicates that the uncertainty on the $^{207}Pb/^{204}Pb$ in the analytical blank might be overestimated. Alternatively, a "Total Pb/U isochron" (Ludwig 2003) yields an age of 91.3 ± 1.4 Ma. An elevated MSWD in this case indicates either unrecognised open system behaviour or variable common Pb composition (or a combination of both). Individual isotopic ages and ratios are listed in Table 5.

Eclogite sample CM20/01

Three handpicked garnet fractions (Grt/1; Grt/2; Grt/3), one garnet fraction containing visible inclusions (Grt dirty), two omphacite fractions (Omp/1; Omp/2), one apatite fraction (Ap), and the whole-rock (wr) have been analysed from this sample (Table 1). The eight data points do not show a perfect fit to a single isochron (MSWD = 11.1), resulting in a poorly defined "mean age" date of 88 ± 5 Ma (ϵNd = $+8.5 \pm 1.2$) (Fig. 9b). Minimum and maximum age estimates can be deduced from individual two-point regression calculations, using pure garnet and/or the wr as reference points (Table 1). In order to eliminate un-equilibrated LREE-rich micro-inclusions (see Petrology section), which might be one reason for the scatter of the data points, one handpicked garnet fraction (Grt/3, Table 1) was thoroughly ground in an agate mortar and subsequently subjected to acid leaching using conc. H_2SO_4 (Anczkiewicz and Thirlwall 2003). Acid treatment of garnet indeed led to a marked increase of the Sm/Nd ratio of the leached garnet residue with a concomitant drop of the Nd concentration compared to the two unleached fractions Grt/1 and Grt/2. The resulting age from the Grt/3–wr regression is 90.1 ± 2.0 Ma which is significantly younger than most of the other two-point regressions (Table 1), but in perfect agreement with the Grt–wr age of sample CM15/01 (see above).

Metapelite sample 9616PMT

From this sample, the whole-rock and four garnet fractions handpicked from two slightly different magnetic splits (1MF, 2MF, where 1MF is slightly more Fe-rich) were analysed. The data include results from two leaching experiments, one performed with 5.8 N HCl (Thöni 2002), the second with concentrated H_2SO_4 (Anczkiewicz and Thirlwall 2003). Figure 9c shows considerable scatter among the data points, and the Sm/Nd ratios for some of the garnet fractions are rather low. Regression over all six data points, including four garnet fractions, wr and HCl leachate from Grt/2-2, yields a poorly defined (MSWD = 41) age of 97 ± 15 Ma, and an initial ϵNd value of -10.3. It is evident from the high Nd concentration of the HCl leachate (Grt/2-2) that the handpicked separates still contain variable amounts of LREE-rich inclusions. Obviously, essential parts of

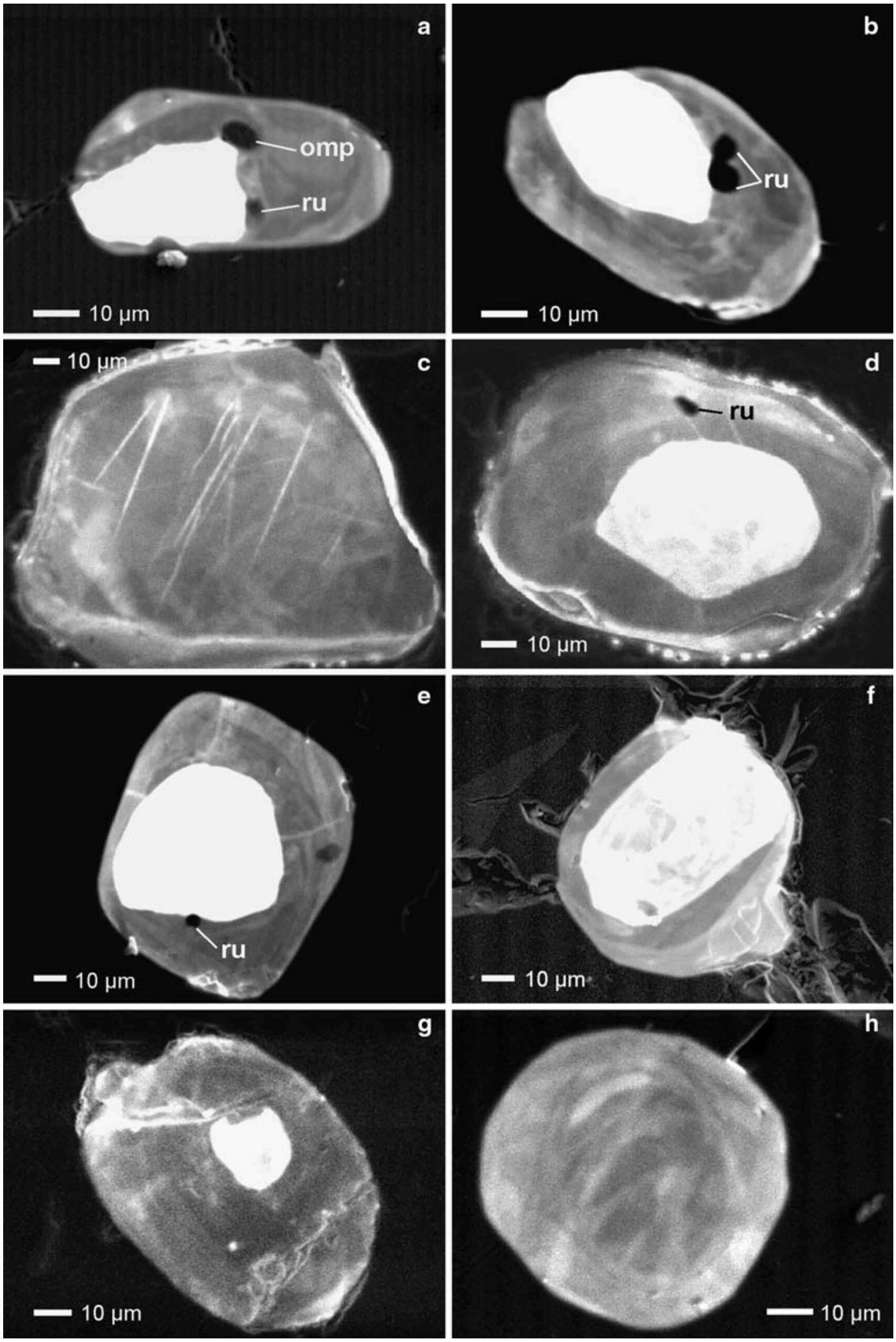

Fig. 7 Cathodoluminescence (CL) images of zircon in Pohorje eclogites CM15/01 and CM20/01, showing featureless low- and bright-CL domains. **a** Zircon included in garnet, containing inclusions of omphacite and rutile; **b** zircon included in garnet, containing rutile inclusions; **c** handpicked low-CL zircon grain#1 analysed by LA-ICP-MS; **d** handpicked zircon grain#3c with bright-CL core analysed by LA-ICP-MS; **e** zircon included in omphacite, containing rutile inclusions; **f** zircon included in garnet and analysed by LA-ICP-MS; **g** matrix zircon; **h** zircon included in rutile and analysed by LA-ICP-MS (#5)

these inclusions (probably including refractory material like zircon) could not be removed even after thorough grinding and H_2SO_4 leaching, since also this latter experiment did not improve the Sm/Nd ratio (Grt/2-3, Table 1). In addition, the data in Table 1 suggest a rather inhomogeneous distribution of contaminating LREE-rich micro-inclusions in the garnet. The garnet fraction Grt/2-1 shows the highest Sm/Nd ratio (^{147}Sm/^{144}Nd = 0.7; Table 1). Regressed with the wr data point, it yields an age of 97.7 ± 2.1 Ma.

Discussion and conclusions

The major, trace element and Sr and Nd isotopic compositions of the Pohorje eclogites are similar to those of

Table 4 Trace element analyses of zircon from Pohorje eclogite CM15/01

(ppm)	Zrn 1 (grain)	Zrn 5 (Rt-incl)	Zrn 3.1[a] (grain)	Zrn 3.2[a] (grain)	Zrn1.1[a] (Grt-incl)	Zrn 1.3 (Grt-incl)
Li	< 1.38	< 1.41	2.93	< 1.69	< 1.56	< 2.47
Sc	1000	971	840	918	894	958
Ti	1.01	2.59	6.15	7.14	1.81	2.08
V	0.10	< 0.07	< 0.07	0.53	0.08	< 0.11
Cr	2.69	< 2.13	< 2.01	< 2.42	< 1.99	3.10
Co	< 0.09	< 0.090	< 0.09	0.15	< 0.10	< 0.154
Rb	< 0.19	0.34	< 0.18	< 0.22	< 0.20	< 0.33
Sr	0.38	0.58	0.27	1.16	0.70	0.44
Y	33.87	34.00	54.37	56.23	105.66	47.86
Nb	1.50	1.64	1.44	1.62	1.63	1.59
Cs	0.30	< 0.10	< 0.09	< 0.11	< 0.10	< 0.16
Ba	< 0.10	< 0.09	< 0.11	0.67	0.29	0.32
La	< 0.01	0.03	0.02	0.21	0.03	< 0.01
Ce	0.09	0.03	0.41	0.38	0.26	0.03
Pr	0.01	0.02	< 0.01	0.08	< 0.01	0.01
Nd	0.07	0.03	0.12	0.58	0.10	0.04
Sm	0.04	0.03	0.37	0.23	0.17	0.04
Eu	0.09	0.07	0.22	0.19	0.15	0.05
Gd	1.05	0.31	1.20	1.48	0.92	0.60
Tb	0.43	0.31	0.34	0.37	0.42	0.45
Dy	3.79	2.71	3.39	3.77	5.98	5.37
Ho	1.12	0.93	1.49	1.58	2.95	1.48
Er	3.21	2.73	7.18	8.42	17.88	4.57
Tm	0.52	0.45	2.08	2.21	4.94	0.74
Yb	3.51	3.03	23.19	26.76	57.05	5.06
Lu	0.69	0.59	6.43	7.69	17.65	1.03
Hf	14024	14975	9540	9323	9505	13342
Ta	0.23	0.16	0.13	0.17	0.12	0.18
Pb	0.08	< 0.03	0.03	< 0.04	0.09	< 0.05
Th	0.01	0.04	0.37	0.28	1.14	0.05
U	6.01	3.02	6.68	6.35	6.09	3.79

[a] Denotes bright-CL domains (see Fig. 8)

the type-locality eclogites and their gabbroic protoliths in the adjacent Koralpe and Saualpe Austroalpine basement nappes (Thöni and Jagoutz 1992; Miller and Thöni 1997) and clearly indicate that the tholeiitic gabbroic precursor rocks originated from an N-MORB type reservoir. The age-corrected Sr and Nd isotopic data form a trend with increasing $^{87}Sr/^{86}Sr$ ratios at near constant Nd isotopic composition (Fig. 2) that may be interpreted by seawater alteration (e.g. Staudigel et al. 1981) as was also inferred for some of the Koralpe and Saualpe eclogites (Miller et al. 1988; Miller and Thöni 1997). It should be mentioned that the N-MORB chemistry need not necessarily imply an origin at a mid-ocean spreading ridge, but could document magmatism in an ocean–continent transition zone as well. Since the metapelitic country rocks also record high-pressure conditions, the latter setting could account for the juxtaposition of mafic and metapelitic rocks prior to collision and for the rarity of ultramafic rocks in these basement nappes.

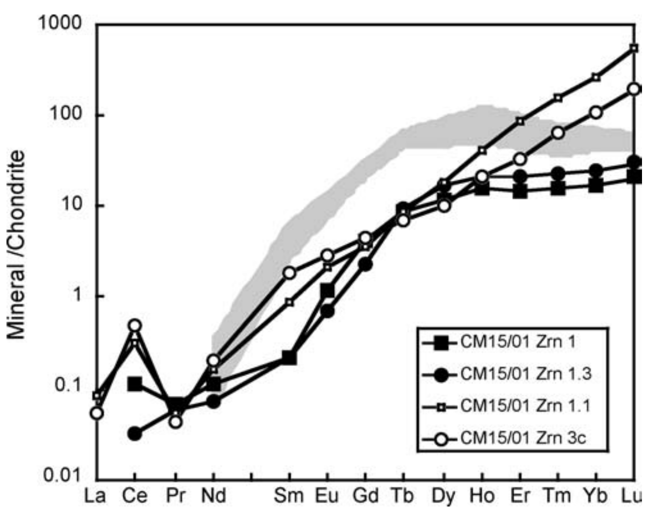

Fig. 8 Chondrite-normalized (using values of Boynton 1984) REE patterns for zircon from Pohorje eclogite CM15/01 showing compositional differences for bright-CL (*open symbols*) and dark-CL (*closed symbols*) domains. *Shaded field* shows the range of garnet analysed close to zircon for comparison

Concerning the question of ultrahigh (Janák et al. 2004) versus high-pressure conditions (Sassi et al. 2004, this work) for the Pohorje eclogites, a word of caution is required. Because of the consequences for geodynamic reconstructions, the presence of an ultrahigh pressure mineral such as coesite and/or diamond should be established beyond doubt as microtextures might be ambiguous (Miller and Konzett 2005), and thermodynamic data sets and solution models are not yet precise enough to allow the calculation of unique pressure and temperature constraints. Zircon is considered to be a

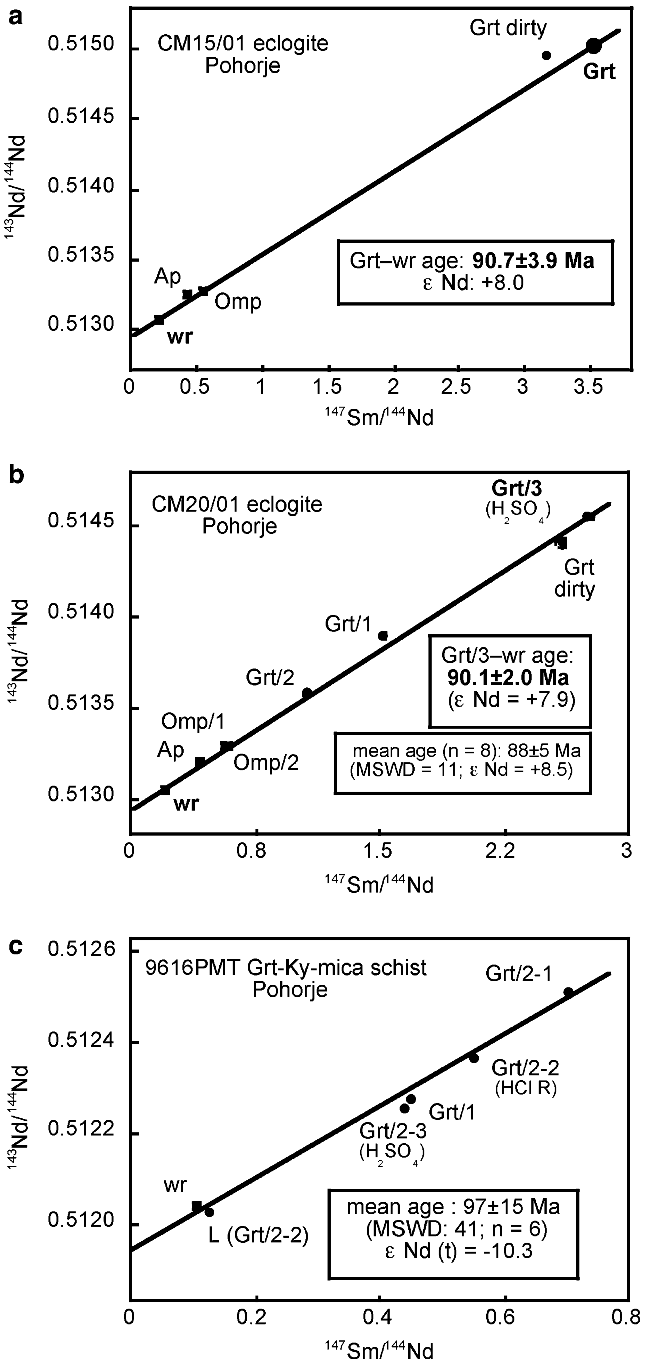

Fig. 9 Sm-Nd mineral–wr isochron plots of eclogites CM15/01 (**a**) and CM20/01 (**b**), and of metapelite 9616PMT (**c**), Pohorje Mountains. See text for discussion

close analogue to diamond in hardness and resistivity (Chopin and Sobolev 1995) and therefore a suitable container of primary minerals in ultrahigh pressure rocks. Our investigation of a large number of zircon grains from different Pohorje eclogite localities yielded the following mineral inclusions: rutile, omphacite, garnet, apatite and quartz (identified by Raman spectroscopy; Miller and Konzett 2005). The composition of these inclusions agrees with the composition of the matrix minerals, excluding the possibility that these zircons are detrital. The presence of a monomineralic quartz inclusion in an unfractured zircon is a strong argument in favour of high-pressure conditions for the Pohorje eclogites.

A combined approach using multiple isotopic systems and different minerals was applied in order to reveal the age of the high-pressure metamorphism. A coherent cluster of single zircon analyses yields a $^{206}Pb/^{238}U$ age of 90.7 ± 1.0 Ma. Its agreement with age estimates from garnet–whole rock and garnet–omphacite Sm-Nd regressions (see below) strongly suggests an age of approximately 90 Ma for the pressure peak of the eclogites in the Pohorje Mountains. We also note that the Sm-Nd and U-Pb ages are associated with an additional ca. 2% uncertainty on the ^{147}Sm decay constant and a ca. 0.1% uncertainty on the ^{238}U decay constant, respectively (Renne et al. 1998; Begemann 2001). In the context of the quoted uncertainty for the U/Pb age (ca. 1%) and the excess scatter of the Sm-Nd data of this study, the decay constant uncertainties are negligible but should, in general, be taken into account or at least should be noted when comparing ages from these istopic systems.

On the basis of an excellent preservation state of the high-pressure assemblages, the homogeneous major element distribution (Fig. 3a, b) and the high Sm/Nd ratios in garnet, combined with consistent initial ϵNd values (Table 1; Fig. 9a, b), the two Grt–wr Sm-Nd ages of 90.7 ± 3.9 Ma and 90.1 ± 2.0 Ma for samples CM15/01 and CM20/01, respectively, are thought to represent a good approximation to the timing of the pressure peak in the Pohorje eclogites. However, if evaluated in more detail, the Sm-Nd data arrays for both these samples (Fig. 9a, b) do not show a perfect isochronous relationship, but are thought to reflect variable isotopic disequilibrium among the different components (Table 1). Garnet from sample CM15/01 and the H_2SO_4-leached Grt/3 fraction from CM20/01 show the highest $^{147}Sm/^{144}Nd$ ratios at concomitantly low Nd contents of 100 and 119 ppb, respectively. Their ages close to 90 Ma (Grt–Omp, Grt–wr: 87–91 Ma, Table 1) are regarded as the geochronologically most reliable dates. In contrast, the isotope characteristics of the garnet fractions Grt/1 and Grt/2 from sample CM20/01 may have been influenced by REE-rich micro-inclusions that remained undetected during handpicking. This is suggested by the lower $^{147}Sm/^{144}Nd$ ratios and the negative correlation of Sm/Nd and the Nd concentrations of these garnet fractions (Table 1), as well as by the leaching experiment performed for Grt/3 itself, where an essential amount of LREE-rich micro-inclusions—in this case most probably apatite—was obviously eliminated during the acid treatment. The analyses of the impure garnet fractions (Grt dirty) of both samples CM15/01 and CM20/01 also suggest a minor amount of components with moderately radiogenic Nd isotope compositions and high Sm/Nd ratios (Fig. 9a), but low Nd contents (most probably rutile and zircon). Thus, it is concluded that the

Table 5 U/Pb isotopic data for eclogite CM15/01, Pohorje Mountains

Sample	(µg)[a] zirc	ppm U	cm Pb[b] (pg)	$^{206}Pb_{sample}/^{206}Pb_{cm}$	Isotopic ratios $^{206}Pb/^{204}Pb$[c]	$^{208}Pb/^{204}Pb$[c]	$^{207}Pb/^{206}Pb$[d]	2σ % er	$^{207}Pb/^{235}U$[d]	2σ % er	$^{206}Pb/^{238}U$[d]	2σ % er	ρ[e]	Isotopic age $^{206}Pb/^{238}U$
CM1501.Z01	0.8	18	1.7	1.42	26	38.4	0.05812	64	0.1135	72	0.01416	8.2	0.9	90.7 ± 7.5
CM1501.Z03	1.1	36	2.7	1.67	31	38.2	0.04616	51	0.0906	55	0.01423	5.2	0.9	91.1 ± 4.7
CM1501.Z04	1.4	33	2.3	1.92	36	38.0	0.04917	38	0.0962	41	0.01419	3.8	0.9	90.9 ± 3.5
CM1501.Z11	2.0	19	1.6	2.12	40	38.0	0.04657	33	0.0906	35	0.01412	3.2	0.9	90.4 ± 2.9
CM1501.Z12	3.8	18	2.5	2.34	44	38.6	0.05309	24	0.1041	26	0.01423	2.7	0.9	91.1 ± 2.5
CM1501.Z13	2.0	24	1.8	2.27	42	38.0	0.04372	29	0.0852	31	0.01414	2.8	0.9	90.5 ± 2.5
CM1501.Z14	2.5	16	2.2	1.86	35	38.1	0.04682	38	0.0909	41	0.01407	4.0	0.9	90.1 ± 3.6
CM1501.Z15	1.7	34	2.0	2.40	45	38.2	0.04736	24	0.0908	27	0.01390	2.5	0.9	89.0 ± 2.3
CM1501.Z16	2.8	22	2.4	2.24	42	38.9	0.05516	27	0.1107	30	0.01456	3.0	0.9	93.2 ± 2.8

Uncertainties of individual ratios and ages are given at the 2σ level and do not include decay constant errors
[a] Sample weight is calculated from crystal dimensions and is associated with as much as 50% uncertainty (estimated)
[b] Total common Pb including analytical blank (analytical Pb blank is 0.8 ± 0.3 pg per analysis)
[c] Measured value corrected for tracer contribution and mass discrimination (0.15 ± 0.09%/amu)
[d] Ratios of radiogenic Pb versus U; data corrected for SEM mass discrimination and fractionation, tracer contribution and common Pb contribution
[e] Correlation coefficient of radiogenic $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$

observed data scatter in the Sm-Nd array of the analysed eclogites is due to disequilibrium between different mineral species (i.e. mainly between micro-inclusions in garnet and garnet itself) rather than to age zoning within the high-pressure minerals.

Despite these complexities, the analysis of the Sm-Nd results from the two eclogite samples definitely support the conclusion that peak-pressure conditions were still effective at c. 90 ± 3 Ma. Considering the weak major element zoning in garnet, this 90 Ma date should probably be interpreted as the final stage of subduction-related high-pressure metamorphism in the Pohorje Mountains, and as an uppermost age limit for decompression and exhumation. The new data are compatible with Sm-Nd ages obtained for eclogites of similar provenance and composition from the Koralpe (localities Mauthnereck, Hohl, Krumbachgraben, Bärofen; Miller and Thöni 1997; Thöni 2002) and the Saualpe (localities Gertrusk, Kupplerbrunn-Prickler Halt; Thöni and Jagoutz 1992). The new data also confirm that lithospheric subduction in the course of the Alpine orogeny affected the eastern parts of the Austroalpine basement much earlier than the Sesia crustal fragment and the Piemont part of the Alpine Tethys where the earliest high-pressure event was detected in the Sesia-Lanzo Zone and was dated at 65 ± 3 Ma (Rubatto et al. 1999).

The Sm-Nd age information obtained from metapelite sample 9616PMT is more complex compared with that recorded by the eclogites and difficult to interpret in detail. Undetected LREE-rich micro-inclusions such as zircon, monazite and apatite (Fig. 5), which were not even eliminated by the leaching techniques (Anczkiewicz and Thirlwall 2003; Thöni 2002), could be responsible for the data scatter and the rather low Sm/Nd ratios in some of the garnet fractions (Table 1; Fig. 9c). In addition, these inclusions do not seem to be in isotopic

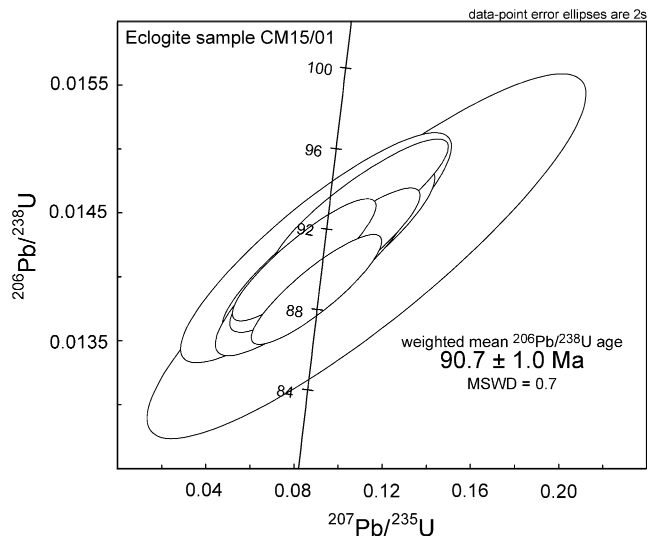

Fig. 10 U-Pb concordia diagram of nine IDTIMS single zircon analyses from Pohorje eclogite CM15/01

equilibrium with garnet. This is not surprising as microstructural observations indicate a more complex crystallization/deformation history for the metapelites than for the eclogites. Garnet fraction Grt/2-1 with the highest Sm/Nd ratio ($^{147}Sm/^{144}Nd = 0.7$; Table 1) is considered to be least influenced by un-equilibrated inclusions. Its age (Grt–wr) of 97.7 ± 2.1 Ma hardly overlaps the age results for the basic eclogites (Table 1).

A Sm-Nd Grt-wr age of 93.0 ± 1.8 Ma has recently been published for another garnet-staurolite-kyanite mica schist (9615PMT) from the locality near Rogla (Thöni 2002). Except for the outermost rims, the almandine-rich garnets of this sample are also essentially unzoned with pyrope contents of up to 27 mol%. Sample 9616PMT from the present study differs from 9615PMT only by its higher kyanite content.

The petrological and isotopic data of the metapelitic samples from the Pohorje mountains are in good agreement with studies on the metapelitic host rocks of the Saualpe-eclogite-type locality, and partly also with those of the Koralpe (Miller and Thöni 1996), indicating a more intense re-equilibration of the felsic compared with the more competent mafic lithologies during late high-pressure metamorphism/early decompression. It should be noted that age relations between metapelitic country rocks and eclogites in the Saualpe and Koralpe area are analogous to those found in the Pohorje area (cf. Thöni 2002). Taken together, data of the available age indicate a near-identical high-pressure metamorphic evolution of the Austroalpine Saualpe, Koralpe and Pohorje domains, and the onset of decompression during early exhumation in the Late Cretaceous.

Acknowledgements We thank M. Jelenc (University of Vienna) for performing the Sr isotope analytical work and A. Zanetti (Pavia) for the LA-ICP-MS analyses. Rb-Sr and Sm-Nd analytical work was supported by the Austrian Science Foundation (FWF), project P13227-GEO, the U/Pb work by the Ann and Gordon Getty Foundation. The University of Innsbruck funded the LA-ICP-MS analyses. Thoughtful reviews by K. Mezger and U. Schaltegger helped improve the manuscript.

References

Altherr R, Lugovic B, Meyer HP, Majer V (1995) Early Miocene post-collisional calc-alkaline magmatism along the easternmost segment of the Periadriatic fault system (Slovenia and Croatia). Mineral Petrol 54:225–247

Anczkiewicz R, Thirlwall F (2003) Improving precision of Sm-Nd garnet dating by H_2SO_4 leaching-a simple solution to the phosphate inclusion problem. In: Vance D, Müller W, Villa IM (eds) Geochronology: linking the isotopic record with petrology and textures. J Geol Soc London Spec Publ 220:83–91

Becker H (1993) Garnet peridotite and eclogite Sm-Nd mineral ages from the Lepontine dome (Swiss Alps): new evidence for Eocene high-pressure metamorphism in the central Alps. Geology 21:599–602

Begemann F (2001) Call for an improved set of decay constants for geochronological use. Geochim Cosmochim Acta 65:111–121

Berman RG (1988) Internally consistent thermodynamic data for minerals in the system Na_2O-K_2O-CaO-MgO-FeO-Fe_2O_3-Al_2O_3-SiO_2-TiO_2-H_2O-CO_2. J Petrol 28:389–414

Berman RG (1990) Mixing properties of Ca-Mg-Fe-Mn garnets. Am Mineral 75:328–344

Berman RG (1991) Thermobarometry using multi-equilibrium calculations: a new technique, with petrological applications. Canad Mineral 29:833–855

Bohlen SR, Wall VJ, Boettcher AL (1983) Experimental investigation and geological applications of equilibria in the system FeO-TiO_2-Al_2O_3-SiO_2-H_2O. Am Mineral 68:1049–1058

Boynton WV (1984) Cosmochemistry of the rare earth elements: meteorite studies. In: Henderson P (ed) Rare earth element geochemistry. Elsevier, Amsterdam, pp 63–114

Brandelik A, Massonne HJ (2004) PTGIBBS-an EXCEL™ Visual Basic program for computing and visualizing thermodynamic functions and equilibria of rock-forming minerals. Comput Geosci 30:909–923

Burton KW, Kohn MJ, Cohen AS, O'Nions RK (1995) The relative diffusion of Pb, Nd, Sr and O in garnet. Earth Planet Sci Lett 107:649–671

Carswell DA, O' Brien PJ, Wilson RN, Zhai M (1997) Thermobarometry of phengite-bearing eclogites in the Dabie Mountains of central China. J Metam Geol 15:239–252

Chopin C, NV Sobolev (1995) Principal mineralogic indicators of UHP in crustal rocks. In: Coleman RG and Wang X (eds) Ultrahigh pressure metamorphism. Cambridge Univ Press, New York, pp 96–131

Coggon R, Holland TJB (2002) Mixing properties of phengitic micas and garnet-phengite thermobarometers. J Metam Geol 20:683–696

De Capitani C (1994) Gleichgewichts-Phasendiagramme: Theorie und Software. Beihefte Eur J Min 6:48–72

Faninger E (1970) Pohorski tonalit in njegovi diferenciati. Geologija 13:35–104

Ganguly J, Tirone M, Hervig RL (1998) Diffusion kinetics of samarium and neodymium in garnet, and a method of determining cooling rates of rocks. Science 281:805–807

Goldstein S, O'Nions RK, Hamilton PJ (1984) A Sm-Nd isotopic study of atmospheric dusts and particulates from major river systems. Earth Planet Sci Lett 70:221–236

Griffin WL, Brueckner HK (1985) REE, Rb-Sr and Sm-Nd studies of Norwegian eclogites. Chem Geol 52:249–271

Hinterlechner-Ravnik A, Moine B (1977) Geochemical characteristics of the metamorphic rocks of the Pohorje Mountains. Geologija 20:107–140

Hoskin PWO, Schaltegger U (2003) The composition of zircon and igneous and metamorphic petrogenesis. Rev Mineral Geochem 53:27–62

Ippen JA (1892) Zur Kenntnis der Eklogite und Amphibolite des Bachergebirges. Mitt naturw Ver Steiermark:328–369

Jagoutz E (1988) Nd and Sr systematics in an eclogite from Tanzania: Evidence for frozen mineral equilibria in the continental lithosphere. Geochim Cosmochim Acta 52:1285–1293

Jagoutz E (1995) Isotopic constraints on garnet equilibration. Terra Abstracts 7:339

Janák M, Froitzheim N, Lupták B, Vrabec M, Krogh Ravna EJ (2004) First evidence for ultrahigh-pressure metamorphism of eclogites in Pohorje, Slovenia: Tracing deep continental subduction in the Eastern Alps. Tectonics 23 TC5014, doi:10.1029/2004TC001641

Kleemann U, Reinhardt J (1994) Garnet-biotite thermometry revisited: The effect of Al^{VI} and Ti in biotite. Eur J Mineral 6:925–941

Koziol MA, Newton RC (1988) Redetermination of the anorthite breakdown reaction and improvement of the plagioclase-garnet-Al_2SiO_5–quartz geobarometer. Amer Mineral 73:216–223

Kretz R (1983) Symbols for rock-forming minerals. Amer Mineral 68:277–279

Krogh Ravna EJ (2000) The garnet-clinopyroxene $Fe2+$ -Mg geothermometer: an updated calibration. J Metam Geol 18:211–219

Krogh Ravna EJ, Terry P (2004) Geothermobarometry of UHP and HP eclogites and schists – an evaluation of equilibria among garnet-clinopyroxene-kyanite-phengite-coesite/quartz. J Metam Geol 22:579–592

Ludwig KR (1980) Calculations of uncertainties of U-Pb isotopic data. Earth Planet Sci Lett 46:212–220
Ludwig KR (2003) User's manual for Isoplot 3.00. Berkeley Geochronoloy Center Special Publication: 74pp
Meyre C, De Capitani C, Partzsch JH (1997) A ternary solid solution model for omphacite and its application to geothermobarometry of eclogites from the Middle Adula nappe (Central Alps, Switzerland). J Metam Geol 15:687–700
Mezger K, Essene EJ, Halliday AN (1992) Closure temperatures of the Sm-Nd system in metamorphic garnets. Earth Planet Sci Lett 113:397–409
Michard P, Gurriet P, Soudant N, Albarède F (1985) Nd isotopes in French Phanerozoic shales: external vs. internal aspects of crustal evolution. Geochim Cosmochim Acta 49:601–610
Miller C (1990) Petrology of the type locality eclogites from the Koralpe and Saualpe (Eastern Alps), Austria. Schweiz Mineral Petrogr Mitt 70:287–300
Miller C, Konzett J. (2005) Comment on " First evidence for ultrahigh-pressure metamorphism of eclogites in Pohorje, Slovenia: Tracing deep continental subduction in the Eastern Alps". Tectonics (in press)
Miller C, Thöni M (1995) Origin of eclogites from the Austroalpine Ötztal basement (Tirol, Austria): geochemistry and Sm-Nd vs. Rb-Sr isotope systematics. Chem Geol 122:199–225
Miller C, Thöni M (1997) Eo-Alpine eclogitisation of Permian MORB-type gabbros in the Koralpe (Austria): new petrological, geochemical and geochronological data. Chem Geol 137:283–310
Miller C, Stosch HG, Hoernes S (1988) Geochemistry and origin of eclogites from the type locality Koralpe and Saualpe, Eastern Alps, Austria. Chem Geol 67:103–118
Mørk MBE, Mearns EW (1986) Sm-Nd isotopic systematics of a gabbro-eclogite transition. Lithos 19:255–267
Muehlenbachs K (1986) Alteration of the oceanic crust and the ^{18}O history of seawater. Rev Mineral 16:425–444
Mundil R, Metcalfe I, Ludwig KR, Renne PR, Oberli F, Nicoll RS (2001) Timing of the Permian-Triassic biotic crisis: implications for new zircon U/Pb age data (and their limitations). Earth Planet Sci Lett 187:131–145
Mundil R, Ludwig KR, Metcalfe I, Renne PR (2004) Age and timing of the Permian mass extinctions: U/Pb dating of closed-system zircons. Science 305:1760–1763
Powell R (1985) Regression diagnostics and robust regression in geothermometer/geobarometer calibration: the garnet-clinopyroxene geothermometer revisited. J Metam Geol 3:231–243
Prince CI, Kosler J, Vance D, Günther D (2000) Comparison of laser ablation ICP-MS and isotope dilution REE analyses–implications for Sm-Nd garnet geochronology. Chem Geol 168:255–274
Renne PR, Karner DB, Ludwig KR (1998) Radioisotope dating–absolute ages aren't exactly. Science 282:1840–1841
Rubatto D (2002) Zircon trace element geochemistry: partitioning with garnet and the link between U-Pb ages and metamorphism. Chem Geol 184:123–138
Rubatto D, Gebauer D (1999) Eo/Oligocene (35 Ma) high-pressure metamorphism in the Gornergrat Zone (Monte Rosa, Western Alps): implications for paleogeography. Schweiz Mineral Petrogr Mitt 79:353–362
Rubatto D, Gebauer D (2000) Use of cathodoluminescence for U-Pb zircon dating by ion microprobe: some examples from the Western Alps. In: Pagel M, Barbin V, Blanc P, Ohnenstetter D (eds) Cathodoluminescence in geosciences. Springer, Berlin Heidelberg New York, pp 373–400
Rubatto D, Hermann J (2003) Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): implications for Zr and Hf budget in subduction zones. Geochim Cosmochim Acta 67:2173–2187
Rubatto D, Gebauer D, Compagnoni R (1999) Dating of eclogite-facies zircons: the age of Alpine metamorphism in the Sesia–Lanzo Zone (Western Alps). Earth Planet Sci Lett 167:141–158
Sassi R, Mazzoli C, Miller C, Konzett J (2004) Geochemistry and metamorphic evolution of the Pohorje Mountain eclogites from the easternmost Austroalpine basement, Eastern Alps, Slovenia. Lithos 78:235–261
Schmädicke E, Mezger K, Cosca MA, Okrusch M (1995) Variscan Sm-Nd and Ar-Ar ages of eclogite facies rocks from the Erzgebirge, Bohemian Massif. J Metam Geol 13:537–552
Stacey JS, Kramers JD (1975) Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet Sci Lett 26:207–221
Staudigel H, Muehlenbachs K, Richardson SH, Hart SR (1981) Agents of low temperature ocean crust alteration. Contrib Mineral Petrol 77:150–157
Stosch HG, Lugmair GW (1990) Geochemistry and evolution of MORB-type eclogites from the Münchberg Massif, southern Germany. Earth Planet Sci Lett 99:230–249
Thöni M (1999) A review of geochronological data from the Eastern Alps. Schweiz Mineral Petrogr Mitt 79:209–230
Thöni M (2002) Sm-Nd isotope systematics in garnet from different lithologies (Eastern Alps): age results, and an evaluation of potential problems for Sm-Nd garnet chronometry. Chem Geol 185:255–281
Thöni M, Jagoutz E (1992) Some new aspects of dating eclogites in orogenic belts: Sm-Nd, Rb-Sr, and Pb-Pb isotopic results from the Austroalpine Saualpe and Koralpe type-locality (Carinthia/Styria, southeastern Austria). Geochim Cosmochim Acta 56:347–368
Thöni M, Miller C (1996) Garnet Sm-Nd data from the Saualpe and the Koralpe (Eastern Alps, Austria): chronological and P-T constraints on the thermal and tectonic history. J Metam Geol 14:453–466
Thöni M, Blichert-Toft J, Armstrong R, Miller C (2001) Garnet Lu-Hf and zircon SHRIMP U-Pb data confirm a Late Cretaceous age and fast exhumation rate for the type-locality eclogites in SE Austria (Saualpe, Eastern Alps). Conference Abstracts (EUG XI) 6/1, 590
Tiepolo M, Bottazzi P, Palenzona M, Vannucci R (2003) A laser probe coupled with ICP-double-focusing sector-field mass spectrometer for in-situ analysis of geological samples and U-Pb dating of zircon. Canadian Mineral 41:259–272
Vance D, O'Nions RK (1990) Isotopic chronometry of zoned garnets: growth kinetics and metamorphic histories. Earth Planet Sci Lett 97:227–240
Vance D, O'Nions RK (1992) Prograde and retrograde thermal histories from the central Swiss Alps. Earth Planet Sci Lett 114:113–129
Visonà D, Hinterlechner-Ravnik A, Sassi FP (1991) Geochemistry and crustal P-T polymetamorphic path of the mantle-derived rocks from the Pohorje area (Austrides, Eastern Alps, Slovenia). Min Slovaca 23:515–525
Waters DJ, Martin HN (1993) Geobarometry in phengite-bearing eclogites. Terra Abst 5:410–411
Whitehouse MJ, Platt JP (2003) Dating high-grade metamorphism-constraints from rare-earth elements in zircon and garnet. Contrib Mineral Petrol 145:61–74