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The evolution of pre-Variscan eclogites of the Tauern Window (Eastern Alps): A Sm/Nd-, conventional and Laser ICP-MS zircon U–Pb study

by *Albrecht von Quadt*[1], *Detlef Günther*[1], *Rolf Frischknecht*[1], *Rolf Zimmermann*[2] and *Gerhard Franz*[2]

Abstract

Geochronological and geochemical analyses were carried out in order to characterize the geological evolution of the pre-Variscan basement of the Tauern Window (Eastern Alps). The Penninic units of the Lower Schist Cover from the central part of the Tauern Window host meta-basalts, ortho- and paragneisses and subordinate quartzites and graphite schists. These units were intruded by several granitoid plutons in Variscan time.

A chronology and isotopic signatures for the Lower Schist Cover (LSC) evolution and magmatism was established dating various eclogitic amphibolites by conventional and laser ablation microprobe (LAM-ICP-MS) U–Pb zircon techniques and Sm–Nd mineral analyses. Zircons of the eclogitic amphibolites yielded an age of 488 ± 12 Ma interpreted as the igneous protolith emplacement age similar to those from the northern part of the Lower Schist Cover. Ages of 418 ± 18 Ma (U-Pb-zircon), 415 ± 18 Ma (LAM ICP-MS, zircon) and 422 ± 16 Ma (Sm–Nd) are the first evidence of a Silurian metamorphic overprint within the Eastern Alps. The new LAM-ICP-MS technique results in concordant U/Pb zircon ages in contrast to the discordant conventional U/Pb zircon age. Analysed zircons did not include an old lead component; an episodic Pb-loss of Variscan and Alpine age causes the discordance of the zircon fractions. The high-pressure metamorphism converted these mafic rocks into eclogites during the Silurian subduction.

Sm–Nd whole rock analyses define a reference line at 845 ± 26 Ma with an initial ε–Nd value of +5.3. Such old protolith ages are known from other parts of the Alps, but in this case no geological significance is attributed to this age. No old intrusion ages are detectable by U–Pb zircon techniques. Thus, the ε–Nd T-500 signatures along with different REE pattern and trace element discrimination diagrams are interpreted to reflect a slightly enriched mantle source. A detailed Sm–Nd whole rock study within one eclogite body demonstrates that the Nd systematics were disturbed after the Cambrian intrusion and partly re-homogenized during the Variscan and/or Alpine metamorphism.

Keywords: U–Pb zircon, Sm–Nd signatures, Cambrian magmatism, Silurian metamorphism, Tauern Window.

Introduction

The geological pattern of the middle part of the Tauern Window of the Eastern Alps was assembled at the end of the Alpine orogeny. The different geological units were formed during the Cadomian, Variscan and Alpine orogenies and the geology framework is the result of different subduction processes, continent-continent collisions and crustal thinning. Post-Variscan sediments cover the crystalline basement. Although largely disrupted and covered by younger sediments it is still obvious that the pre-Alpine basement is part of the overall European basement, formed at Cadomian and Variscan times.

Pre-Variscan/Cambrian magmatic rock suites are rare phenomena within the European Variscides including the Alps. Several pre-Cambrian ages were recovered on felsic and mafic rocks, which are scattered throughout the Alps (MAGETTI and FLISCH, 1993; STILLE and TATSUMOTO, 1985; VON QUADT, 1992). Their interpretation remains unclear.

Various eclogites from different tectonic units

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Tab. 1 Summary of pre-Variscan protolith ages.

author	age	method	region	interpretation
STILLE, 1980	500 ± 80 Ma	Rb/Sr whole rock	Berisal complex	alteration process
STILLE et al., 1985	1018 ± 59 Ma	Sm–Nd whole rock	Berisal complex	protolith age
STILLE et al., 1985	1017 ± 43 Ma	Sm–Nd whole rock	Berisal complex	protolith age
VOSHAGE et al., 1987	607 ± 19 Ma	Sm–Nd whole rock	Ivrea zone	protolith age
PIN and SILLS, 1986	596 ± 35 Ma	Sm–Nd whole rock	Ivrea zone	formation age
VON QUADT, 1992	644 ± 12 Ma	Sm–Nd zircon	HF*	protolith age
VON QUADT, 1992	657 ± 15 Ma	U–Pb zircon	HF*	protolith age
VON QUADT, 1992	539 ± 10 Ma	U–Pb zircon	HF*	magmatic arc system
VON QUADT, 1992	486 ± 496 Ma	U–Pb zircon	HF*	intrusion
EICHHORN et al., 1995	593 ± 22 Ma	U–Pb zircon	HF*	zircon crystallisation
EICHHORN et al., 1995	544 ± 15 Ma	U–Pb zircon	HF*	zircon crystallisation
MÜLLER et al., 1996	532 ± 32 Ma	U–Pb zircon	Silvretta	protolith age
SCHALTEGGER et al., 1997	520 – 525 Ma	U–Pb zircon	Silvretta	protolith age
SCHALTEGGER et al., 1997	609 ± 3 Ma	U–Pb zircon	Silvretta	protolith age

sw* HF = Habach formation, Tauern Window

of the Alps, including the Eastern Alps, (PAQUETTE et al., 1989; NEUBAUER et al., 1987) also contain Archean to Proterozoic zircons. Thus, the detection of pre-Variscan magmatic events in the Alps is of major importance for understanding the evolution of the continental and oceanic domains that were involved in the Variscan orogenic belt. There are however only a few well-studied pre-Variscan basement areas, which contain mafic / ultramafic rock associations (Tab. 1). Most of these protolith ages cluster around the Cambrian event and a few points to the existence of a Precambrian geological event.

The studied mafic-ultramafic rocks occur within the Lower Schist Cover (LSC). The LSC is bordered by the eclogite zone in the south and by the Central Gneisses in the north (Fig. 1). Post-Variscan sediments did not cover the southern part of the central Tauern Window. It is preferable to use zircons from eclogitic amphibolites and Sm/Nd whole rock analyses in order to obtain reliable intrusion ages.

The selected area within the central part of the Tauern window represents one of the famous and rare eclogite formations within the pre-Variscan complex. The combined use of U–Pb and Sm–Nd methods give the possibility to detect the protolith age as well as geochemical information about the source rock.

This study presents U–Pb zircon, Laser ICP-MS zircon, Sm–Nd mineral and Sm–Nd whole rock ages and major-, minor and trace element data aimed at: (1) dating of the primary magmatic age of protoliths of the eclogitic amphibolites, (2) comparing U–Pb zircon and Sm–Nd whole rock analysis and (3) constraining source rocks by Sm–Nd signatures.

Geological, petrographic and geochronological framework

The Tauern Window exposes Eastern Alpine Penninic nappes below the Austroalpine nappe piles. The main geological units are: Altkristallin, Lower Schists Cover (LSC), Upper Schists Cover (USC) and the granites. The structurally lowest unit within the Tauern Window comprises a pre-Variscan basement complex composed of a crystalline unit (Altkristallin Formation), the volcano-metasedimentary Habach formation (LSC), the igneous/granitoid Variscan Central Gneisses as well as the USC with Mesozoic schists, gabbros and metabasalts. The Central Gneisses are composed of granitic to tonalitic gneisses and migmatites, which intruded the crystalline complex and the Habach Formation during Variscan time (JÄGER et al., 1969; CLIFF, 1971; CLIFF, 1977 and 1981). This lowest unit is tectonically overlain by the USC (Fig. 1) which consists of Mesozoic carbonates and the Mesozoic Bündnerschiefer unit composed of metasediments, mafic and ultramafic rocks including eclogites (FRASL, 1958; FRASL and FRANK, 1966; MILLER, 1974). Subduction of oceanic crust realm and subsequent continent-continent collision of the edge of the European continent under the northward moving Adriatic plate caused intense metamorphism and deformation in the Penninic units. The basement complex behaved as a coherent, yet internally deformed body with well preserved intrusive contacts between the gneisses and the Lower schist cover. The cover sequence can be subdivided into individual thrust sheets with different burial and exhumation paths.

Mineral assemblages and oxygen isotopes indicate that the Alpidic metamorphic grade in the Tauern Window changes from amphibolite to greenschist facies from the center towards the border (HOERNES and FRIEDRICHSEN, 1974; MORTEANI, 1974). High-pressure mineral assemblages are observed in eclogites of the Upper Schist Cover (USC; MILLER, 1974; MILLER et al., 1980; FRANK et al., 1987), where the garnet-clinopyroxene pair yields minimum P-T estimates of 20 kbar and 550–600 °C.

The allochthon units of the USC covered the basement rocks and consist of carbonat-rich schists, metabasalts, metagabbros, quarzites and graphite schists. Based on geochemical characteristics the source of the volcanic rock leads to an ocean floor environment.

From the LSC, ZIMMERMANN and FRANZ (1988) described an eclogitic garnet-omphacite assemblage characterized by pressures of 8–12 kbars and temperatures of 450–500 °C. ZIMMERMANN et al. (1994) provided, based on $^{40}Ar/^{39}Ar$ mineral dating, an Eocene-Oligocene (32–36 Ma) minimum age for the high pressure metamorphism in Penninic units.

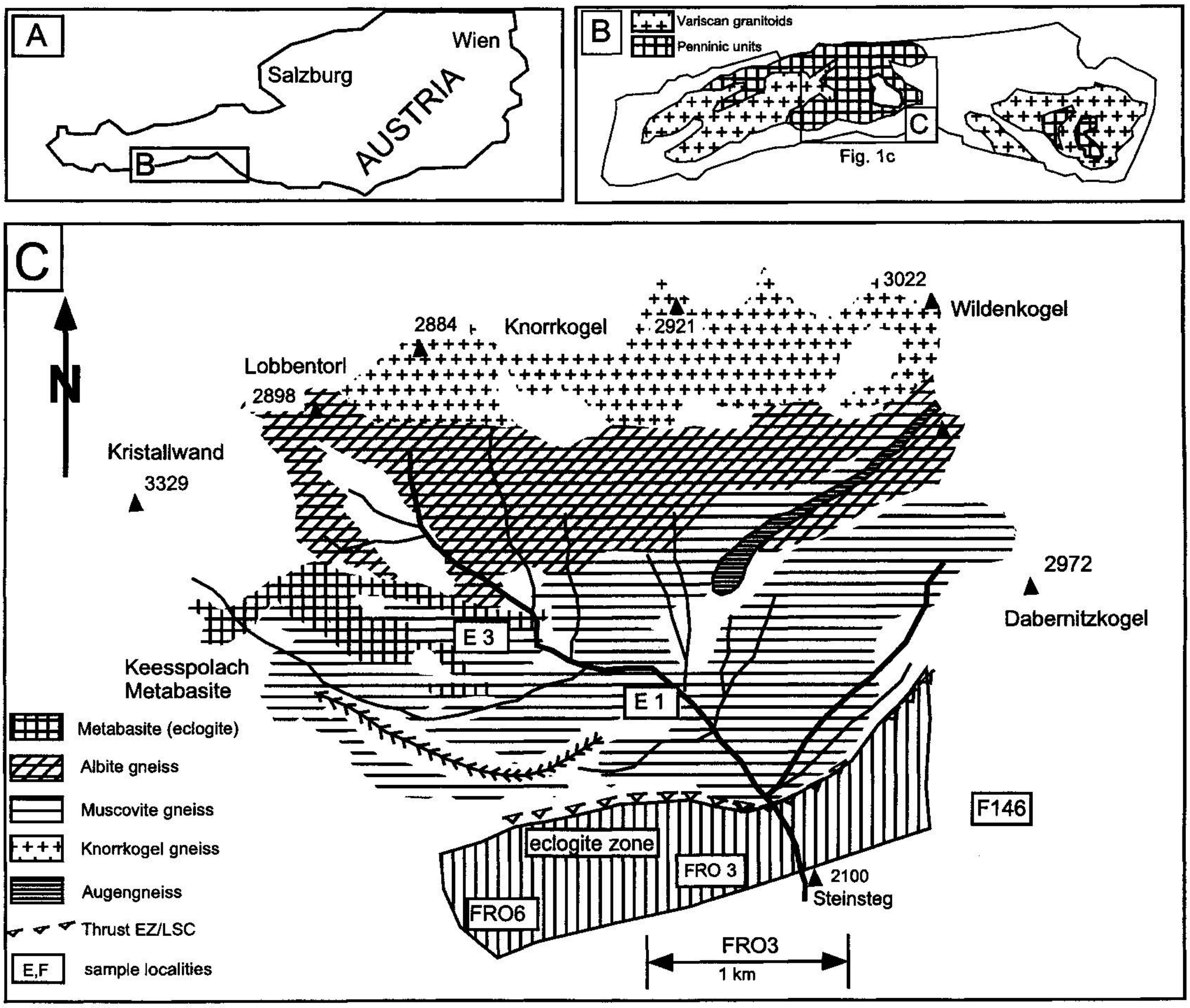


Fig. 1 Geological position of the studied area A: Location of the Tauern Window. B: Variscan granitoids (Central Gneisses, crosses) and the pre-Variscan basement (hetching) of the Venediger nappe. C: Simplified structural and geological map of the Lower schist cover of the southern central Tauern window with sample locations.

Tab. 2 Sample description, sample numbers refer to locations presented on figure 1c.

sample no.	sample	sample description	rock type
1	E 1	grt II, cpx, qtz, czo, ep, rt, op, sph	eclogite
2	E 3	qtz, grt I, amph, op, sph, ap	eclogite
3	F 146	omph, amph, alb, pyr, qtz, ap, sph	eclogite
	LT 25–87	grt I, II, sei, czo, ep, sph	eclogite
5	LT 26–87	grt II, cpx, qtz, czo, rt, op, sph, ep	eclogite
6	LT 28–87	qtz, cpx, grt II, czo, rt, sph	eclogite
7	LT 29–87	amph, rt, gln, omph, grt I, II,	eclogite
8	LT 36–89	amph, plag, grt I, II, omph, rt, phen, czo,	eclogite

Abbreviations: qtz – quartz; grt I, II – garnet first, second generation; amph – amphibole, sph – sphene; ep – epidote; rt – rutile; ap – apatite; czo – clinozoisite; sei – sericite; plag – plagioclase; op – opaque; omph – omphacite; gln – glaucophane; phen – phengite

All samples (Tab. 2) were collected from a small area of the Fronitz valley (Fig. 1c) near the contact between the LSC and the Eclogite Zone (Fig. 1c). All eclogitic amphibolites represent mafic rocks with basaltic composition (Tab. 3).

The eclogitic amphibolites are fine/medium-grained rocks with an intensive foliation. The boudins consist of amphibole and symplectitic garnet-rich layers. Most of the symplectites contain amphibole, plagioclase, omphacite and clinozoisite. Three generations of garnet can be recognized: garnet I has a continous zoning without inclusions in the core; garnet II consists of small euhedral crystals independent of garnet I crystals; garnet III is represented by rims around the garnet II generation. Their rims (grt III) are enriched in almandin in the core and depleted in pyrope as well as the grossular component increased towards the rim. More detailed information mineralogical composition is given in table 2 and for further details we refer to ZIMMERMANN (1992).

The Eclogite Zone within the central part of the Tauern Window is intercalated between the pre-Alpine units of the LSC and the USC. In contrast to the surrounding rock units the metamorphic evolution was independent. According to lithological similarities with the USC a Mesozoic protolith age for the metabasic rocks is probable. At the time of 32–36 Ma the Eclogite Zone was thrust between the LSC and USC at about 600 °C and 20 kbar (eclogites facies) and cooled to blueschist conditions at 450 °C and 10 kbar (ZIMMERMANN et al., 1994).

Analytical methods

Zircon, garnet, clinopyroxene and omphacite were extracted from fresh 5–15 kg rock samples, and final mineral separates were selected grain by grain according to their shape, homogeneity, transparency and color under a binocular. Garnets (II) were selected according to thin section characteristics (inclusions, grt I).

U–Pb zircon dissolution and chemical separation for conventional analysis were performed according to the method decribed by MANHES et al. (1984). Mass discrimination for U and Pb were determined to be 0.1%/amu (± 0.05%/amu). Linear regression and uncertainties were calculated after LUDWIG (1980), and all errors are quoted of the 95% confidence level. Common lead correction was made using the STACEY and KRAMERS (1975) evolution curve.

Laser ablation ICP-MS spot ages were done using an Excimer laser (ArF 193 nm, Compex 110i, Lambda Physik Göttingen) with a gas mixture containing 5% fluorine in Ar with small amounts of He and Ne, connected to a PE SCIEX Elan 6000 ICP-MS. The sample is placed in a closed cell together with the standard material (NIST 612), from which the ablated material is carried out into the ICP-MS by an argon gas stream. An aperture behind the field lens consists of round holes, which varied from 4 μm to 80 μm to obtain an ablation pit of 5 μm diameter to 2.5 mm to obtain a 100 μm pit. In this study we used a spot diameter of 40 μm. The laser pulse repetition rate was 10 Hz. The elements have been detected with 10 ms dwell time and 3 ms quadrupole settling time. The measurement efficiency was around 70%. Backgrounds were measured for 30 s and the transient signals from the sample material to be analysed were acquired for approximately 30 s. Calibration for the zircon analyses were carried out using NIST 612 glass as an external standard. Limits of detection (μg/g) are calculated as 3 times the standard deviation of the background (cps) normalised to the

Tab. 3 Chemical composition of the eclogites.

sample	E 1	E 3	F 146	LT 25–87	LT 26–87	LT 28–87	LT 29–87	LT 36–87
SiO_2	47.37	46.07	43.37	48.12	48.99	48.18	43.48	46.65
TiO_2	2.82	2.28	4.68	3.07	2.98	2.12	4.16	4.54
Al_2O_3	13.86	12.38	10.83	14.72	15.00	14.22	13.82	14.71
Fe_2O_3	13.75	12.16	14.45	12.92	16.19	20.74	20.65	15.84
MnO	0.26	0.16	0.23	0.15	0.19	0.25	0.22	0.19
MgO	6.16	4.45	7.66	6.01	5.43	3.23	6.08	6.65
CaO	9.71	14.50	13.24	9.91	9.35	8.90	10.38	10.51
Na_2O	3.04	2.45	1.52	4.73	4.72	1.39	2.82	2.39
K_2O	0.46	0.12	0.26	0.28	0.12	0.26	0.02	1.00
P_2O_5	0.08	0.63	0.79	0.11	0.10	0.77	1.46	0.04
H_2O	1.02	1.04	0.44	1.02	0.0	0.06	0.46	0.13
Total	**98.55**	**96.26**	**97.53**	**101.04**	**103.07**	**100.12**	**103.55**	**102.65**
F	1581	233	799					
Ba	69	542	70	224	98	63	46	677
Rb	8	8	8	2.5	0.0	0.0	0.0	10.8
Sr	275	110	889	201	92	64	187	115
Y	26	11	13	20	25	72	79	21
Zr	412	191	266	44	47	538	242	63
V	393	438	229	425	402	168	261	505
Cr	326	69	221	53	81	46	72	61
Ni	177	19	160	13	15	9.9	31	12
Co	111	66	70	70	95	55	38	57
Cu	9	3	44	9	31	26	49	42
Zn	154	126	130	121	178	138	156	99
Sc	33	67	15	53	47	62	49	44
S	298	50	1585					
Nb	52	4	40	6.3	6.9	16.8	58.1	6.4

* major and trace element data were analysed by XRF method

	F 146	LT 28–87	LT 36a–87	LT 36b–87
La	89.92	6.24	17.62	10.64
Ce	172.3	11.48	35.4	22.1
Sm	187.3	3.92	8.55	5.08
Eu	5.92	1.84	2.44	1.65
Tb	1.93	0.75	1.93	0.91
Yb	4.46	3.47	10.66	5.08
Lu	0.49	0.42	1.56	0.77

* REE data are produced by ICP-MS technique

sensitivity (cps/µg/g). The reproducibility of the data during this work was estimated measuring the NIST 612 standard. The errors for the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ were 2.9% and 3.5% std. dev., respectively. No common lead correction was made. For further details we refer to GÜNTHER et al. (1997 a, b). All errors are quoted of the 95% confidence level.

VON QUADT (1992) describes the procedure for Sm–Nd analysis. The Nd-isotopic ratios were normalised to $^{146}Nd/^{144}Nd$ = 0.7219. The reproducibility of the data was estimated by measuring the La Jolla Standard. The mean of 25 runs during this work was $^{143}Nd/^{144}Nd$ = 0.511848 ± 0.000006 (1 SD). The model ages, TDM and TCH, were calculated with present-day parameters of $^{147}Sm/^{144}Nd$ = 0.213 and 0.1966 respectively, and with $^{143}Nd/^{144}Nd$ = 0.513150 and 0.512638, assuming a model of a depleted mantle that evolved linearly with time (GOLDSTEIN et al., 1984).

Trace element data

The major and trace element data are reported in table 3. Based on their modal composition most of these rocks probably correspond to basaltic rocks.

The REE patterns (Fig. 2b) display a homogeneous flat REE distribution with a (La/Yb)n ratio between 1.1 and 1.4 except for F146 with a (La/Yb)n value of 13.5.

Eu anomalies are often present in eclogites (PAQUETTE et al., 1995; VON QUADT and GEBAUER, 1993) and pointed to primary magmatic feature. These eclogites show no anomalies and thus, no fluid phase of the Variscan and Alpine metamorphism may have changed the REE pattern. The large ion lithophile element diagram (Fig. 2a) normalised to PEARCE (1982) displays enrichment with increasing incompatibility of the elements, except for Rb, K and Sr. We cannot rule out that this depletion points to a primary situation. No negative Nb anomalies are recognizable. Most mafic samples show between Cr and Nb similar geochemical characteristics. Compared to island arc lavas the eclogites from the Tauern window have higher Ti contents. They represent no cumulates as their Cr content with 46–326 ppm seem to be a normal distribution for basaltic rocks.

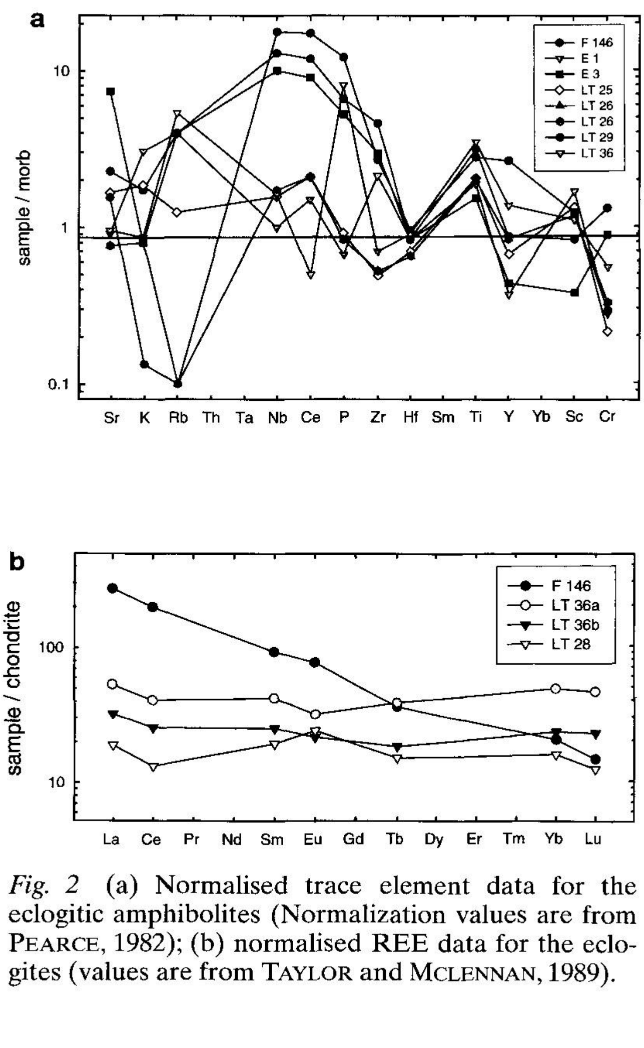


Fig. 2 (a) Normalised trace element data for the eclogitic amphibolites (Normalization values are from PEARCE, 1982); (b) normalised REE data for the eclogites (values are from TAYLOR and MCLENNAN, 1989).

The high Zr/Y, Ti/V, Zr/Nb element ratios and Nb–Y–Zr relationship allow us to rule out an island arc origin for these mafic rocks (VOLPE et al., 1988), but a modern OIB source is preferred. Thus, there are only a few possibilities for a tectonic setting of these rocks: they were intruded in a young ensialic basin, earliest stage of a back-arc spreading during the transition from continental margin to ocean floor magmatism. The alkaline affinity for sample F146 prefers a similar geotectonic evolution. The metabasalts of the Upper schist cover resemble a within-plate origin, too (RAITH et al., 1977).

U–Pb Zircon results

Several representative rock types were taken from the Frosnitz valley to constrain the age of the magmatic protolith formation (Fig. 1) and the zircons were analysed by the U–Pb method. Based on their Zr content up to several hundred ppms (Tab. 4), sample E1, E3 and F146 were selected for the U–Pb study. The F146 sample does not contain zircon, the Zr is thus incorporated in the omphacite (ZIMMERMANN, 1991).

Zircons extracted from eclogite E1 are euhedral, colorless and free of cores. Their U content ranges between 238 and 445 ppm (Tab. 4). Shape and size of these zircons are uniform. The U–Pb ages of four fractions lie between 398 and 445 Ma, and the $^{207}Pb/^{206}Pb$ age range from 482 to 494 Ma (Tab. 4), as displayed in the concordia diagram of Fig. 3a.

The four zircon fractions define a regression line with an upper intercept age of 488 ± 12 Ma. As the four zircon analyses display a small scatter within their $^{207}Pb/^{206}Pb$ ratios, we tried to get more concordant data points using the new LAM-ICP-MS spot dating technique; four spot ages (Tab. 5, points 9–12) plot onto the calculated discordia, too, but near the upper intercept. The mean

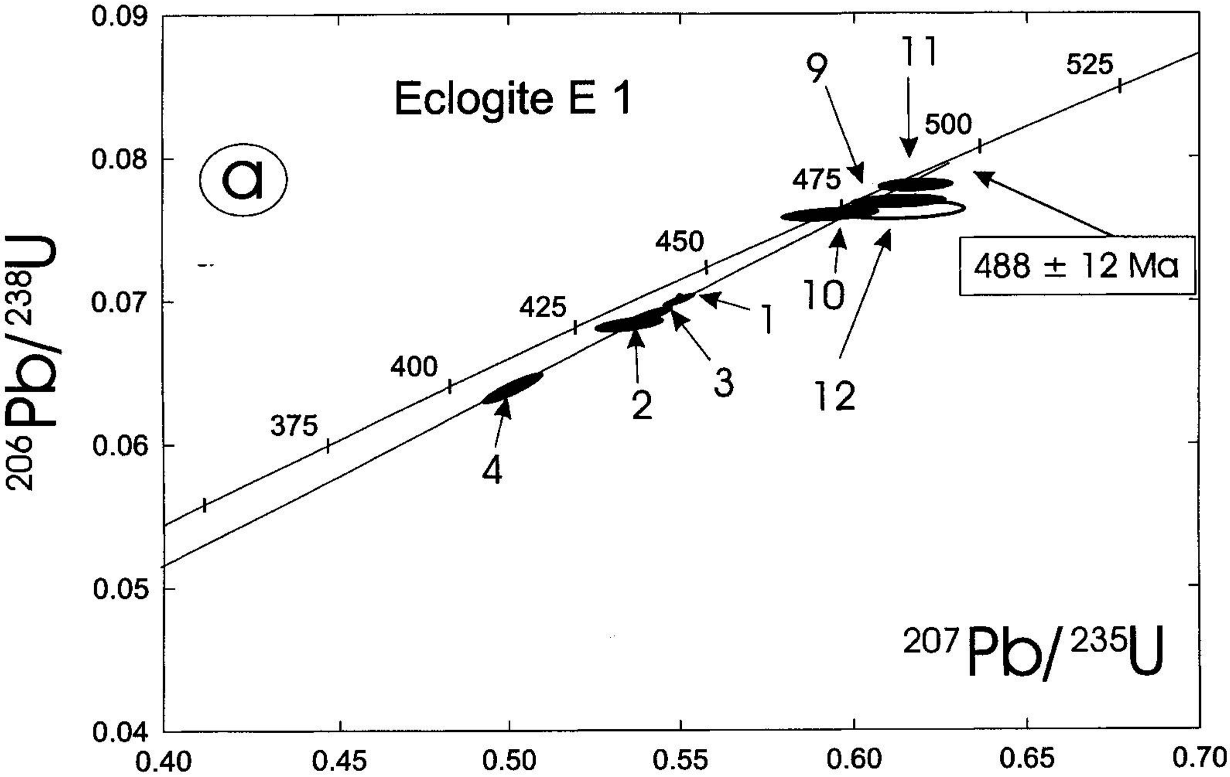
Tab. 4 Conventional U–Pb analytical zircon data.

	sample	fraction in µm	weight in mg	U ppm	Pb_{rad} ppm	Pb_{com} ppm	$^{206}Pb/^{204}Pb$	atomic ratios $^{206}Pb/^{238}U$	error	$^{207}Pb/^{235}U$	error	$^{207}Pb/^{206}Pb$	apparent $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	ages $^{207}Pb/^{206}Pb$	Corr
1	E 1	125–180	1.38	346	23.73	5.8	276	0.07028	0.00022	0.54996	0.0027	0.05676	437	445	482	0.66
2	E 1	100–120	1.14	445	29.93	15.8	145	0.06866	0.00041	0.53852	0.0045	0.05689	428	437	487	0.64
3	E 1	80–120	1.04	418	28.00	9.5	567	0.06867	0.00035	0.54050	0.0054	0.05709	428	438	494	0.70
4	E 1	> 125	0.96	238	17.31	1.4	656	0.06385	0.00099	0.50108	0.0085	0.05692	398	412	488	0.98
5	E 3	100–125	1.19	165	8.12	1.9	164	0.04274	0.00032	0.32735	0.0070	0.05555	269	287	434	0.71
6	E 3	80–100	1.98	131	7.67	1.8	216	0.05129	0.00034	0.38766	0.0076	0.05481	322	332	404	0.70
7	E 3	61–80	0.95	120	6.57	2.65	160	0.05066	0.00032	0.38382	0.0041	0.05495	319	330	410	0.62
8	E 3	41–61	1.05	109	5.14	2.48	246	0.04819	0.00039	0.36461	0.0081	0.05487	303	316	407	0.69
9	E 3	< 41	1.93	101	3.99	1.1	262	0.04180	0.00026	0.32073	0.0081	0.05565	263	282	438	0.61

common lead correction: $^{208}Pb/^{204}Pb = 38.07$, $^{207}Pb/^{204}Pb = 15.602$, $^{206}Pb/^{204}Pb = 18.21$; Corr: correlation coefficient $^{206}Pb/^{238}U \pm {}^{207}Pb/^{235}U$

Tab. 5 Laser ablation (LAM ICP-MS) zircon data.

		atomic ratios $^{206}Pb/^{238}U$	error	$^{207}Pb/^{235}U$	error	apparent $^{206}Pb/^{238}U$	ages $^{207}Pb/^{235}U$
9	E 1	0.0760	0.0008	0.6096	0.0140	472	483
10	E 1	0.0749	0.0008	0.5838	0.0131	466	467
11	E 1	0.0777	0.0005	0.6178	0.0135	482	488
12	E 1	0.0752	0.0005	0.6176	0.0180	467	488
13	E 3	0.0646	0.0005	0.5818	0.0159	404	466
14	E 3	0.0702	0.0007	0.7046	0.0105	437	542
15	E 3	0.0650	0.0023	0.5346	0.0120	406	435
16	E 3	0.0626	0.0019	0.9436	0.0301	391	675
17	E 3	0.0675	0.0007	0.5425	0.0175	421	440
18	E 3	0.0688	0.0005	0.5786	0.0108	429	464
19	E 3	0.0631	0.0025	0.8144	0.0252	394	605
20	E 3	0.0696	0.0005	0.7653	0.0276	434	577



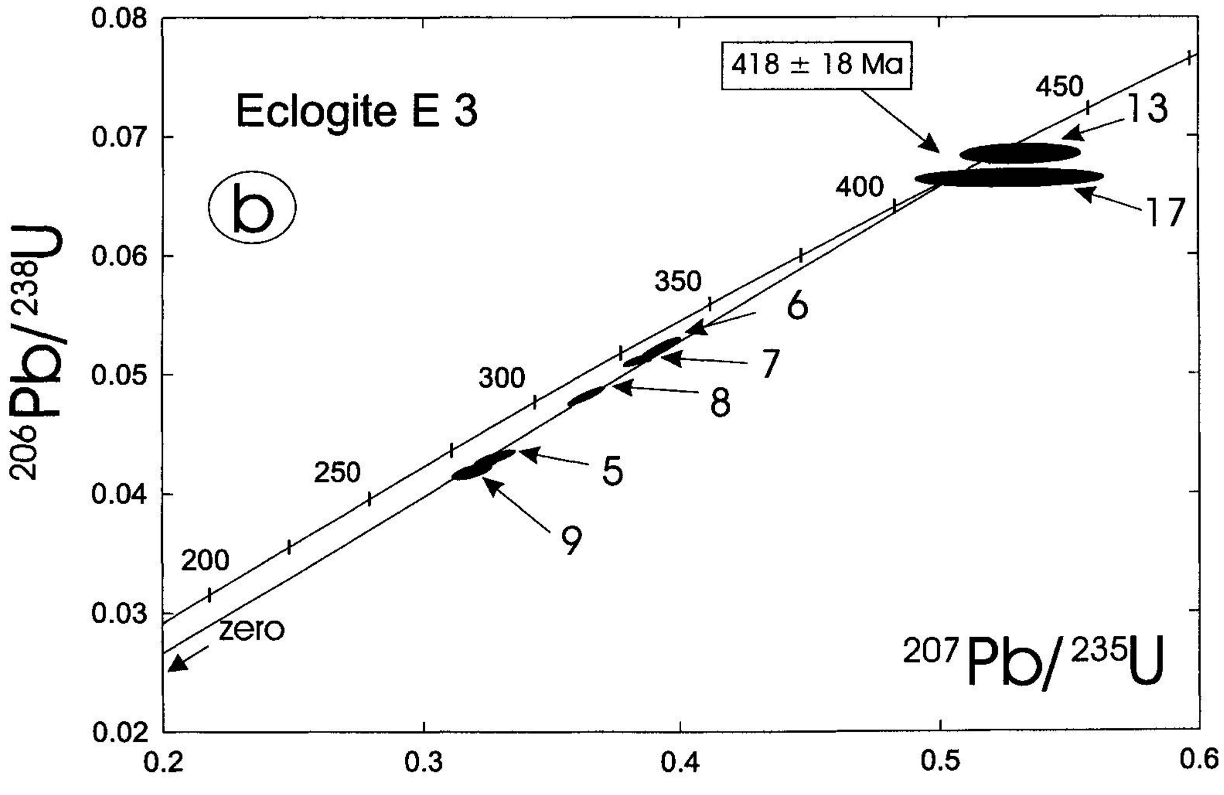


Fig. 3 (a) $^{207}Pb/^{235}U$ vs $^{206}Pb/^{238}U$ plot for zircons from the E1 sample; (b) $^{207}Pb/^{235}U$ vs $^{206}Pb/^{238}U$ plot for zircons from the E3 sample.

Tab. 6 Sm/Nd whole rock/mineral data.

sample	rock type/ mineral concentrate	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	error	T-DM in Ga	T-CHin Ga	ε–Nd T-0	ε–Nd T-420	ε–Nd T-500	ε–Nd T-840
25–87	eclogite	1.04	2.868	0.2189	0.512921	6	0.0	1.95	5.5	4.3	4.1	3.1
26C–87	eclogite	5.94	24.42	0.1467	0.512644	5	1.17	0.0	0.12	2.8	3.3	5.5
26B–87	eclogite	4.12	16.16	0.1539	0.512674	18	1.24	0.0	0.70	3.0	3.4	5.3
29–87	eclogite	14.92	65.53	0.1375	0.512572	20	1.17	0.17	–1.3	1.9	2.5	5.1
LT36B	eclogite	2.68	9.037	0.1790	0.512821	16	1.47	0.0	3.6	4.5	4.7	5.5
LT28 WR	eclogite	3.39	11.72	0.1749	0.512787	12	1.45	0.0	2.9	4.1	4.3	5.3
LT28 CPX	clinopyroxene	3.69	11.45	0.1944	0.512811	4			3.9	3.5		
LT28 GRT	garnet	0.931	4.374	0.1285	0.512631	6			0.14	3.5		
LT36A WR	eclogite	6.84	25.78	0.1601	0.512669	6	1.38	0.0	0.6	2.6	2.9	4.6
LT36A CPX	clinopyroxene	6.75	25.24	0.1614	0.512710	15			1.4	3.3		
LT36A GRT	garnet	5.95	20.85	0.1722	0.512710	8			1.4	2.7		
FRO 6 *	eclogite	3.66	12.88	0.1717	0.513023	6	0.47	0.0	7.5	8.9	9.1	10.2
FRO 3 *	eclogite	1.70	6.193	0.1659	0.513094	8	0.21	0.0	8.9	10.6	10.9	12.2
FRO 3 GRT *	garnet	0.875	2.231	0.2370	0.512936	4			5.8	3.7		
E3	eclogite	9.20	47.31	0.1174	0.512487	6	1.06	0.29	–2.9	1.3	2.1	5.6
E1	eclogite	2.72	9.178	0.1787	0.512687	12	2.04	0.0	0.96	1.9	2.1	2.9
TW22-89	eclogite	4.41	21.59	0.1232	0.512497	11	1.12	0.29	–2.8	1.2	1.9	5.2
TW22-89 OMPH	omphacite	1.33	6.515	0.1231	0.512478	14			–3.1	0.8		
TW21-89 PHEN	phengite	17.62	96.44	0.1103	0.512795	8			3.1	7.7		

* sample FRO 3 and FRO 6 were collected from the Eclogite zone (Fig. 1)

$^{206}Pb/^{238}U$ age of 473 ± 8 Ma is identical to the upper intercept age of 488 ± 12 Ma within error of conventional U–Pb zircon analysis, but show weak discordance (Fig. 3).

The zircons for sample E3 are rounded, colorless and free of cores. Uranium contents are lower between 101 and 165 ppm. As commonly observed in magmatic zircon populations, a low U content probably reflects a metamorphic overprint. The zircon fractions yielded discordant U–Pb ages between 263 and 332 Ma, and $^{207}Pb/^{206}Pb$ ages between 404 and 438 Ma. These data are plotted in figure 3b and a regression line with an upper intercept age of 418 ± 11 Ma can be obtained, the lower intercept age correspond to zero (Fig. 3b). In table 5 we report several Laser ICP-MS data for this zircon population; as the U and the Pb concentrations decrease to lower than 150 ppm and 8 ppm respectively, the uncertainty of the $^{207}Pb/^{235}U$ ratios increases and thus the $^{206}Pb/^{238}U$ ratios were used only. In figure 3b we plotted only two data points which plot within their errors near the upper intercept age of 418 Ma. The mean $^{206}Pb/^{238}U$ age for eight Laser-ICP-MS analyses is 415 ± 17 Ma (Tab. 5).

Sm/Nd results

Sm–Nd analyses of eclogitic amphibolites were performed to constrain the source of these mafic/ultramafic rocks and to get information on the age of the high-pressure metamorphism as well as on protolith intrusion. A partial re-homogenisation of the Sm–Nd whole rock system by Variscan and Alpine overprints has therefore to be envisaged. Several small samples were taken from a small area (< 10 m) within the Keespölach occurrence to study small-scale heterogenity of eclogitic layers (Fig. 5). These whole rock analyses are reported in table 6 and displayed in figure 4.

The Keespölach occurrence displays an intensive folding of the eclogitic amphibolites. The $^{147}Sm/^{144}Nd$ ratios for the eclogitic amphibolites range between 0.1174 and 0.2189. Except for samples LT36A, E1 and 25–87, all other whole rock samples plot on a reference line, yielding an age of 845 ± 26 Ma (MSWD 0.41) with a ε–Nd T-845 value of + 5.34 ± 0.18 (Fig. 4b). The 840 Ma corrected ε–Nd show least scatter. Based on their $^{147}Sm/^{144}Nd$ values the TDM model ages range from 1.06 Ga up to 2.04 Ga. Two whole-rock analyses from eclogites of the Alpine metamorphic eclogite zone (Type 1 and 3, MILLER, 1977) point to a different more depleted source with higher ε–Nd T-0 values of +7.5 and +8.9 (FRO 3, FRO 6).

The U–Pb zircon data point to a Cambrian intrusion age (Fig. 3a) and therefore ε–Nd were calculated for 420 and 488 Ma age, resulting in a large scatter of the Sm/Nd data between +1.9 and +4.5. Only two samples, E3 and TW 22–89, show considerably lower ε–Nd signature of +1.2 and +1.3 respectively.

To gain more information on the metamorphic evolution of the eclogites Sm–Nd analyses of carefully separated garnet, cpx and omphacite mineral concentrates were performed (Tab. 5). Only in the case of garnet concentrate LT 28 we are convinced that it represents one single generation. Omphacite and whole rock of TW 22–89 have similar $^{147}Sm/^{144}Nd$ values and garnet, cpx and whole rock of LT 36A show no isotopic homogenisation. The whole rock LT 28 and garnet (grt II) pair gives a reference line with an age of 422 ± 16 Ma (Fig. 6), which supports our conclusion that the 418 ± 11 Ma zircon data represents metamorphic growths.

Geochronological interpretation and discussion

The geodynamic evolution shows two important phases of tectonic activity: (1) The opening of the pre-Cambrian/Cambrian ocean started at a back-arc basin change with a transition to an ocean floor spreading for a long period (540–486 Ma) of magmatism (VON QUADT, 1992; EICHHORN et al., 1995). The mafic volcanism within the LSC of the Tauern Window occurred between the lowest volcano-sedimentary sequence, probably Proterozoic in age, and the fine layered tuffs and sediments of the Habach formation of unknown age. The volcanic rocks represent basalts with a time-integrated enriched mantle signature; the acid part of the mafic volcanic suite (or dacites, rhyolites and acid tuffs) is not detectable. (2) The first metamorphic overprinting of this volcanic sequence occurred in Silurian time. The metamorphic process, based on the grt-cpx geobarometry (ZIMMERMANN and FRANZ, 1988), reached temperatures of 400–500 °C and pressures between 8–12 kbar. The calculated moderate temperatures of 400–500 °C are in agreement with two coexisting pyroxene minerals (Jad 40–50, Jad 11–15) and albite (ZIMMERMANN and FRANZ, 1988). The post-eclogitic retrograde path represents a symplectitic transformation of omphacite to plagioclase, diopside and amphibole. ZIMMERMANN and FRANZ (1988) argued that the estimated P-t values (7 kbar, 550 °C) during symplectitic recrystallisation relate to Alpine crystallisation. In contrast, Ar–Ar dating on white micas revealed the existence of the Variscan overprint in the southern

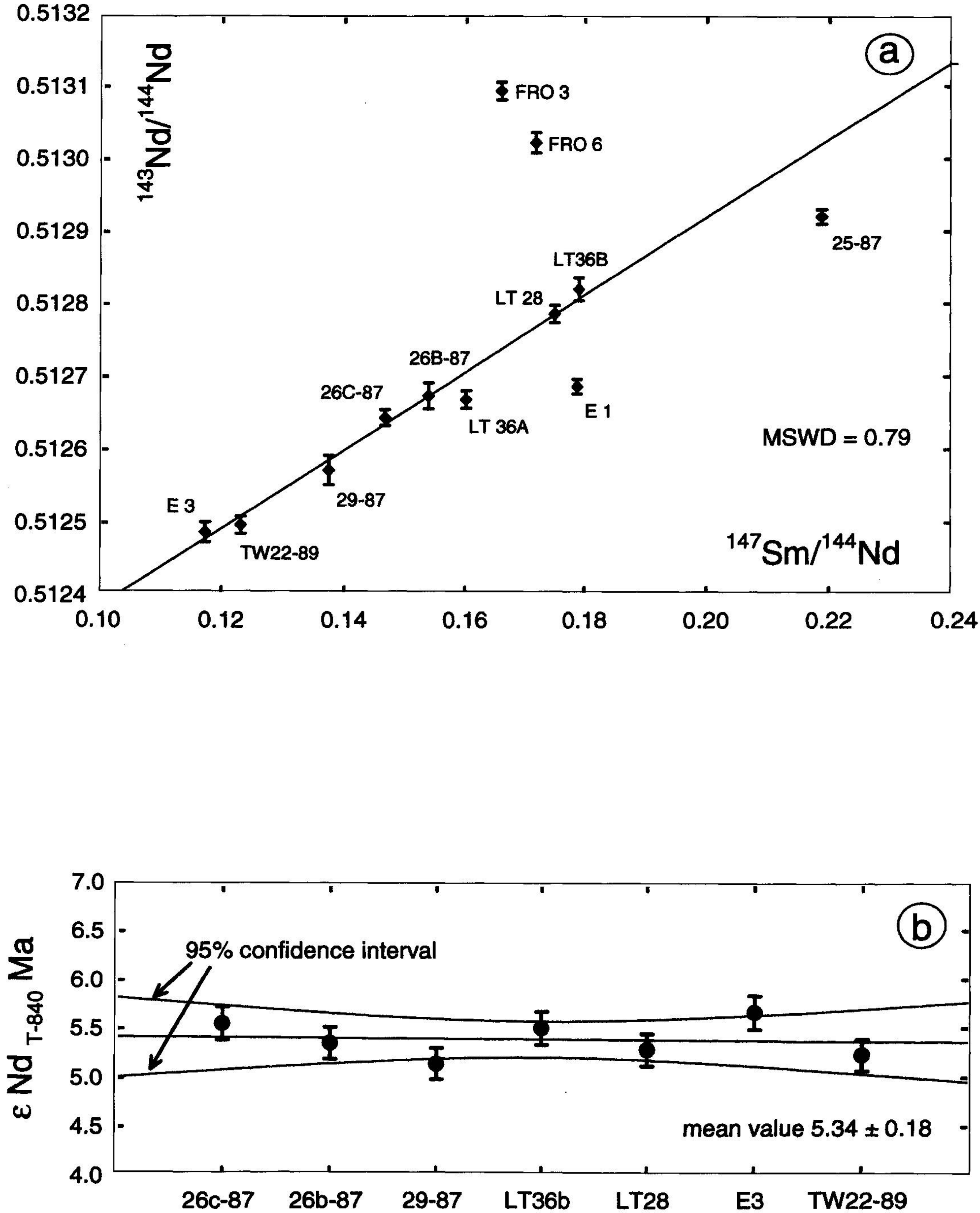


Fig. 4 (a) Sm–Nd whole rock plot for the eclogitic amphibolites; (b) ε–Nd plot for T = 840 Ma.

part of the Lower Schist Cover (ZIMMERMANN et al., 1994), whereas our U–Pb zircon data show no Variscan overprint.

Conventional zircon analyses from the E3 eclogitic amphibolite define an upper intercept age of 418 ± 18 Ma, Laser ICP-MS zircon data define a mean $^{206}Pb/^{238}U$ age of 415 ± 17 Ma and a Sm–Nd garnet-whole rock age of 422 ± 16 Ma, which can be interpreted to date the recrystallisation of these zircons during the eclogite metamorphism. This tectono-metamorphic event converted the magmatic protoliths to layered and folded eclogitic amphibolites. As both eclogite bodies are located in the same area it is surprising that one eclogite type displays the time of the protolith formation age whereas the second one records the Silurian high pressure overprint. The use of the new laser ablation technique leads in this case to further U/Pb age information within one single zircon crystal. Several Laser ICP-MS shots on zircons of samples E1 and E3 confirm the existence of both geological events. No indication of an older event is present.

The 420 Ma age of zircons E3 is the first indication of a Silurian high pressure metamorphic event in this part of the eastern Alps; PAQUETTE et al. (1989) reported ages indicative of a Silurian overprint from the Alpine External Massif (western Alps). VON QUADT and GEBAUER (1993) and GEBAUER (1991) find similar high pressure indications for ultramafic rocks from the Bohemian Massif and DUCROT et al. (1983), PIN and LANCELOT (1982) and PAQUETTE et al. (1995) described high pressure Silurian ages on mafic rocks from the French Central Massif. VON QUADT (1985, 1992) and EICHHORN et al. (1995) could not find indication for such Silurian metamorphism in the northern part of the Lower schist cover within the Tauern Window.

The recrystallisation of the zircon (sample E3) during Silurian time leads to a Pb-loss and the Uranium decreases to concentration lower than 160 ppm. The primary U content of such mafic zircons (eclogite E1) range from 300 to 460 ppm. The conditions during Alpine metamorphism reached the garnet-hornblende stability field and would have produced a Pb-loss in all zircon crystals. As all analysed zircons underwent Variscan metamorphism overprint (PESTAL, 1983; VON QUADT, 1992; EICHHORN et al., 1995), the different degrees of discordance of the zircons can be interpreted as episodic Pb-loss during both metamorphic overprints.

Several small eclogitic bodies occur in the southern part of the Lower Schist Cover of the central Tauern Window. The northern part of the Lower Schist Cover has been reported to have tholeiitic to calc-alkaline signatures and the

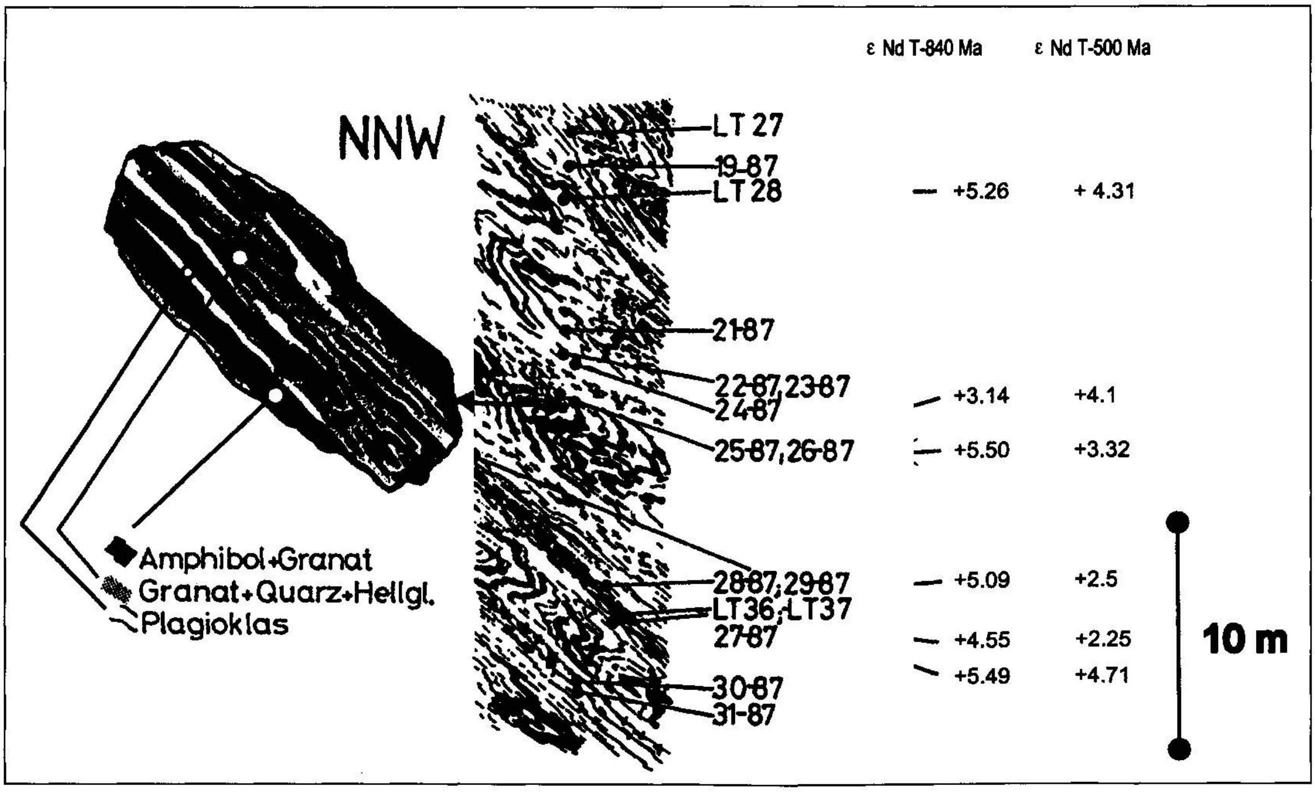


Fig. 5 Detailed Sm–Nd whole rock study for the eclogitic amphibolites of the Keespölach occurrence with ε–Nd values for T = 500 °C, 840 Ma.

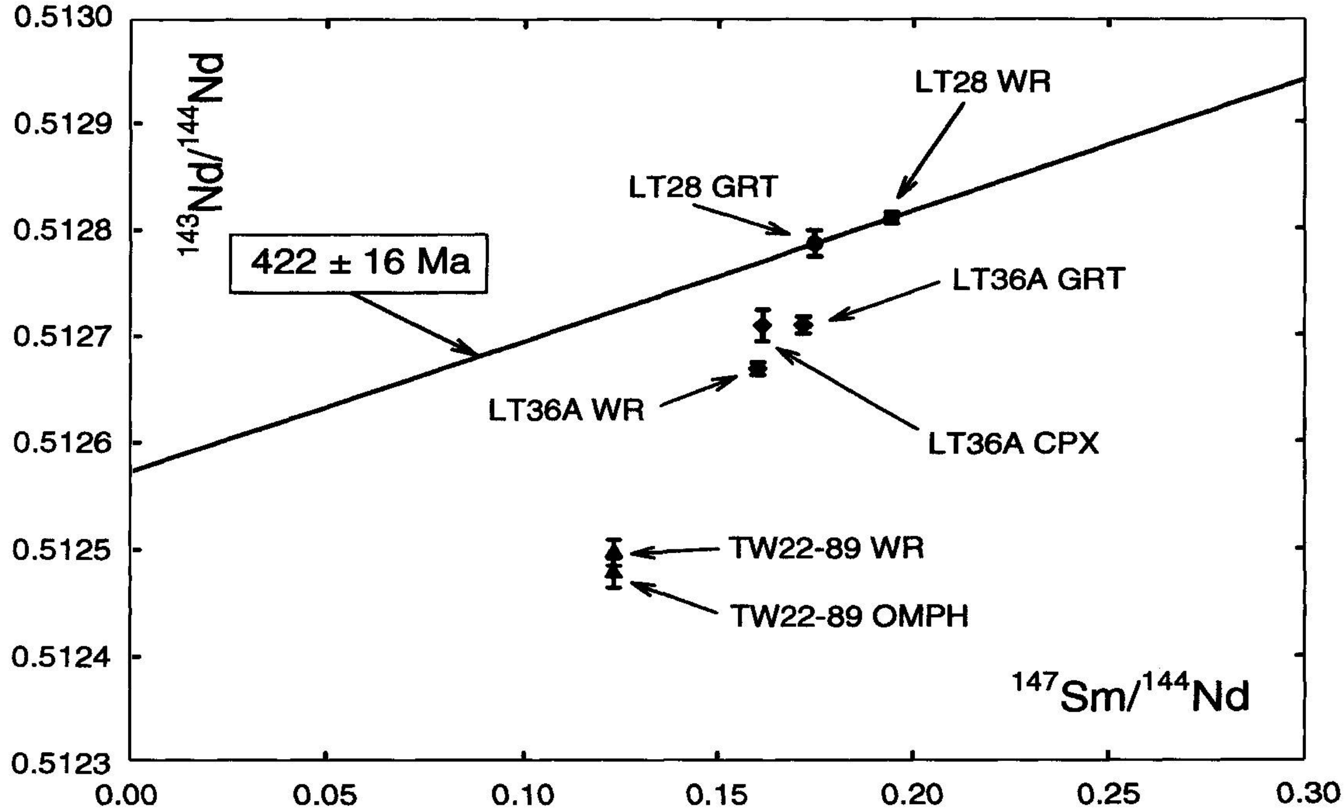


Fig. 6 Sm–Nd whole rock and mineral separates plot for the eclogitic amphibolites.

southern part a back-arc/WPB-related chemical signature (PESTAL, 1987; VON QUADT, 1992). The dated eclogitic amphibolites (E1) from the southern part show that these protolith ages were coeval and co-genetic with mafic rocks from the northern part of the Lower schist cover (VON QUADT, 1992; EICHHORN et al., 1995).

The back-arc/within-plate related signatures of these eclogitic amphibolites could explain the existence of continental crust input. The ε–Nd signatures for T-500 Ma scatter from +1.9 up to +4.2 and thus, a mixture between two or more components has to be taken into account. Using the Nd mantle evolution model for rocks derived from sub-European lithosphere (STILLE and SCHALTEGGER, 1996) our ε–Nd T-840 mean value of +5.34 plots several ε–Nd units lower than those representing the northern part of the Lower schist cover (VON QUADT, 1992) as well as those from other areas (e.g. Gotthard Massif; GEBAUER et al., 1988). Similar ε–Nd values for WPB related eclogites, range from +1.2 in the French Central Massif or +3.2 from the Bohemian Massif, are reported by VON QUADT (1993) and PAQUETTE et al. (1995). As no Cambrian high-pressure process has been detected with isotopic investigations until now, the existence for a Cambrian subduction scenario within the Alps can be excluded. Investigations on metagabbros and high-pressure shear-zones within these mafic rocks indicate only one geological event (520 Ma; SCHALTEGGER et al., this volume).

Seven up to ten samples define a mean ε–Nd T-840 value of 5.34 ± 0.18. The regression line (Fig. 4a) of 840 ± 16 Ma suggests a Nd-homogenisation in Riphean time. GEBAUER et al. (1988) reported a similar protolith age of 870 Ma for eclogites from the Gotthard massif and SCHENK (1993) displayed with a Sm–Nd study an age of 985 ± 21 Ma of meta-basalts from the southern Penninic domain, but the interpretation of the "isochron" (840 ± 16 Ma) remains in this case difficult since no U–Pb zircon data reflect such geological event.

Summary and conclusions

The zircon U–Pb age of 418 ± 18 Ma for the E3 eclogite sample and the Sm–Nd mineral isochron age of LT28 (422 ± 16 Ma) are interpreted to date the time of the metamorphic overprint, most likely during a high-pressure metamorphic event. No disturbance on their U–Pb and Sm–Nd systems during subsequent Variscan and Alpine metamorphism can be detected.

The combined use of the conventional and laser ablation (LAM-ICP-MS) in situ dating techniques using zircon leads to the detection of the protolith age for the eclogitic amphibolites. The Cambrian intrusion age of 488 ± 12 Ma is comparable to protolith ages from the northern part of the Lower schist cover of the central part of the Tauern Window and other areas within the Alpine basement (Berisal Complex, STILLE and TATSUMOTO, 1985; Gotthard, OBERLI et al., 1995; Aar, ABRECHT et al., 1995).

The samples from mafic/ultramafic rocks of the Frosnitz valley of the southern part of the Tauern window display a homogenous Sm–Nd isotopic distribution 840 Ma ago. The ε–Nd T-840 values of +5.34 ± 0.18 point to an enriched magma source. The enriched mantle source can be detected by mean of discrimination diagrams based on trace element data (Zr, Nb, and Ti), that they probably point to basalt-related WPB. The existence for an enriched mantle source within the Variscides, probably of Proterozoic age, was documented for the metagabbros of the KTB (continental deep drilling, Germany, VON QUADT, 1997), for metabasic rocks of the Neukirchen massif (MIETHIG, 1995), for eclogites from the Gotthard massif (GEBAUER et al., 1988), and for the Saxonian granulite massif (VON QUADT, 1993). In contrast, the young (Alpidic eclogitised) mafic rocks of the eclogite zone relate to a depleted mantle source.

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