

Metamorphic peak conditions of eclogites in the Tauern Window, Eastern Alps, Austria: Thermobarometry of the assemblage garnet + omphacite + phengite + kyanite + quartz

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Abstract

Metamorphic peak P – T conditions of five kyanite eclogites from the Tauern Window, Austria, are evaluated on the basis of recent calibrations of the assemblage garnet + omphacite + phengite + kyanite + quartz. Results are about 25 kbar, 630 °C according to the dataset of Holland and Powell [Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology* 16, 309–343 (updated 2002)]. Mostly higher P – T values are calculated with the calibrations of Krogh Ravna and Terry [Krogh Ravna, E.J., Terry, M.P., 2004. Geothermobarometry of UHP and HP eclogites and schists—an evaluation of equilibria among garnet–clinopyroxene–kyanite–phengite/coesite/quartz. *Journal of Metamorphic Geology* 22, 579–592] and Brandelik and Massonne [Brandelik, A., Massonne, H.-J., 2004. PTGIBBS—an EXCEL Visual Basic program for computing and visualizing thermodynamic functions and equilibria of rock forming minerals. *Computers and Geosciences* 30, 909–923], in part already in the stability field of coesite. However, no indications for this phase are evident from the Tauern samples. The presence of talc is consistent with these P – T values and high H_2O activities. In contrast, the stability limits of paragonite and zoisite are situated at lower pressure and suggest a later formation during the decompression stage. THERMOCALC pseudosections in the NCFMASH system are constructed with the incorporation of fractional crystallization of garnet. Calculated garnet zonations are in better agreement with the observed compositions at peak pressures of about 25 kbar than results at lower pressures. This is also consistent with values from thermobarometry obtained with the same program.

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1. Introduction

The Eclogite Zone, Tauern Window, Austria (Fig. 1) is a tectonic thrust sheet intercalated between the basal Venediger nappe (Central Gneis and metabasites of Lower Schieferhülle) and the upper position of the Glockner nappe (metasediments and metabasites of the Upper Schieferhülle). Lithological members of the Eclogite Zone are mesozoic metasediments (calcareous schists, pelitic schists, quartzites, marbles) and metabasites metamorphosed during the alpidic plate collision at higher P – T conditions than the adjacent units. According to Glodny et al. (2005) the age of this event was 31.5 Ma based on the

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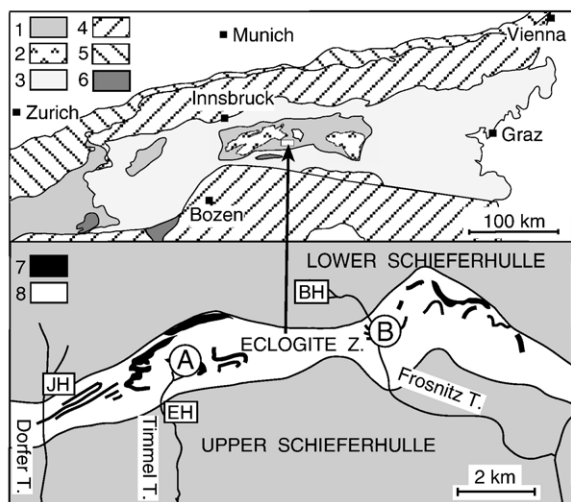


Fig. 1. Simplified geological map of the Eastern Alps with the Tauern Window in center. 1 Penninic units, 2 Central Gneiss, 3 Austroalpine units, 4 Basement, Northern Calcareous and Southern Alps, 5 Helvetic units, 6 Tertiary intrusives, 7 major eclogite units, 8 metasedimentary rocks; sample locations: A—Eissee (2447, 2536, 2544), B—Steinsteg (2519, 2188); BH—Badenerhütte, EH—Eisseehütte, JH—Johannishütte.

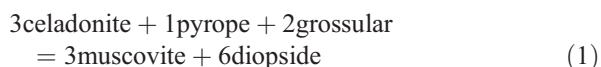
Rb/Sr method applied to mineral assemblages in eclogites and 32–36 Ma based on phengite Ar data (Zimmermann et al., 1994).

Metamorphic peak conditions of the high pressure event are constrained mainly due to metabasites at about 600 °C, 20 kbar according to e.g. Miller (1978): 500–550 °C; Holland (1979): 620 °C, 19.5 kbar; Selverstone et al. (1992): 625 °C; Kurz et al. (1998): 550–635 °C, 19–23 kbar; Hoschek (2001): 594–627 °C, 19.2–22.4 kbar; Miller and Konzett (2003): 623 °C, 20.4 kbar; Hoschek (2004): 629 °C. The conditions of this high pressure event are rarely preserved in adjacent metasediments, e.g. according to Franz and Spear (1983): 600 °C, 18–25 kbar; Spear and Franz (1986): 590 °C, 19 kbar; Dachs (1986): 600 °C, 20 kbar; Stöckert et al. (1997): 600 °C, 25 kbar; Hoschek (2001): 617 °C, 21.7 kbar.

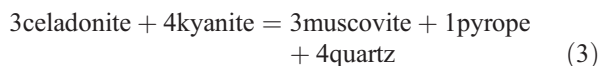
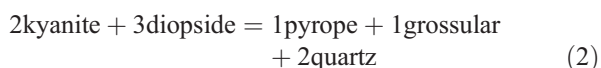
Despite these data it seems appropriate to address the metamorphic peak conditions in eclogites due to several points. According to textural relations, some P – T estimates are based on mineral equilibria which were attained during a later decompression event. Paragonite commonly replaces kyanite and therefore peak conditions exceeding paragonite stability are suggested. Another example is the observation of tremolite replacing omphacite+talc. Likewise this holds for chloritoid overgrowing a.o. paragonite

+amphibole; the latter phases are regarded as retrograde products of kyanite+omphacite breakdown (Miller and Konzett, 2003). Furthermore comparison of natural assemblages with experiments in simplified systems is of restricted value, e.g. phengite barometry based on KMAH experiments. In addition, recent calibrations of thermobarometer reactions as well as updated thermodynamic databases and solution models should be considered.

Kyanite eclogites with the assemblage garnet + omphacite + kyanite + phengite + quartz are representative of metamorphic peak conditions in the Tauern area. A partly recently calibrated thermobarometer is defined by three reactions.



has the advantage of a relatively temperature independent reaction, applicable also in quartz absent rocks. Presence of kyanite defines two further more temperature dependent reactions



An intersection point is defined in the Fe-free KCMASH system and therefore independent of commonly used Fe–Mg exchange thermometers. This offers an advantage with regards to garnet + clinopyroxene which is prone to retrograde changes and uncertainty in Fe^{3+} content of omphacite.

Calibration 1 uses updated versions of the thermodynamic data set and activity models in the THERMOCALC and AX programs (Holland and Powell, 1998; updated data set 2002; Powell et al., 1998). Comparison with results for reaction (1) according to other calibrations is of interest as reported by e.g. Hoschek (2001), Proyer et al. (2004) and Zhang et al. (2005). Calibration 2 is based on the thermobarometry of quartz/coesite + phengite + kyanite eclogites proposed by Krogh Ravna and Terry (2004). This user-friendly Excel program incorporates the thermodynamic database of Holland and Powell (1998) and activity models for garnet (Ganguly et al., 1996), clinopyroxene (Holland, 1990) and phengite (Holland and Powell, 1998). Application to worldwide samples

over a wide P – T region showed good consistency with petrographic evidence, a.o. the presence of quartz, coesite or diamond. Furthermore net transfer reactions (2) and (3) are suggested to be less affected by later thermal re-equilibration than the common cation exchange thermometers. Results for the samples from the Western Gneiss region, Norway and Dabie Mountains, China are around 2–5 kbar higher than the calibration of Waters and Martin (1993). Further application of this calibration is reported by e.g. Song et al. (2003). Calibration 3 uses PTGIBBS, a software developed by Brandelik and Massonne (2004). An updated version of the thermodynamic database of Berman (1988) and various solution models are based a.o. on the experimental data of Massonne and Szpurka (1997). The user-friendly Excel program is supplemented by Mincalc, a program for the conversion of mineral analyses to end-member values used in solution models. A first application of this method is cited by Massonne and Kopp (2005) for an phengite+talc eclogite from the Saxonian Erzgebirge, Germany. Calibration 4 is an updated version of the Waters and Martin (1993) barometer for reaction (1). It is based on the thermodynamic data set of Holland and Powell (1990) with activity models for garnet (Newton and Haselton, 1981), clinopyroxene (Holland, 1990) and ideal mixing for phengite. Application to eclogites were reported by e.g. Carswell et al. (1997), Nowlan et al. (2000), O'Brien et al. (2001), and Zhang et al. (2005). Recalibration of reaction (1) was done by Waters (1996, cited in Wain et al., 2001) based on experimental results for phengite eclogite assemblages by Schmidt (1993). Results were approximately 3 kbar lower than the original version. This updated barometer was used by e.g. Schmid et al. (2000) and Proyer et al. (2004). In the present study the program PET, which incorporates omphacite ordering (Dachs, 2004) was used for calibration 4.

The aim of the present paper is to apply these recent calibrations for the determination of the metamorphic peak conditions in five kyanite eclogites from the Tauern Window. In addition garnet profiles are calculated from NCFMASH pseudosections with the incorporation of garnet fractionation. Comparison with observed zonations offers another approach towards reconstruction of metamorphic P – T paths.

2. Sample description

At locality Eisse, Timmeltal, eclogites are intercalated with calc mica schists, mica schists,

quarzites and marbles. Banded eclogites are partly boudinaged and range from 10 m to cm dimensions. Minor eclogitic layers in pelitic and calcareous metasediments represent tuffitic admixtures. Samples 2447, 2536 and 2544 are from outcrops near Eisse. A sedimentary component is suggested for sample 2544 due to a comparatively higher K_2O content. At locality Steinste, Frosnitz Tal (samples 2519, 2188) meter sized eclogite layers are exposed alternating with mica schists, calc mica schists and marbles.

Photomicrographs and BSE images are shown in Figs. 2 and 3; mineral assemblages, bulk rock chemistry and representative mineral compositions are presented in Tables 1–4. Mineral compositions were measured with a JEOL microprobe at the Institute of Mineralogy–Petrography in Innsbruck. Operating conditions were 15 kV, beam current 10 nA, and a 20 s measuring time in wavelength dispersive mode. Spot measurements were used except for micas with a $\sim 10 \mu m$ scanning mode. Natural minerals were used as standards. The citzaf correction was applied for data reduction. Rock bulk composition was gained from XRF wavelength dispersive analyses of fused glass-discs.

Hand specimens 2447, 2519 and 2536 are relatively homogeneous, whereas a weak layering is exhibited in 2544 and 2188. Sample 2447 is dominated by up to 5 mm sized green omphacite blades

Table 1
Mineral assemblages in eclogites

	2447	2519	2536	2544	2188
Garnet	X	X	X	X	X
Omphacite	X i,m	X i,m	X i,m	X i,m	X i,m
Kyanite	X	x i,m	x i,m	x i,m	x
Phengite	x	x i,m	x	X i,m	x
Quartz	X i,m	x i,m	x i,m	x i,m	x i,m
Zoisite	x	X	X i,m	X	x i,m
Cl-zoisite	x i	x i,m	x i,m	x i,m	x i,m
Paragonite	X i,m	x i,m	x i,m	x i,m	x i,m
Talc		X i,m	X i,m		x
Biotite	tr i	tr i,m	tr i		
Chlorite	tr i	tr i	tr i		tr i
Hornblende	x i,m	X i,m	x i,m	x i,m	x i,m
Glaucofanite		tr			X
Plagioclase	x i,m	tr			tr i
Rutile	x i,m	x i,m	x i,m	x i,m	x i,m
Titanite	tr i				tr i
FeTiO ₃	tr i	tr i	tr i	tr i	tr i
Magnetite		x			tr i,m
Dolomite		tr		x i,m	tr i,m
Pyrite	tr				

X, x, tr: major, minor and trace amount; i — garnet inclusion; m — additional matrix phase.

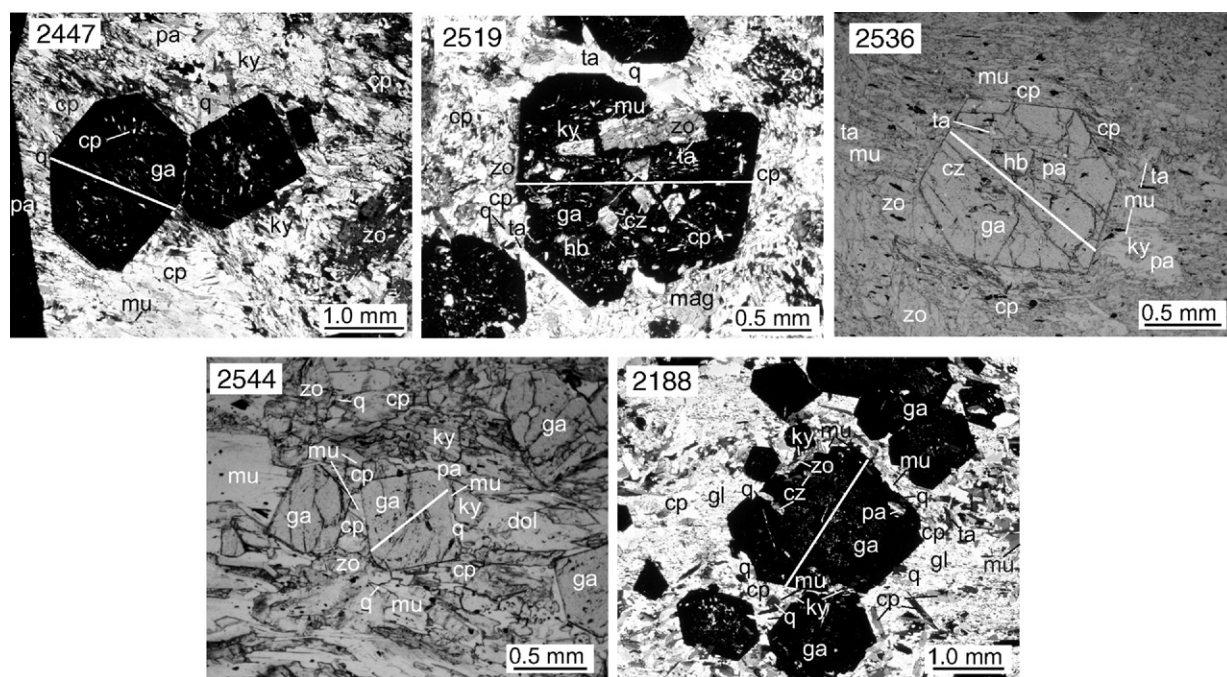


Fig. 2. Photomicrographs of eclogites with crossed (2447, 2519, 2188) and plane polarized light (2536, 2544). See text for sample description. Position of garnet profiles (Fig. 4) is marked. Abbreviations: ga – garnet, cp – omphacite, ky – kyanite, mu – phengite, pa – paragonite, ta – talc, zo – zoisite, cz – clinozoisite, hb – hornblende, gl – glaucophane, ch – chlorite, law – lawsonite, q – quartz, mag – magnesite, dol – dolomite, ru – rutile.

and red garnet porphyroblasts (1–3 mm) set in a groundmass of recrystallized omphacite in the range of tenth mm size, kyanite, paragonite, zoisite laths and quartz. Accessories are phengite, hornblende, rutile and pyrite and as inclusion phases only clinozoisite, rarely plagioclase and titanite. In sample 2519 garnet with diameter 1–2 mm is situated in a groundmass of small omphacite. Large randomly oriented zoisite (up to 3 mm in length) is abundant compared with smaller clinozoisite (c. 0.4 mm). Additional phases are talc, phengite, paragonite, amphibole, magnesite, rutile and small amounts of quartz. In 2536 garnet with c. 1 mm size, small groundmass omphacite (max. 0.1 mm) defining a parallel orientation, randomly oriented zoisite (up to 4 mm in length) and talc are major phases. Phengite, paragonite, amphibole, clinozoisite are present in minor and quartz in very low amounts. The main part of sample 2544 consists of parallel oriented white mica (c. 1 mm), zoisite (1–3 mm) and in part elongated omphacite (up to 1 mm) plus euhedral garnet (0.5–1, rarely up to 2 mm), kyanite, amphibole, quartz, dolomite and rutile as additional phases. A second layer consists of large porphyroblasts of zoisite and clinozoisite in a groundmass of omphacite (c. 0.1 mm) with subordinate amounts of

garnet and white mica. Layering in sample 2188 is due to alternating proportions of red garnet and green omphacite/amphibole. In thin section omphacite, frequently as euhedral blades with 0.3–1 mm length, white mica and kyanite delineate a weak preferred orientation. Other major matrix phases are quartz and amphiboles.

Garnet is mostly euhedral with 0.5–3 mm size. Compositional zoning (Fig. 4, Table 4) is characterized by core to rim increase in pyrope, decrease in almandine and constant or slight decrease in grossular. Elevated contents of spessartine in the core decreasing towards rim are observed in samples 2536, 2544 and 2188, causing a depression of almandine in the composition profile. A strong reversal of this zoning pattern is exhibited at the outer garnet rim in 2447 and to a lesser extent in parts of sample 2536. Variations of grossular and almandine contents are also found at some outer rims of garnet in 2519 and 2544. In Fig. 3, a BSE image of another garnet of sample 2447 shows a similar zonation at outer rim, around inclusions and partly included phases. Darker and, more rarely, brighter veins in this image cast doubt as to the “primary” nature of some inclusions. Similar patterns have been

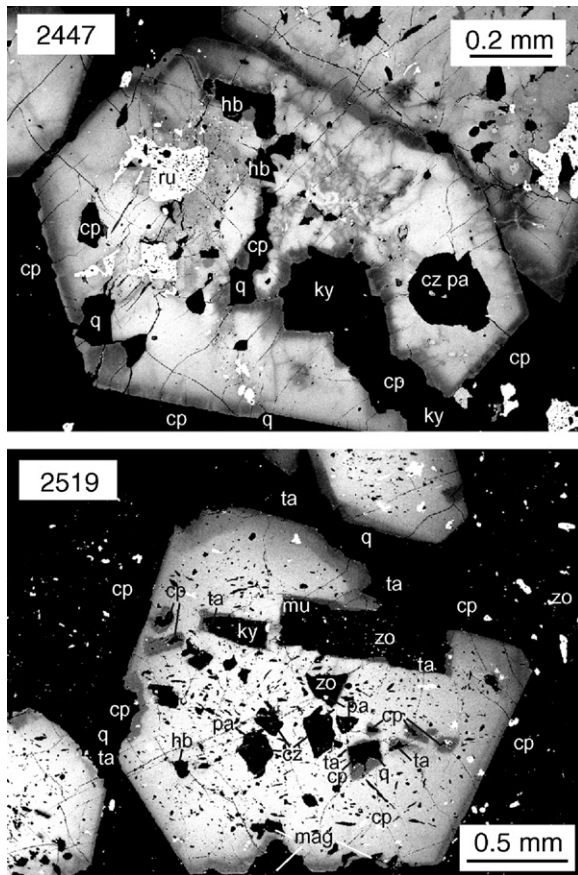


Fig. 3. BSE images. Sample 2447: Garnet with rim zonation, in part also around inclusions. Darker and more rarely brighter veins, probably annealed cracks. Sample 2519: Dark halos around garnet inclusions of omphacite and talc with similar composition as garnet rim. Abbreviations as in Fig. 2.

interpreted as annealed cracks in garnet (Kurz et al., 1998; Zack et al., 2002). Likewise, in the BSE image of garnet from sample 2519 (Fig. 3) dark halos around inclusions of omphacite and talc are evident with compositions similar to the outer rim. Inclusions in garnet are dominated by omphacite with higher Fe content than matrix phases, paragonite and cl-zoisite. Rarely, aggregates of both latter phases with distorted rectangular outlines are found (2519, 2447), presumably representing pseudomorphs after lawsonite. Amphibole inclusions are predominantly barroisite (Leake et al., 1997) but ferri taramite and magnesio taramite are also found. Phengite is present as inclusion in samples 2519 and 2544 with Si in the same range as matrix phases. Additional inclusions are talc (2519, 2536), kyanite (2519, 2536, 2544), quartz and rutile (all samples). In 2188 rutile is confined to the garnet rim and titanite to core region.

Omphacite in matrix is partly zoned with higher jadeite and lower Fe contents in rims compared with cores. Reversals of this zoning are rarely found in sample 2447. Compositions of omphacites are plotted in Fig. 5.

Kyanite is frequently replaced by *paragonite*, more rarely by *phengite*. In all five samples phengite is characterized by a Tschermak substitution in the range of Si 3.34–3.49 cations per formula unit (11 Oxygen), Fig. 6, Table 4. With an increase in Si, a concomitant increase in Mg with approximately constant Fe values results in a slight decrease in the Fe/Mg ratio. Na and K display a negative resp. positive correlation with Si, except in sample 2447 with relatively constant K values. Total K+Na is in the range 0.95–0.98 c.p.f.u. (11 Oxygen). Phengite as replacement product of kyanite shows relatively low Si and high Na contents within the range given in Fig. 6. Generally no systematic differences in phengite core/rim compositions or in matrix/inclusion phases exist. In rare cases only decreasing celadonite content towards rim is found. *Talc* is present in matrix and garnet inclusions of samples 2519 and 2536, in 2188 talc is partly in contact with kyanite and phengite.

Zoisite commonly forms large randomly oriented porphyroblasts overgrowing groundmass omphacite in all samples, except in 2188 where zoisite is very rare. Minor amounts of *clinozoisite* are present in varying amounts in all samples. Intergrowths of zoisite and clinozoisite in the matrix of 2519 have Fe total 0.10–0.13 and 0.30–0.32 c.p.f.u. (12.5 Oxygen). *Amphiboles* as matrix phases are predominantly

Table 2
Rock bulk composition

	2447	2519	2536	2544	2188
SiO ₂	50.73	44.36	48.88	44.88	51.44
TiO ₂	1.74	1.79	1.08	0.72	1.44
Al ₂ O ₃	18.28	17.09	15.09	21.41	16.90
Fe ₂ O ₃	10.00	11.16	9.15	7.09	10.22
MnO	0.16	0.19	0.13	0.11	0.12
MgO	5.22	8.36	8.62	5.05	7.60
CaO	9.12	11.41	11.49	12.21	7.24
Na ₂ O	4.43	2.45	2.96	2.54	3.84
K ₂ O	0.10	0.06	0.16	1.56	0.40
P ₂ O ₅	0.21	0.07	0.10	0.06	0.13
L.o.i.	0.08	2.41	1.15	4.25	0.59
Total	100.07	99.35	98.81	99.88	99.92

Weight% from XRF analyses in wavelength dispersive mode of fused glass-discs; Fe as Fe₂O₃ total; l.o.i. at 1000 °C/2 h; analysis on dry basis (105 °C/24 h).

Table 3
Selected microprobe mineral analyses for matrix phases

	Garnet					Omphacite					Phengite				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	2447	2519	2536	2544	2188	2447	2519	2536	2544	2188	2447	2519	2536	2544	2188
SiO ₂	40.38	39.84	40.77	40.02	40.19	57.68	56.23	56.95	57.03	57.17	51.45	50.62	51.16	51.09	51.12
TiO ₂	0.06	0.04	0.05	0.05	0.06	0.05	0.08	0.10	0.07	0.04	0.29	0.28	0.25	0.30	0.25
Al ₂ O ₃	22.69	22.31	22.25	22.39	22.24	13.65	10.39	10.78	11.85	12.52	27.31	26.89	27.31	28.18	27.42
Cr ₂ O ₃	0.03	0.04	0.08	0.02	0.00	0.05	0.08	0.09	0.01	0.00	0.10	0.11	0.11	0.02	0.00
FeO	22.66	20.66	20.86	23.00	22.08	2.09	3.17	3.15	4.20	2.62	1.43	1.50	1.36	1.48	1.10
MnO	0.28	0.40	0.30	0.43	0.11	0.01	0.02	0.01	0.02	0.02	0.00	0.00	0.00	0.01	0.02
MgO	9.36	9.60	9.79	7.93	9.59	8.01	9.71	9.58	8.18	8.48	3.34	3.86	3.91	3.55	3.91
CaO	6.76	7.68	8.01	7.81	6.75	11.83	14.30	13.97	11.91	12.13	0.03	0.02	0.02	0.00	0.02
Na ₂ O	0.02	0.01	0.03	0.07	0.01	7.83	6.38	6.72	7.68	7.66	0.74	0.76	0.76	0.89	0.80
K ₂ O	0.00	0.00	0.00	0.00	0.03	0.02	0.01	0.00	0.00	0.03	9.89	10.08	10.44	10.50	10.06
Total	102.24	100.58	102.16	101.72	101.06	101.22	100.37	101.35	101.12	100.67	94.59	94.13	95.33	96.03	94.71
Si	3.002	2.996	3.019	3.009	3.016	1.993	1.983	1.986	1.993	1.994	3.430	3.405	3.400	3.373	3.406
Ti	0.003	0.002	0.003	0.003	0.003	0.001	0.002	0.003	0.002	0.001	0.015	0.014	0.012	0.015	0.013
Al	1.988	1.978	1.942	1.985	1.967	0.556	0.432	0.443	0.488	0.515	2.147	2.132	2.140	2.194	2.154
Cr	0.002	0.002	0.005	0.001	0.000	0.001	0.002	0.002	0.000	0.000	0.005	0.006	0.006	0.001	0.000
Fe ³⁺	0.002	0.024	0.013	0.000	0.000	0.000	0.033	0.032	0.041	0.015	0.000	0.000	0.000	0.000	0.000
Fe ²⁺	1.406	1.275	1.278	1.446	1.386	0.060	0.060	0.060	0.081	0.062	0.080	0.084	0.076	0.082	0.061
Mn	0.018	0.025	0.019	0.027	0.007	0.000	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.001	0.001
Mg	1.037	1.076	1.080	0.889	1.072	0.413	0.510	0.498	0.426	0.441	0.323	0.387	0.387	0.349	0.388
Ca	0.538	0.619	0.636	0.629	0.543	0.438	0.540	0.522	0.446	0.453	0.002	0.001	0.001	0.000	0.001
Na	0.003	0.001	0.004	0.010	0.002	0.525	0.436	0.455	0.521	0.518	0.096	0.099	0.098	0.114	0.103
K	0.000	0.000	0.000	0.000	0.003	0.001	0.000	0.000	0.000	0.001	0.842	0.866	0.886	0.885	0.856
Total	8.000	8.000	8.000	8.000	8.000	3.989	4.000	4.000	4.000	4.000	6.948	6.995	7.007	7.014	6.984

	Paragonite			Talc			Zoisite				Cl-zoisite	
	16	17	18	19	20	21	22	23	24	25	26	
	2447	2519	2544	2519	2536	2188	2447	2519	2536	2544	2544	
SiO ₂	46.46	46.71	46.84	62.22	61.59	62.45	39.50	39.62	39.52	39.41	39.43	
TiO ₂	0.16	0.10	0.06	0.02	0.00	0.02	0.10	0.06	0.04	0.06	0.13	
Al ₂ O ₃	39.05	39.01	39.56	0.45	0.31	0.45	32.62	32.00	31.81	32.10	29.04	
Cr ₂ O ₃	0.00	0.08	0.04	0.01	0.03	0.00	0.00	0.06	0.10	0.05	0.03	
FeO	0.14	0.40	0.39	3.01	3.41	3.07	0.92	1.80	1.81	1.74	5.05	
MnO	0.00	0.04	0.00	0.02	0.02	0.00	0.01	0.02	0.00	0.00	0.01	
MgO	0.14	0.15	0.18	29.73	29.87	29.86	0.05	0.07	0.07	0.08	0.27	
CaO	0.35	0.34	0.27	0.02	0.01	0.02	24.38	24.64	24.21	24.31	24.41	
Na ₂ O	7.33	7.39	7.49	0.05	0.02	0.07	0.02	0.02	0.02	0.03	0.01	
K ₂ O	0.61	0.59	0.56	0.00	0.03	0.02	0.01	0.01	0.01	0.00	0.04	
Total	94.24	94.80	95.39	95.53	95.31	95.96	97.61	98.32	97.60	97.76	98.43	

Si	2.999	3.002	2.991	3.975	3.957	3.973	3.007	3.005	3.016	3.002	3.017
Ti	0.008	0.005	0.003	0.001	0.000	0.001	0.006	0.003	0.002	0.003	0.008
Al	2.971	2.956	2.978	0.034	0.024	0.034	2.927	2.861	2.862	2.882	2.620
Cr	0.000	0.004	0.002	0.000	0.002	0.000	0.000	0.004	0.006	0.003	0.002
Fe ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	0.059	0.114	0.115	0.111	0.323
Fe ²⁺	0.007	0.021	0.021	0.161	0.183	0.163	0.000	0.000	0.000	0.000	0.000
Mn	0.000	0.002	0.000	0.001	0.001	0.000	0.001	0.001	0.000	0.000	0.001
Mg	0.014	0.014	0.017	2.831	2.861	2.832	0.006	0.008	0.008	0.009	0.031
Ca	0.024	0.024	0.019	0.001	0.001	0.001	1.989	2.003	1.980	1.984	2.002
Na	0.918	0.922	0.927	0.007	0.002	0.009	0.003	0.003	0.003	0.004	0.001
K	0.051	0.048	0.046	0.000	0.002	0.002	0.001	0.001	0.001	0.000	0.004
Total	6.991	6.998	7.003	7.011	7.033	7.015	7.997	8.004	7.992	7.999	8.006

	Amphibole								Magnesite	Dolomite
	27	28	29	30	31	32	33	34	35	36
	2447	2519	2519	2519	2536	2544	2188	2188	2519	2544
SiO ₂	50.08	53.42	57.14	56.56	54.10	51.89	53.78	59.35	0.03	0.00
TiO ₂	0.17	0.09	0.09	0.00	0.08	0.15	0.11	0.04	0.01	0.02
Al ₂ O ₃	10.80	8.48	11.62	1.40	6.78	10.94	9.24	11.99	0.00	0.01
Cr ₂ O ₃	0.13	0.05	0.10	0.03	0.02	0.06	0.04	0.03	0.01	0.00
FeO	9.24	5.99	5.62	5.31	6.29	7.24	5.52	4.30	10.06	4.23
MnO	0.14	0.04	0.01	0.03	0.05	0.04	0.02	0.01	0.08	0.04
MgO	14.12	17.92	14.26	22.21	18.27	16.38	17.85	14.24	44.06	21.60
CaO	9.15	8.84	2.69	12.10	9.46	8.23	9.19	1.10	0.45	31.74
Na ₂ O	3.74	3.37	6.34	0.77	2.75	3.81	3.30	7.02	0.01	0.01
K ₂ O	0.19	0.13	0.05	0.06	0.11	0.26	0.18	0.03	0.01	0.01
Total	97.73	98.33	97.92	98.48	97.89	98.99	99.12	98.11	54.72	57.65
Si	7.093	7.332	7.694	7.783	7.467	7.115	7.311	7.883	0.000	0.000
Ti	0.018	0.009	0.009	0.000	0.008	0.015	0.011	0.004	0.000	0.000
Al	1.803	1.372	1.845	0.227	1.103	1.769	1.481	1.877	0.000	0.000
Cr	0.015	0.005	0.011	0.003	0.002	0.007	0.011	0.003	0.000	0.000
Fe ³⁺	0.077	0.269	0.191	0.056	0.250	0.311	0.187	0.090	0.000	0.000
Fe ²⁺	1.018	0.419	0.442	0.555	0.476	0.519	0.440	0.387	0.113	0.100
Mn	0.017	0.005	0.001	0.003	0.006	0.005	0.002	0.001	0.001	0.001
Mg	2.981	3.665	2.862	4.555	3.758	3.347	3.616	2.819	0.879	0.919
Ca	1.389	1.300	0.388	1.784	1.399	1.209	1.339	0.157	0.006	0.979
Na	1.027	0.897	1.655	0.205	0.736	1.013	0.870	1.808	0.000	0.000
K	0.034	0.023	0.009	0.011	0.019	0.045	0.031	0.004	0.000	0.000
Total	15.472	15.296	15.106	15.182	15.225	15.355	15.293	15.034	1.000	2.000

Formulas calculated with program AX v 2000 based on the following Oxygen numbers: garnet=12; omphacite=6; phengite, paragonite, talc=11; amphibole=23; (cl)-zoisite=12.5. In the latter case input was Fe₂O₃ recalculated from microprobe FeO.

Table 4

Selected composition parameters for matrix phases of kyanite eclogites

Sample	Ga core				Ga inner rim				Ga outer rim				Omph core				Omph rim				Phengite		Parag	Talc	
	Py	Gr	Al	Sp	Py	Gr	Al	Sp	Py	Gr	Al	Sp	Jd	Di	He	Ac	Jd	Di	He	Ac	Si	Na	K	Fe	Al
2447	9	24	65	2	33	18	48	1	25	24	49	2	47	36	11	6	57	36	6	0	3.35–3.47	0.08–0.13	0.04–0.10		
2519	16	20	62	1					36	21	42	1	38	45	6	10	43	47	6	4	3.35–3.45	0.08–0.15	0.05–0.09	0.16	0.04
2536	11	22	63	4					36	21	43	0.5	38	46	7	8	43	47	5	5	3.39–3.47	0.04–0.13	0.05–0.07	0.18	0.04
2544	9	22	56	13					29	22	48	1	45	39	6	9	47	41	6	6	3.34–3.44	0.05–0.13	0.04–0.09		
2188	5	31	56	8					36	18	46	0	41	45	6	8	50	43	6	0	3.38–3.49	0.05–0.13	0.05–0.09	0.16	0.05

Sample	Zoisite		Cl-zoisite		Amphibole								Plag	Mag	Dol
	Fe		Fe		Si	Al	Mg	Ca	Na	An	Fe		Fe		
2447	0.03–0.11				6.73–7.31	1.50–2.13	2.57–3.47	1.12–1.69	0.84–1.27	2–15					
2519	0.08–0.15		0.28–0.42		7.21–7.54	1.03–1.70	3.20–3.93	1.12–1.63	0.59–1.05	3–10	0.11–0.23		0.09		
2536	0.08–0.16		0.28–0.31		7.39–7.69	0.61–1.39	3.41–4.18	1.29–1.63	0.43–0.89						
2544	0.08–0.17		0.28–0.36		7.06–7.32	1.69–1.92	3.18–3.45	1.07–1.34	0.94–1.11				0.10		
2188	0.08–0.15		0.29		6.97–7.49	1.20–2.05	3.33–3.93	1.28–1.50	0.75–1.03		0.12–0.18		0.09		
					7.77–7.97	1.83–1.92	2.71–2.95	0.04–0.32	1.72–1.91						

Figures for garnet, omphacite and plagioclase represent mol% of end-members; cations p.f.u. as in Table 3.

barroisite (Leake et al., 1997), in part with cores of omphacite. In addition and more rarely, tremolite–actinolite is present and aluminoferropergarnite at

contacts and in cracks of garnet. Glaucophane is a major matrix phase in 2188 where it is present as aggregates of small (0.02–0.15 mm), commonly

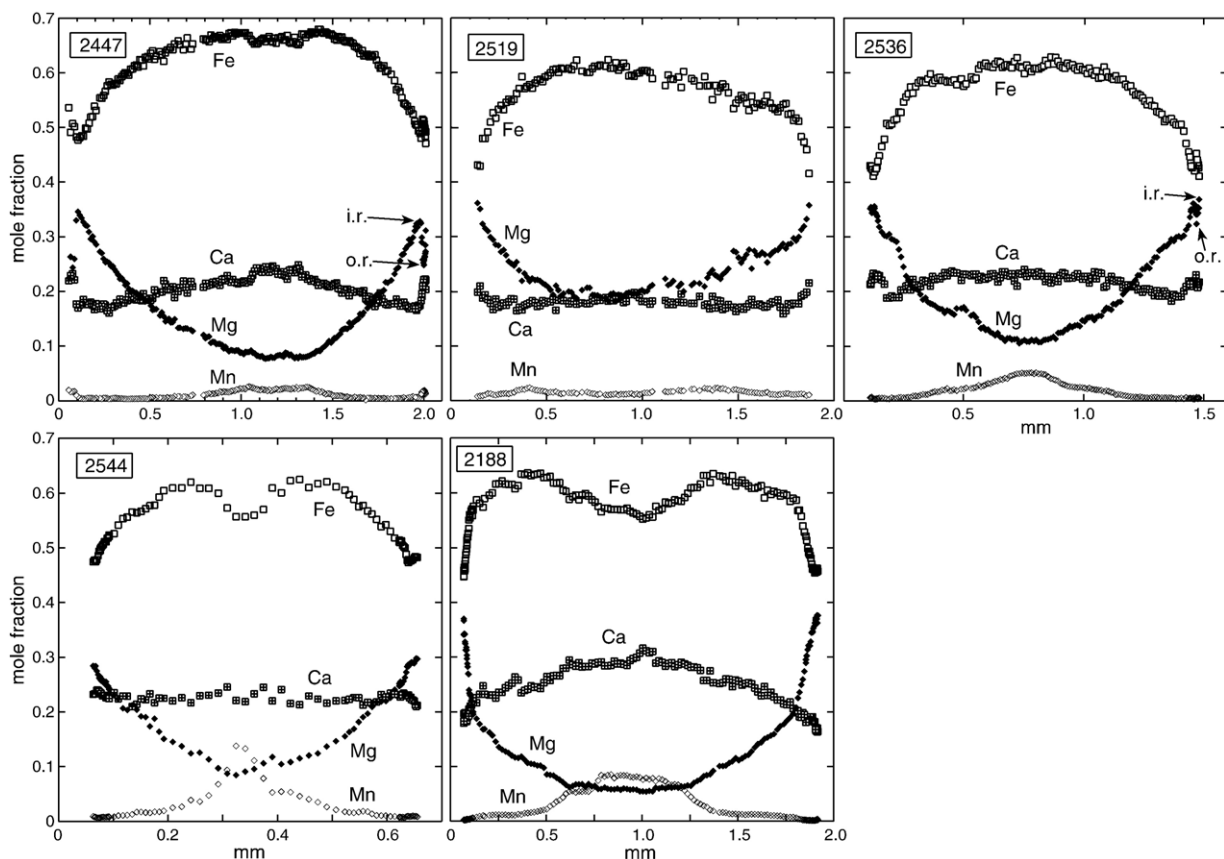


Fig. 4. Representative garnet profiles marked in photomicrographs, Fig. 2. Mole fraction = cation/(Fe+Mg+Ca+Mn); i.r. — inner rim; o.r. — outer rim.

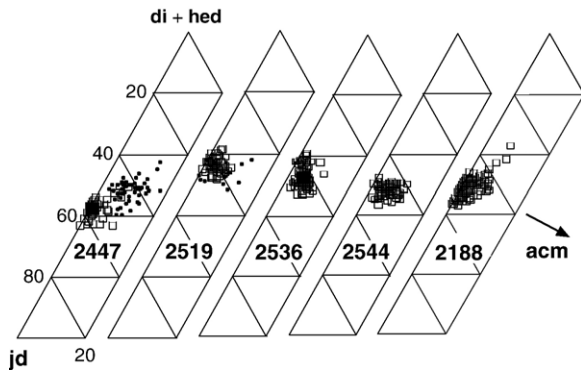


Fig. 5. Omphacite analyses. Open squares — matrix rim and core, points — garnet inclusions; additional symbols in 2447: filled square — mean matrix rim; 2536: filled square — mean matrix rim and core.

ehedral crystals with lower Fe and higher Ca contents towards rim. In 2519 glaucophane is present in very low amounts. *Magnesite* is a matrix phase in 2519 and *dolomite* in 2544.

3. Thermobarometry

Analyses of garnet, omphacite and phengite from several microdomains of each sample were processed according to calibrations 1–4 cited above. THERMOCALC 3.21 was used for calibration 1, combined with mineral activities according to the program AX v 2000, except a $\text{zoi} = 1 - \text{Fe}/(\text{Fe} + \text{Al} - 2)$.

In Fig. 7 results are plotted according to various calibrations for a single microdomain of sample 2544. Analyses for garnet rim, omphacite and phengite are given in Table 2 (Nr. 4, 9, 14). Reactions (1)–(3), intersection points and garnet omphacite Fe–Mg exchange reaction are shown according to programs of calibrations 1–3. In addition the latter reaction following calibrations of Krogh (1988, 2000) and Powell (1985) as well as reaction (1) from calibration 4 calculated with program PET (Dachs, 2004) are plotted. The coesite–quartz equilibrium is shown for comparison following Holland and Powell (1990, 1998) and Berman (1988). Intersection points are situated near

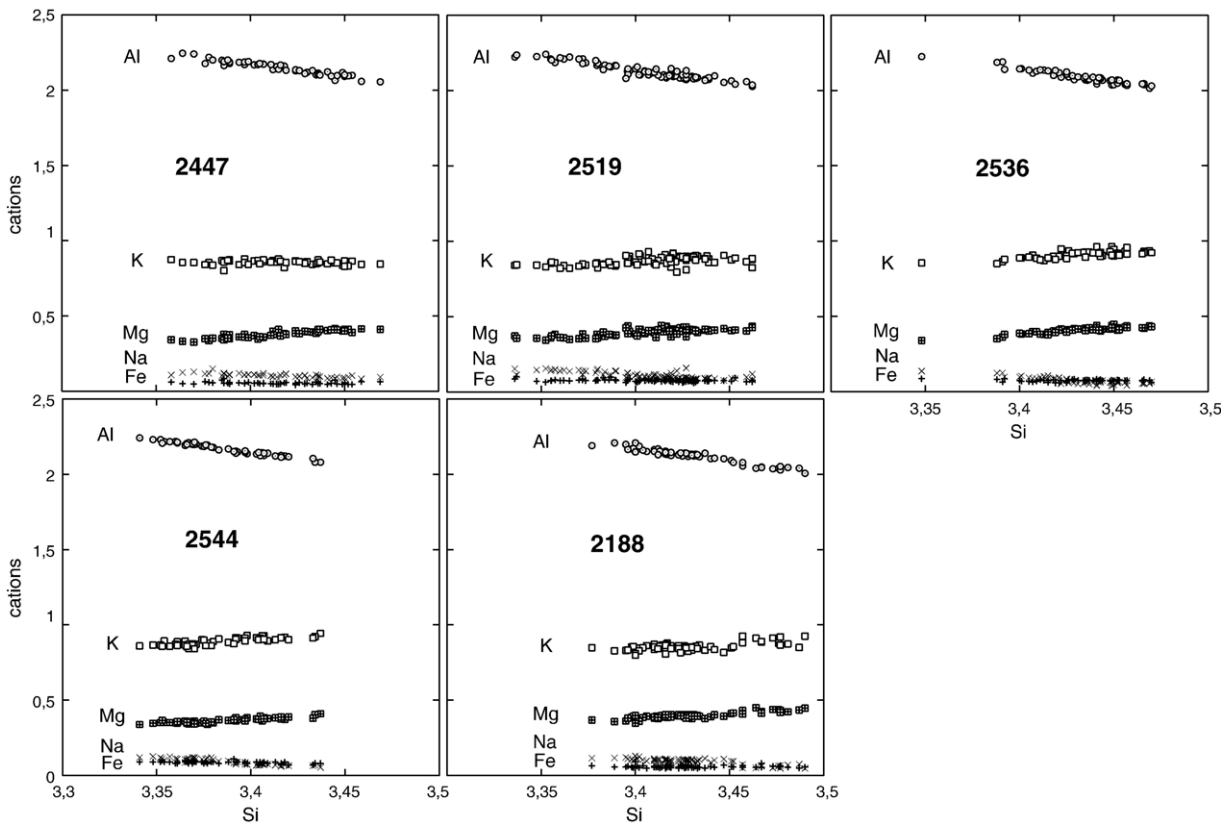


Fig. 6. Phengite analyses with cations per formula unit 11 Oxygen. Tschermak type $\text{Mg} + \text{Si} = 2\text{Al}$ substitution is evident in all samples. Na and K display negative resp. positive correlation with Si, except in sample 2447.

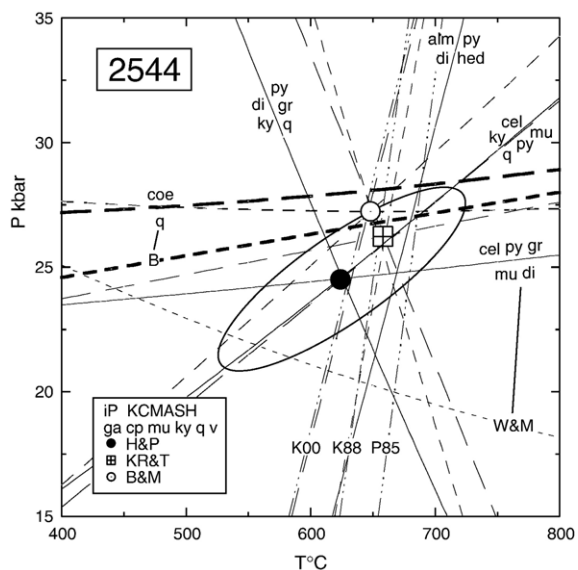


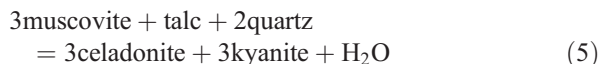
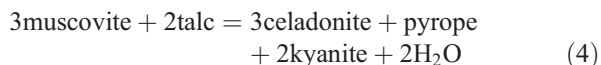
Fig. 7. P – T peak estimates of kyanite eclogite 2544 for selected analyses from Table 2 (garnet 4, omphacite 9, phengite 14). Reactions (1)–(3), intersection point and garnet omphacite Fe–Mg exchange reaction are plotted according to calibrations: 1—Holland and Powell (1998, updated data set Nov 2002) full lines; 2—Krogh Ravna and Terry (2004) long hatched lines; 3—Brandelik and Massonne (2004) short hatched lines; 4—Waters and Martin (1993, updated 1996) very short hatched lines. Garnet omphacite temperatures are according to Krogh (1988, 2000) and Powell (1985), all as dotted hatched lines. Coesite quartz equilibrium is included for comparison (Holland and Powell, 1990, 1998; B—Berman, 1988). Abbreviations: py – pyrope, gr – grossular, alm – almandine, mu – muscovite, cel – celadonite, di – diopside, jd – jadeite, hed – hedenbergite, v – H_2O , others as in Fig. 2.

25 kbar, 620 °C (calibration 1) and at higher P – T values (calibrations 2–3), both latter points already near the coesite–quartz transition.

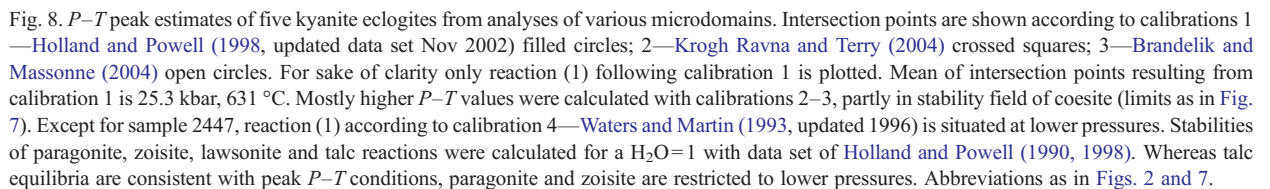
In Fig. 8 intersection points are plotted for several microdomains of each sample calculated by the three programs mentioned above. For all five samples a mean value of 25.3 kbar, 631 °C results from 54 intersection points according to calibration 1. Higher P – T values were generally calculated with calibrations 2–3, in part already in coesite stability field. For the purpose of comparison, quartz was always used as the SiO_2 phase in reactions (2)–(3). Reaction (1) has a relatively low positive dP/dT slope according to programs of calibrations 1–3. In Fig. 8 this is evident in the case of calibration 1. Contrary to this, the earlier commonly used calibration 4 of Waters and Martin (1993) exhibits a negative slope and with the exception of sample 2447 plots at lower pressure. Garnet and omphacite rim compositions together with phengite from microdomains were used for calculations. Due to lack of unambiguous criteria for

coexisting mineral compositions, in some cases mean values of several analyses in microdomains were used. Reversals in garnet rim zoning are mainly observed in samples 2447 and 2536. Using alternative rim compositions result in shifts of intersection points to higher pressure. For 2447 garnet outer rim and 2536 garnet inner rim, mean differences with calibration 1 are +0.8 kbar, –16 °C; +1.1 kbar, +39 °C. Different results between calibrations 1–3 are due to several factors, e.g. different thermodynamic data bases and different mixing models as cited above. Comparison of these calibrations with experiments of reaction (3) by Hermann (2003) would be of interest, but his present data are restricted to an Fe-free system.

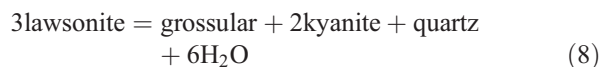
Peak pressure values around 25 kbar for reaction (1) with calibration 1 are not unreasonable, despite a relatively large uncertainty of ~3 kbar. Higher values, commonly calculated from calibrations 2–3 are in part already in coesite stability field. However this is not confirmed from thin sections, because any indications of the former presence of coesite, e.g. radial cracks or polycrystalline quartz in garnet, are not observed. A relatively large spread of intersection points from these five samples or even from different microdomains of one sample and identical calibration is notable. Nowlan et al. (2000) found a large range of peak metamorphic conditions from garnet + omphacite + phengite barometry in eclogites of the UHP unit, Dora Maira Massif, Western Alps. Their comments on this scatter are likewise applicable for Tauern eclogites. In particular, the selection of equilibrium mineral compositions and calculated Fe^{3+} content of omphacite is a source of major uncertainty. Furthermore, equilibria involving talc are applicable in samples 2519, 2536 and 2188



Additional presence of magnesite in samples 2519 and 2188 enables calculation of very low amounts of $x\text{CO}_2 \sim 0.01$. In 2544 dolomite coexists with peak assemblage at the intersection point and $x\text{CO}_2 \sim 0.02$. In view of this, the assumption of pure H_2O for these samples and carbonate absent rocks 2447 and 2536 does not seem unreasonable. A general compatibility of talc equilibria (4)–(5) with intersection points due to calibration 1 is evident from Fig. 8. Additionally, the stability limits of paragonite, zoisite and lawsonite



are plotted, according to following reactions calculated with the [Holland and Powell \(1990, 1998\)](#) data set and pure H₂O



Compared with intersection points, paragonite is restricted to lower pressure. This is compatible with commonly observed corrosion of kyanite by paragonite, presumably during retrograde decompression.

Zoisite high *P* stability is shown for mean compositions and the range of grossular component in garnet rims. For reasons of clarity only two limiting lines of zoisite stability band are plotted. In sample 2188 zoisite is very rare and a single line is drawn according to grossular activity in this microdomain. Zoisite is also restricted to lower pressures than the intersection points. However, in comparison to paragonite, this is only broadly constrained due to considerable variations of grossular activity and the large uncertainty (~5 kbar) for reaction (7). Among other factors, different bulk compositions, e.g. lower Ca/Na ratios, could be responsible for the lower pressure stability of zoisite in 2447 and 2188 compared with other samples. The higher pressure limit is representative of the outer garnet rim and more compatible with a texturally indicated late formation of zoisite. Despite lack of evidence of a discrete replacement reaction, zoisite formation during a later decompression stage is also suggested as mentioned above for paragonite. In the latter case H₂O availability during at least part of the retrograde path is documented due to widespread corrosion of kyanite by paragonite. Other evidences for H₂O presence during this stage are reaction textures suggesting: diopside + talc > tremolite at decreasing pressure (samples 2519, 2536; [Hoschek, 2001](#)); glaucophane + kyanite + grossular/diopside component > barroisite + paragonite (sample 2188); chloritoid overgrowing a.o. paragonite + calcic amphiboles, both products of retrograde breakdown of kyanite + omphacite ([Miller and Konzett, 2003](#)). Observation of post kinematic growth of hydrous phases, partly with large euhedral shapes, postulates availability of a H₂O rich fluid. The intimate association of metabasites with metasediments in the Tauern Window could have involved hydrous fluid influx into eclogites during

exhumation. From a similar lithologic tectonic area, Trescolmen, Adula nappe, Swiss Alps, the influx of limited amounts of H₂O into eclogite bodies was advocated. Peak conditions of stage 1 at 25 kbar, 635 °C were followed by decompression to stage 2 at 19 kbar, 650 °C and a later stage 3 at amphibolite to greenschist facies conditions. Fluid influx from surrounding metapelitic rocks into eclogites between stage 1 and 2 was responsible for growth of e.g. paragonite and amphibole ([Zack et al., 2001, Fig. 1](#); [Zack et al., 2002](#)). Alternatively if zoisite was formed at peak conditions of Tauern eclogites in the assemblage garnet + omphacite + phengite + kyanite + quartz, calculated lower *P* conditions could be due to several factors. Amongst others, to uncertainties of thermodynamic data or solution models. According to calibration 1 program, reactions (1) and (7) are associated with *sdP* ~ 3 and ~ 5 kbar, which is large compared with *sdP* ~ 0.7 kbar for paragonite stability, reaction (6).

Lawsonite is a probable phase on the prograde path according to some pseudomorphs in garnet of samples 2447 and 2519. Intersection points are partly situated in the lawsonite field of [Fig. 8](#). This seems at variance with the absence of this phase in matrix assemblages. However, lawsonite reactions in these rocks probably involved additional phases (e.g. omphacite), but only the maximum stability of lawsonite according to reactions (8)–(9) is shown.

4. *P–T* pseudosection

In another attempt to reconstruct metamorphic conditions, pseudosections in a simplified NCFMASH system were calculated for sample 2447 at H₂O excess conditions. Neglect of K₂O component seems justified because phengite is the only stable phase around peak conditions. Ti is present in rutile only and the Mn content of garnet is very low. THERMOCALC 3.1, updated data set Sept 1999 and solid solution models of [Wei et al. \(2003\)](#) were used. Changes in bulk composition due to garnet fractionation ([Stüwe, 1997](#); [Marmo et al., 2002](#)) were improved in comparison with [Hoschek \(2004\)](#). Calculated amounts of newly formed garnet were subtracted from bulk composition along selected prograde *P–T* paths A, B and B* after each *P–T* increment (maximum d*T* 10°, maximum d*P* 400 bar). A similar approach was used by [Konrad-Schmolke et al. \(2005\)](#). For example, along path B initial composition a) ends with composition b) at peak conditions of 650 °C, 23.7 kbar. A strong modification of pseudosection due to bulk composition change is evident by comparing [Fig. 9a](#) and b.

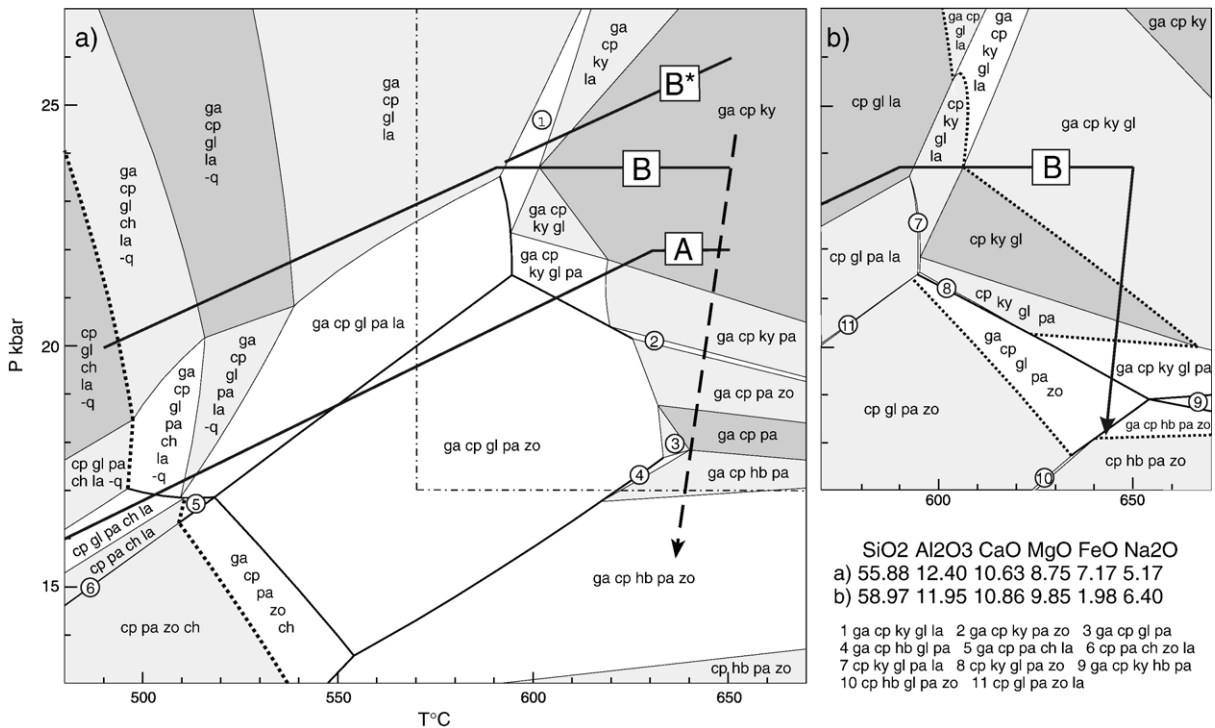


Fig. 9. THERMOCALC P – T pseudosections for sample 2447 in NCFMASH system at H₂O excess conditions, data set [Holland and Powell \(1998, updated 1999\)](#), solid solution models of [Wei et al. \(2003\)](#). Bulk composition a) in mol% was used at start of P – T path in a garnet-free assemblage. Composition b) results from fractional garnet crystallization until end of path B in peak assemblage garnet+omphacite+kyanite+quartz (+ glaucophane) at 650 °C, 23.7 kbar. Strong modification of pseudosections due to bulk composition change is evident by comparing Fig. 9a and b. A retrograde decompression path is indicated, with formation of garnet+omphacite+paragonite+zoisite+hornblende+quartz, calculated with composition b). This corresponds to the observed assemblage in this sample with kyanite as relict and phengite as additional phase. Abbreviations: la – lawsonite, -q – quartz-free assemblage, others as in [Figs. 2 and 7](#).

Glaucophane is an additional phase to the peak assemblage garnet+ omphacite+ kyanite in [Fig. 9b](#). No glaucophane was observed in this sample despite numerous analyses, possibly due to a hornblende forming reaction during a later decompression stage.

Calculated modes and garnet zonation are plotted in [Figs. 10 and 11](#). Mole=mode/oxide sum in mineral formula, as defined in THERMOCALC. Garnet radius was calculated with the assumption of spherical growth. Normalization of calculated radius at the end of P – T path was done in comparison with the observed garnet profile of sample 2447 ([Fig. 4](#)). A better match for paths B and B* than for path A is evident, particularly with regard to observed relatively high pyrope and low grossular contents. Better accordance at higher pressures around 25 kbar is also consistent with thermobarometry based on calibration 1. A distinct reversal of prograde zonation is observed at the outermost garnet rim. Simulation of a retrograde event was done with bulk composition b) at peak conditions of path B. Garnet composition was calculated at low pressure end of this

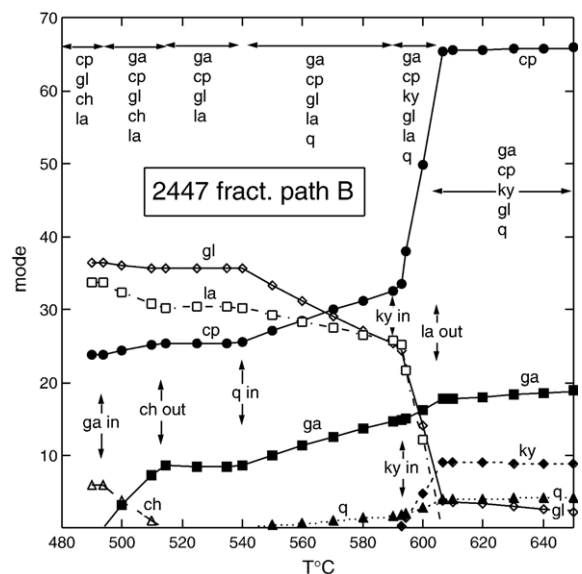


Fig. 10. Calculated modes along prograde P – T path B in [Fig. 9](#).

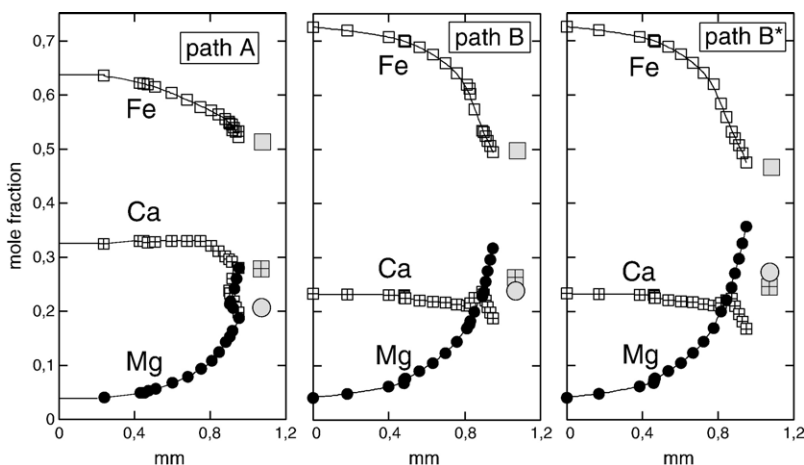


Fig. 11. Calculated garnet zoning profiles along prograde P – T paths A, B and B* in Fig. 9. Comparison with measured garnet zonation in sample 2447 (Fig. 4) reveals a better match for paths B and B* than for path A, particularly with regard to relatively high pyrope and low grossular contents observed. A retrograde reversal of outer garnet rim was simulated with bulk composition b) and decompression as shown in Fig. 9b. The final assemblage garnet+omphacite+paragonite+zoisite+hornblende+quartz+H₂O corresponds to the observed matrix assemblage with relict kyanite and additional phengite. Calculated garnet composition is shown at the right side of Fig. 11. However, these symbols are not drawn to radius scale because garnet is consumed along the retrograde path. Reversal of calculated prograde trends of pyrope and grossular is in qualitative accordance with observed profile.

path (Fig. 9b) in the assemblage garnet+omphacite+paragonite+zoisite+hornblende+quartz+H₂O. This corresponds to the observed matrix assemblage, assuming kyanite as relict phase. Results are plotted as symbols on the right side in Fig. 11. However, this is not drawn to radius scale because of garnet consumption along the retrograde path. Reversal of the calculated prograde trend of pyrope and grossular is in qualitative accordance with the observed profile.

5. Conclusions

- 1) Calculated pressure based on reaction (1) in the assemblage garnet+omphacite+phengite is about 25 kbar according to calibration 1 of Holland and Powell (1998, updated database 2002). In most cases calibration 2 (Krogh Ravna and Terry, 2004) and calibration 3 (Brandelik and Massonne, 2004) result in higher values, in part in the stability field of coesite. In contrast calibration 4 (Waters and Martin, 1993; updated 1996) mostly shows lower values. Additional presence of kyanite+quartz in this metamorphic peak assemblage enables calculation of reactions (2)–(3) and an intersection point. Calibration 1 results in temperature of about 630 °C, whereas in part higher temperatures result from both other calibrations 2–3.
- 2) Different P – T results for the metamorphic peak assemblage garnet+omphacite+phengite+kyanite+quartz are due to different thermodynamic data

sets and solid solution models in calibrations 1–3. A relatively large spread in P – T values from different microdomains of the same sample and calibration is mostly due to variations in selected coexisting mineral compositions and calculated Fe³⁺ content of omphacite.

- 3) Presence of talc in some samples is consistent with these P – T values at high H₂O activities. In contrast, stability limits of zoisite and paragonite are situated at lower pressures and suggest later formation during a decompression stage. However according to calibration 1 program, relatively large uncertainties are associated with reaction (1) $\text{sd}P \sim 3$ kbar and the stability of zoisite, reaction (7) $\text{sd}P \sim 5$ kbar, compared with stability of paragonite, reaction (6) $\text{sd}P \sim 0.7$ kbar.
- 4) THERMOCALC pseudosections in NCFMASH system were constructed with incorporation of fractional crystallization of garnet. A better accordance of observed and calculated garnet zonation is achieved for P – T paths with a peak pressure of about 25 kbar compared with values of lower pressure. This is consistent with thermobarometry based on calibration 1 of Holland and Powell (1990, 1998).

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References

- Berman, R.G., 1988. Internally consistent thermodynamic data for minerals in the system Na₂O–K₂O–CaO–MgO–FeO–Fe₂O₃–Al₂O₃–SiO₂–TiO₂–H₂O–CO₂. *Journal of Petrology* 29, 445–522.
- Brandelik, A., Massonne, H.-J., 2004. PTGIBBS—an EXCEL Visual Basic program for computing and visualizing thermodynamic functions and equilibria of rock forming minerals. *Computers & Geosciences* 30, 909–923.
- Carswell, D.A., O'Brien, P.J., Wilson, R.N., Zhai, M., 1997. Thermobarometry of phengite-bearing eclogites in the Dabie Mountains of central China. *Journal of Metamorphic Geology* 15, 239–252.
- Dachs, E., 1986. High-pressure mineral assemblages and their breakdown-products in metasediments South of the Grossvenediger, Tauern Window, Austria. *Schweizerische Mineralogische und Petrographische Mitteilungen* 66, 145–161.
- Dachs, E., 2004. PET: petrological elementary tools for Mathematica: an update. *Computers & Geosciences* 30, 173–182.
- Franz, G., Spear, F.S., 1983. High pressure metamorphism of siliceous dolomites from the Central Tauern Window, Austria. *Schweiz. American Journal of Science* 283-A, 396–413.
- Ganguly, J., Cheng, W., Tirone, M., 1996. Thermodynamics of aluminosilicate garnet solid solution: new experimental data, an optimized model, and thermometric applications. *Contributions to Mineralogy and Petrology* 126, 137–151.
- Glodny, J., Ring, U., Kühn, A., Gleissner, P., Franz, G., 2005. Crystallization and very rapid exhumation of the youngest Alpine eclogites (Tauern Window, Eastern Alps) from Rb/Sr mineral assemblage analysis. *Contributions to Mineralogy and Petrology* 149, 699–712.
- Hermann, J., 2003. Experimental evidence for diamond facies metamorphism in the Dora Maira massif. *Lithos* 70, 163–182.
- Holland, T.J.B., 1979. High water activities in the generation of high pressure kyanite eclogites of the Tauern Window, Austria. *Journal of Geology* 87, 1–27.
- Holland, T.J.B., 1990. Activities of components in omphacitic solid solutions. An application of Landau theory to mixtures. *Contributions to Mineralogy and Petrology* 105, 446–453.
- Holland, T.J.B., Powell, R., 1990. An enlarged and updated internally consistent thermodynamic data set with uncertainties and correlations: the system K₂O–Na₂O–CaO–MgO–MnO–FeO–Fe₂O₃–Al₂O₃–TiO₂–SiO₂–C–H₂–O₂. *Journal of Metamorphic Geology* 8, 89–124.
- Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology* 16, 309–343.
- Hoschek, G., 2001. Thermobarometry of metasediments and metabasites from the eclogite zone of the Hohe Tauern, Eastern Alps, Austria. *Lithos* 59, 127–150.
- Hoschek, G., 2004. Comparison of calculated P–T pseudosections for a kyanite eclogite from the Tauern Window, Eastern Alps, Austria. *European Journal of Mineralogy* 16, 59–72.
- Konrad-Schmolke, M., Handy, M.R., Babist, J., O'Brien, P.J., 2005. Thermodynamic modelling of diffusion controlled garnet growth. *Contributions to Mineralogy and Petrology* 149, 181–195.
- Krogh, E.J., 1988. The garnet–clinopyroxene Fe–Mg geothermometer — a reinterpretation of existing experimental data. *Contributions to Mineralogy and Petrology* 99, 44–48.
- Krogh, E.J., 2000. The garnet–clinopyroxene Fe²⁺–Mg geothermometer: an updated calibration. *Journal of Metamorphic Geology* 18, 211–219.
- Krogh Ravna, E.J., Terry, M.P., 2004. Geothermobarometry of UHP and HP eclogites and schists — an evaluation of equilibria among garnet–clinopyroxene–kyanite–phengite/coesite/quartz. *Journal of Metamorphic Geology* 22, 579–592.
- Kurz, W., Neubauer, F., Dachs, E., 1998. Eclogite meso- and microfabrics. implications for the burial and exhumation history of eclogites in the Tauern Window (Eastern Alps) from P–T–d paths. *Tectonophysics* 285, 183–209.
- Leake, B.E., Woolley, A.R., et al., 1997. Nomenclature of amphiboles: report of the subcommittee on amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names. *American Mineralogist* 82, 1019–1037.
- Marmo, B.A., Clarke, G.L., Powell, R., 2002. Fractionation of bulk rock composition due to porphyroblast growth: effects on eclogite facies mineral equilibria, Pam Peninsula, New Caledonia. *Journal of Metamorphic Geology* 20, 151–165.
- Massonne, H.-J., Kopp, J., 2005. A low variance mineral assemblage with talc and phengite in an eclogite from the Saxonian Erzgebirge, Central Europe, and its P–T evolution. *Journal of Petrology* 46, 355–375.
- Massonne, H.-J., Szpurka, Z., 1997. Thermodynamic properties of white micas on the basis of high pressure experiments in the systems K₂O–MgO–Al₂O₃–SiO₂–H₂O and K₂O–FeO–Al₂O₃–SiO₂–H₂O. *Lithos* 41, 229–250.
- Miller, C., 1978. Chemismus und phasenpetrologische Untersuchungen der Gesteine aus der Eklogitzone des Tauernfensters, Österreich. *Tschermak's Mineralogische und Petrographische Mitteilungen* 24, 221–277.
- Miller, Ch., Konzett, J., 2003. Magnesiochloritoid–talc–garnet assemblages from the Tauern Window, Eastern Alps, Austria: high-pressure metamorphosed oceanic hydrothermal veins. *Geophysical Research Abstracts* 5, 05206.
- Newton, R.C., Haselton, H.T., 1981. Thermodynamics of the garnet–plagioclase–Al₂SiO₅–quartz geobarometer. In: Newton, R.C., Navrotsky, A., Wood, B.J. (Eds.), *Thermodynamics of Minerals and Melts*. Springer, New York, pp. 131–147.
- Nowlan, E.U., Schertl, H.-P., Schreyer, W., 2000. Garnet–omphacite–phengite thermobarometry of eclogites from the coesite-bearing unit of the southern Dora-Maira Massif, Western Alps. *Lithos* 52, 197–214.
- O'Brien, P.J., Zotov, N., Law, R., Khan, M.A., Jan, M.Q., 2001. Coesite in Himalayan eclogite and implications for models of India–Asia collision. *Geology* 29, 435–438.
- Powell, R., 1985. Regression diagnostics and robust regression in geothermometer/geobarometer calibration: the garnet–clinopyroxene geothermometer revisited. *Journal of Metamorphic Geology* 2, 33–42.
- Powell, R., Holland, T., Worley, B., 1998. Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC. *Journal of Metamorphic Geology* 16, 577–588.
- Proyer, A., Dachs, E., McCammon, C., 2004. Pitfalls in geothermobarometry of eclogites: Fe³⁺ and changes in the mineral chemistry

- of omphacite at ultrahigh pressures. *Contributions to Mineralogy and Petrology* 147, 305–318.
- Schmid, R., Franz, L., Oberhänsli, R., Dong, S., 2000. High-Si phengite, mineral chemistry and P–T evolution of ultra high pressure eclogites and calc silicates from Dabie Shan, eastern China. *Geological Journal* 35, 185–207.
- Schmidt, M.W., 1993. Phase relations and compositions in tonalite as a function of pressure: an experimental study at 650 °C. *American Journal of Science* 293, 1011–1060.
- Selverstone, J., Franz, G., Thomas, S., Getty, S., 1992. Fluid variability in 2 GPa eclogites as an indicator of fluid behavior during subduction. *Contributions to Mineralogy and Petrology* 112, 341–357.
- Song, S.G., Yang, J.S., Xu, Z.Q., Liou, J.G., Shi, R.D., 2003. Metamorphic evolution of the coesite-bearing ultrahigh-pressure terrane in the North Qaidam, Northern Tibet, NW China. *Journal of Metamorphic Geology* 21, 631–644.
- Spear, F.S., Franz, G., 1986. P–T evolution of metasediments from the eclogite zone, south-central Tauern Window, Austria. *Lithos* 19, 219–234.
- Stöckert, B., Massonne, H.-J., Nowlan, E.U., 1997. Low differential stress during highpressure metamorphism. The microstructural record of a metapelite from the Eclogite Zone, Tauern Window, Eastern Alps. *Lithos* 41, 103–118.
- Stüwe, K., 1997. Effective bulk composition changes due to cooling: a model predicting complexities in retrograde reaction textures. *Contributions to Mineralogy and Petrology* 129, 43–52.
- Wain, A.L., Waters, D.J., Austrheim, H., 2001. Metastability of granulites and processes of eclogitisation in the UHP region of western Norway. *Journal of Metamorphic Geology* 19, 607–623.
- Waters, D.J., Martin, H.N., 1993. Geobarometry in phengite-bearing eclogites. *Terra Abstracts* 5, 410–411.
- Wei, C.J., Powell, R., Zhang, L.F., 2003. Eclogites from the south Tienshan, NW China: petrological characteristic and calculated mineral equilibria in the Na₂O–CaO–FeO–MgO–Al₂O₃–SiO₂–H₂O system. *Journal of Metamorphic Geology* 21, 163–179.
- Zack, T., Rivers, T., Foley, S.F., 2001. Cs–Rb–Ba systematics in phengite and amphibole: an assessment of fluid mobility at 2.0 Gpa in eclogites from Trescolmen, Central Alps. *Contributions to Mineralogy and Petrology* 140, 651–669.
- Zack, T., Foley, S.F., Rivers, T., 2002. Equilibrium and disequilibrium trace element partitioning in hydrous eclogites (Trescolmen, Central Alps). *Journal of Petrology* 43, 1947–1974.
- Zhang, J.X., Yang, J.S., Mattison, C.G., Xu, Z.Q., Meng, F.C., Shi, R. D., 2005. Two contrasting eclogite cooling histories, North Qaidam HP/UHP terrane, western China: petrological and isotopic constraints. *Lithos* 84, 51–76.
- Zimmermann, R., Hammerschmidt, K., Franz, G., 1994. Eocene high pressure metamorphism in the Penninic units of the Tauern Window (Eastern Alps): evidence from ⁴⁰Ar–³⁹Ar dating and petrological investigations. *Contributions to Mineralogy and Petrology* 117, 175–186.