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Pseudosection modelling for a selected eclogite body from the Koralpe (Hohl), Eastern Alps

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Abstract In the Kor-, Saualpe and Pohorje regions of the Eastern Alps eclogite bodies occur within metapelitic gneisses. The bodies are between 1 meter and several hundreds of meters in size and some of them were defined by Haüy (1822) as the type locality for the rock type "eclogite". A growing body of petrological work has documented the metamorphic evolution of the metapelites surrounding the eclogites. However, few phase diagrams have been constructed for the eclogite bodies themselves. Here we use recently available activity models for amphiboles to present new thermodynamic pseudosections for the Hohl locality of the Koralpe eclogites. We show that this eclogite reached peak conditions in a narrow *PT* field obliquely oriented in *PT* space between 16.5 and 20.5 kbar and 620°C to 720°C and that its metamorphic evolution was likely to have occurred under water saturated conditions. We conclude that eclogite and the surrounding metapelites have certainly undergone the same metamorphic peak in Eo-alpine time. Comparison of our results with different *PT* estimates on the eclogite from Pohorje, suggest that a *PT* gradient from Koralpe to Pohorje is likely.

Introduction

In many terrains around the world eclogites have been studied to understand the processes that form and exhume high pressure metamorphic rocks to the surface of Earth (e.g. Monte Rosa nappe western Alps: Lapen et al. (2006); Franciscan of California: Moore and Blake (1989); Bohemian massif: Stipska et al. (2006)). A series of models have been developed that are used to explain this exhumation and that of their host rocks (see review of Platt 1993 or Ring et al. 1999). Some of the classic models include those of England and Holland (1979) who suggested that eclogites may be exhumed together with their carbonaceous hosts due to their buoyancy; that of Chemenda et al. (1996) who suggested that the exhumation may be due to extrusion from the more dense mantle wedge during subduction and, more recently, that of Froitzheim et al. (2003) who suggested a model where the extraction of a mantle wedge during subduction emplaces lower plate rocks into the middle crust.

The Kor-Saualpe-Pohorje region of the eastern Alps is one of the classic eclogite localities in the world and there are about 200 eclogite bodies that are embedded in a voluminous sequence of garnet micaschists (Fig. 1). While the *PT* estimates for the metapelitic hosts are well-constrained in many locations of the Saualpe and Koralpe (e.g. Stüwe and Powell 1995; Thöni and Miller 1996; Miller and Thöni 1997; Tenczer and Stüwe 2003; Faryad and Hoinkes 2003), the formation conditions or *PT* paths of the eclogites are not so well known. Indeed, there has been some debate about the relationship between the formation conditions of the eclogites in the Koralpe and in its southernmost extension—the Pohorje massif of Slovenia (Fig. 1): While Janak et al. (2004) argue for some 30 kbar in the Pohorje massif and 20 kbar in the Koralpe (thus inferring a field gradient of some 10 kbar over 50 km lateral distance), Miller and Konzett (2005) argue that today's geobarometry may not be well enough calibrated to allow the interpretation of such a field gradient. In fact, Miller and Konzett (2005) and Miller et al. (2007) argue that Kor-

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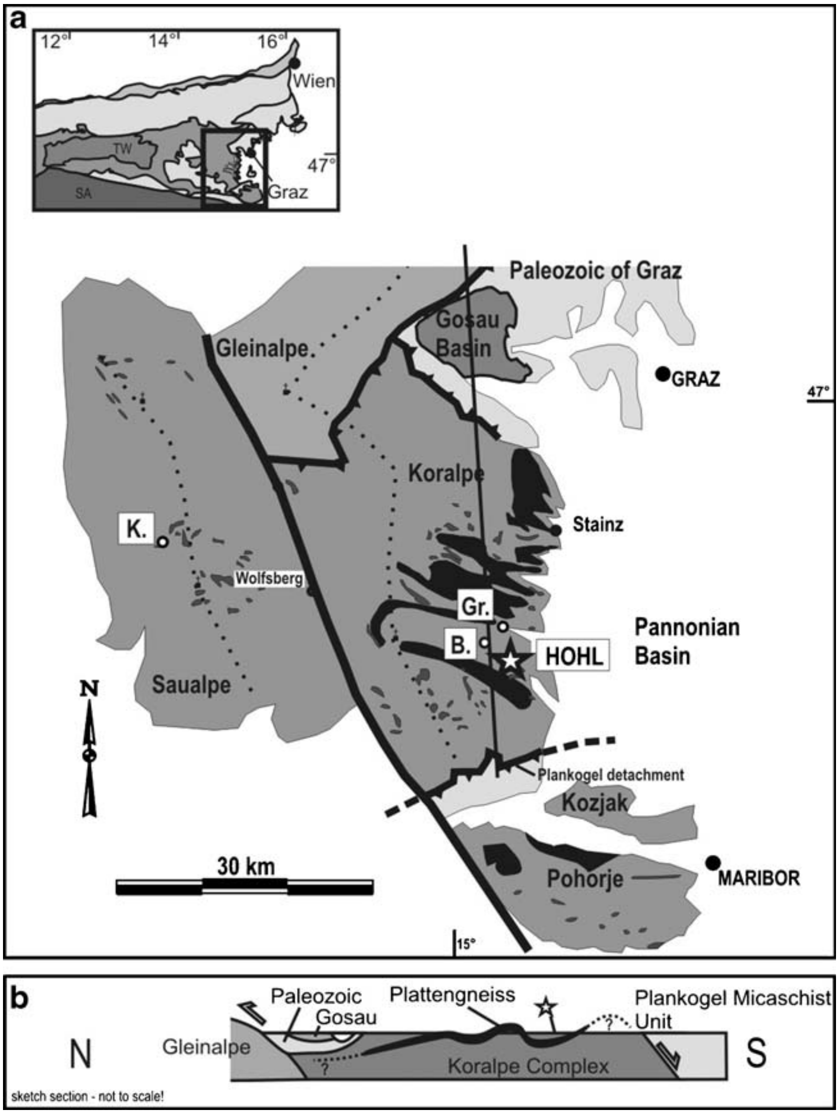


Fig. 1 Sketch of geologic map showing the Kor-Saualpe-Pohorje region in the Eastern Alps (modified after Putz et al. 2006). On the inset TW stands for the Tauern Window and SA for the Southern Alps. The Austroalpine nappes are shown as the shaded units. **a** Plattengneiss is shown in black and eclogite bodies in dark grey. The line shows the profile studied by Tenczer and Stüwe (2003). Approximate watersheds are indicated as dotted lines. The sample K19 location (Hohl) is shown by a white star (GPS coordinates: N 46°43′32″, E 15° 08′44″). The locations K., Gr. and B. correspond respectively to Kirchberg (Fig. 2c), Gressenberg (Fig. 2b) and Bärofen (Fig. 2a) localities. **b** North-south section from Gleinalpe dome to Plankogel detachment showing the position of the Plattengneiss through the Koralpe region. As in **(a)** the star represents the location of K19 sample studied here

Saualpe-Pohorje eclogites are more likely to be characterised by 24–28 kbar but that—within the uncertainty of these estimates—these three regions are indistinguishable and may have experienced similar metamorphic pressures. Miller and Konzett (2005) are correct: the large uncertainties associated with eclogite-barometry are due to the fact that most calibrated individual barometers are associated with standard deviations of the derived pressures of about 2–4 kbars. Conversely, more accurate pseudosections have been difficult to calculate as until recently there have been no activity models for amphiboles, a common phase of the peak metamorphic assemblage in the Koralpe-Saualpe region. For that very reason, thermodynamic modelling of mafic rocks has long been neglected in general. However, the complex activity models required for amphiboles have successively been improved over the last years (Dale et al. 2005; Diener et al. 2007) and pseudosection modelling of mafic rocks has therefore now become a wide open field of research (e.g. Stipska and Powell 2005).

In this contribution we make use of the new activity models for amphiboles (recently published by Diener et al. 2007) to construct refined pseudosections for a selected mafic body from the Koralpe. The pseudosections we present are for a sample from what is known as the 'Low-Mg eclogite from Hohl' (sample K19) and will be presented here as a basis for further discussion. It is shown that metamorphic conditions of the eclogites are comparable to (or only slightly higher than) those published for the surrounding metapelites and that the *PT* path is consistent with both mafic and pelitic rocks having experienced a common evolution during the Eo-alpine metamorphic cycle. Our conclusion foreshadows that a strong pressure increase of the peak metamorphic conditions of the eclogites towards the Pohorje Mountains is likely.

The mineral abbreviations used in the following figures and below in the article are: ky = kyanite; pl = plagioclase; q = quartz; g = garnet; di = diopsidic clinopyroxene; o = omphacitic clinopyroxene; amph = amphibole (hb = hornblende; act = actinolite; gl = glaucophane); cz = clinozoisite; ru = rutile; sph = sphene; law = lawsonite; opx = orthopyroxene; lm = ilmenite; ta = talc; chl = chlorite.

Geological setting

The Koralpe complex is part of the crystalline basement of the Austroalpine nappe complex of the Eastern Alps. Together with the Saualpe complex to the west it forms the largest area in the Alps that experienced high pressure metamorphism during the Cretaceous Eo-alpine event. It is predominantly made up of metasedimentary rocks but also contains eclogite bodies (Fig. 1). Haüy (1822) was the first to describe these eclogites and defined them as the type locality for this rock type. The eclogites occur as bodies between one meter and few hundred meters in size and there is a total of about 200 occurrences of such bodies (Fig. 1). In the field, the proportion of eclogite to metapelite is negligible and blueschists, serpentinite or ophicalcite are absent. From the metapelites, it is known that the Saualpe-Koralpe region also experienced Permian metamorphism prior to the Eo-alpine event (e.g. Miller and Thöni 1997). Schuster and Stüwe (2008) showed that the spatial distribution of the Permian metamorphic event is similar to the distribution of the later Eo-alpine event so that the Koralpe region is also characterised by Permian low-P metamorphism underlying the Eo-alpine signature (Tenczer et al. 2006). The eclogites themselves have Permian intrusive ages, but no distinct Permian metamorphic signature (e.g. Thöni and Jagoutz 1993; Thöni et al. 2008).

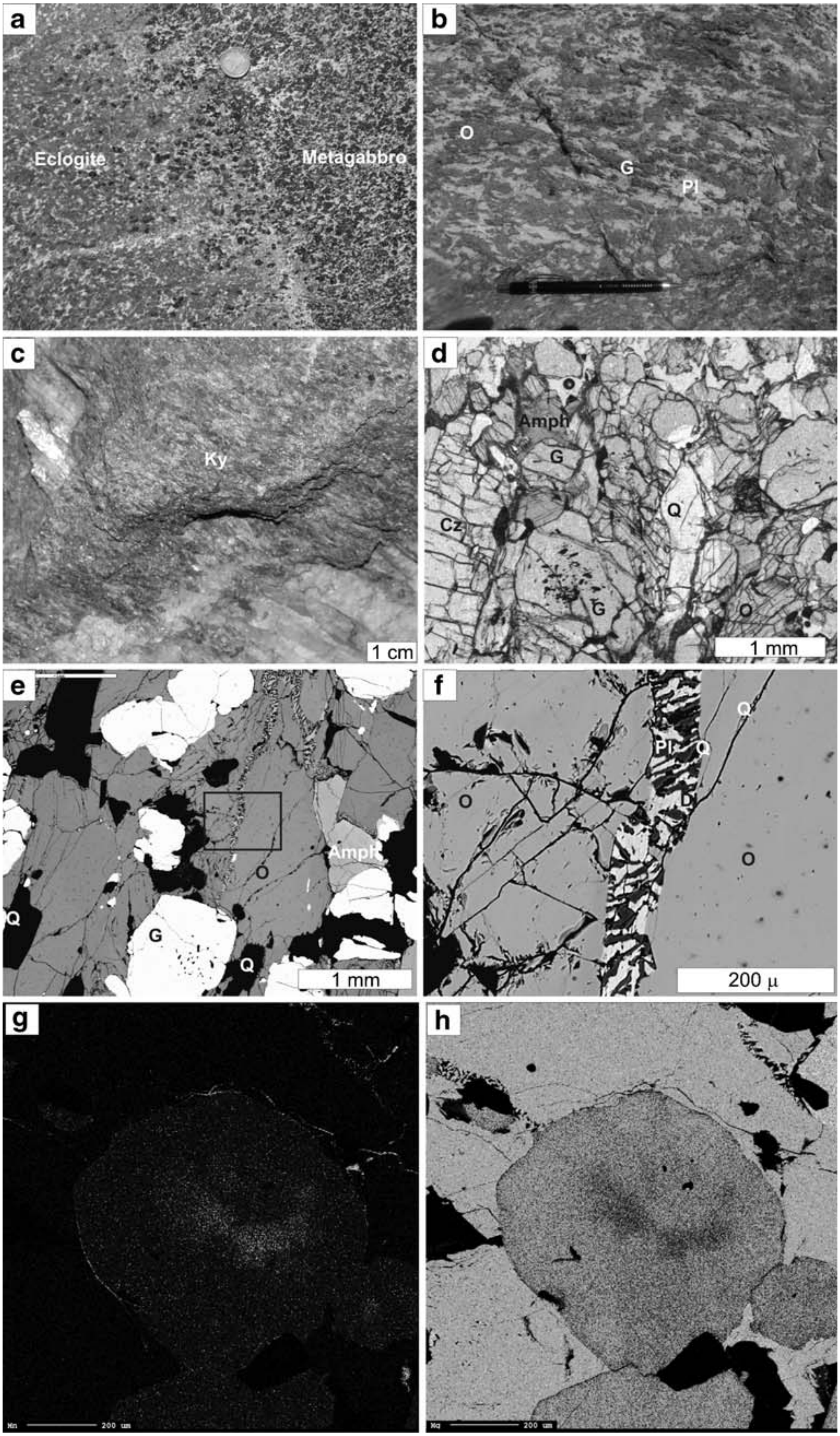
During the Eo-alpine event the Saualpe-Koralpe region was substantially deformed and metamorphosed. Tenczer and Stüwe (2003) documented the Eo-alpine field gradient across the Koralpe-Pohorje region and showed that the metamorphic grade of the metapelites decreases continuously to the north and abruptly to the south: to the north, the grade drops from eclogite facies (15 kbar and 700°C) to mid amphibolite facies conditions (10 kbar and 575°C Tenczer and Stüwe 2003) in the Gleinalpe complex—about 30 km further north (Fig. 1). In the south, the abrupt change occurs across the so-called Plankogel detachment (Kurz et al. 2002), which separates the Saualpe-Koralpe region from the Plankogel-Micaschist Unit (Fig. 1). Also, during this event, a crustal scale shear zone formed in the centre of the region: the Plattengneiss shear zone. This shear zone is the largest in the Eastern Alps and Kurz et al. (2002) interpreted it to be responsible for the (partial) exhumation of the high-pressure rocks from the Saualpe-Koralpe region. However, three-dimensional modelling of the shear zone showed that eclogite bodies occur both above and below the shear zone (Putz et al. 2006), so that this model is still open to discussion. Froitzheim et al. (2003) presented slab extraction as an alternative interpretation for exhumation of the high pressure rocks. It is possible that the Plattengneiss is a potential example for this mechanism, being a suture zone for a crustal section that was southward extracted together with a mantle wedge (Roffeis et al. 2008).

The eclogites

The eclogitic protoliths (metabasites) were emplaced into sedimentary rocks during a Permian rifting event as gabbros and possibly also as volcanics (Thöni and Jagoutz 1993) and experienced eclogite facies metamorphism in the Cretaceous between 95 and 88 Ma (Thöni and Miller 1996; Miller and Thöni 1997; Thöni 2006). However, the tectonic setting of the high pressure metamorphism and subsequent exhumation remain a matter of debate. Several authors propose an intracontinental subduction setting for Eo-Alpine high pressure metamorphism in the Austroalpine basement (Thöni and Jagoutz 1993; Neubauer et al. 2000; Janak et al. 2004; Schuster and Kurz 2005). An argument of Janak et al. (2004) is the existence of a southward increase of the metamorphic conditions of the eclogites from the Koralpe to even higher pressures in the Pohorje Mountains. However, Tenczer and Stüwe (2003) showed that the metamorphic field gradient drops dramatically between the Koralpe and the Plankogel series. Miller and Konzett (2005) argued that conventional geobarometry is not well-enough constrained yet to infer details of the field gradient from the metabasites. As such, several questions on the relationship between mafic and pelitic rocks, the field gradient as a whole and its tectonic setting remain open. In any case, the initial stages of the rapid exhumation have occurred at 90–88 Ma (Miller et al. 2005a; Thöni 2006; Thöni et al. 2008) and final exhumation is documented by fission track ages to have occurred around 50–40 Ma from the entire Koralpe region (Hejl 1997).

Geochemically, the Koralpe eclogites have two types of N-MORB precursors: low-Mg and high-Mg bulk compositions (Miller et al. 2007). The difference between these compositions relates to the igneous differentiation of the protolith: the high-Mg rocks represent a cumulate gabbro (Fig. 2a, b, c), while the low-Mg eclogites may represent non-cumulate gabbro (Fig. 2d, e, f). The bulk composition of the low-Mg precursors is lower in MgO and Cr_2O_3 but higher in TiO_2 and incompatible elements than that of the

Fig. 2 Representative photographs of the eclogites from the Kor- and Saualpe. **a**–**c** Examples of high-Mg metagabbro/eclogite. **d**–**h** Examples of low-Mg eclogite from Hohl (K19 sample). **a** Gabbro–eclogite transition in a rock from the Bärofen gabbro, Koralpe. Crystals in the left hand part of the image are omphacite and garnet. **b** Field appearance of an eclogite with gabbroic texture from Gressenberg, Koralpe. **c** Macroscopic sample showing big tablets of blue/green kyanite from Kirchberg locality. **d** Light microscope photograph showing big crystals of clinozoisite, garnet, omphacite, quartz and amphibole following the foliation; from Hohl (sample K19). **e** BSE image of K19 sample showing peak paragenesis of o - g - q - amph - cz - ru (cz and ru are not within field of view). **f** detail of **(e)**, showing very minor formation of retrograde symplectite (di - pl - q). **g** Mn and **h** Mg distribution maps of garnet from low-Mg eclogite show a higher Mn (the visible variation in grey shade from core to rim corresponds to 1–2 wt.% change) and lower Mg (2–3 wt. % compare to the rim) content in the core of the garnet



high-Mg rocks. Petrographically, the low-Mg eclogites contain coarse grained omphacite, garnet, quartz and amphiboles as well as little clinozoisite and rare kyanite (Fig. 2d, e, f, g, h). Amphibole may occur as part of the peak assemblage and as a product of re-equilibration during decompression (e.g. Miller and Thöni 1997). In contrast, the high-Mg eclogites always contain substantial amounts of blue kyanite but have otherwise a similar Eo-alpine peak assemblage (Fig. 2c).

During the Eo-alpine metamorphism, the high-Mg eclogites typically equilibrated often much less than the low-Mg eclogites. The high-Mg rocks often feature relic gabbroic texture (Fig. 2a, b) and even some of the original gabbroic mineralogy with plagioclase and two pyroxenes are usually preserved. Eclogitisation is patchy (Fig. 2a) and is usually stronger in deformed regions like outcrop scale shear zones. However, even then, the equilibration is most of the time only partial and prograde corona textures around original gabbroic clinopyroxenes are often preserved. In contrast, the low-Mg eclogites are much better equilibrated, possibly because of their much finer grain size. Detailed descriptions of the mineralogy and petrography of these rocks are provided by Miller (1990); Miller and Thöni (1997) as well as Miller et al. (2005a,b, 2007) and will not be repeated here.

The low-Mg sample from Hohl (K19)

In order to constrain the formation conditions for the Koralpe eclogites closer, it is important to investigate a well-equilibrated rock. Many of the thin sections of the high-Mg eclogites of the Koralpe retain too much of their Permian record to be useful (for example some samples from the classic locations at Bärofen and Gressenberg, Fig. 1). At the classic location of Hohl (Fig. 1), parts of the occurrence are also badly-equilibrated, but some thin sections show well-equilibrated textures and were chosen for further study here. In the chosen sample (K19), omphacite (about 45 vol.%) and garnet (about 40 vol.%) are the most abundant phases and are usually of the order of 1 mm in size (Fig. 2d, e, f) (volumetric proportions were estimated using Philpotts (1989)). There are also some large crystals of quartz, clinozoisite and amphibole which define together with garnet and omphacite the weak foliation present in the sample. Kyanite is absent and rutile, ilmenite and zircon occur as accessory components. It should also be said that rutile occurs along grain boundaries and as inclusions in garnets across the entire thin section, while ilmenite was only found sporadically and as inclusions in garnet cores. As we will show below, only the garnet rims are part of the peak assemblage and ilmenite is therefore probably not part of it. From these observations we infer the paragenesis omphacite – garnet – amphibole – quartz – clinozoisite (with accessory rutile) as the stable equilibrium assemblage. The stable equilibrium assemblage is only overprinted by small symplectites of diopside-plagioclase and quartz along within omphacite (Fig. 2e, f).

To determine the mineral chemistry of the phases, we used the Superprobe JEOL JXA 8200 of the Universitätszentrum für Angewandte Geowissenschaften (UZAG) at the University of Leoben (Austria) and the scanning electron microprobe JEOL JSM-6310 at the University of Graz with a point beam at 15 kV and 10 nA. Garnet occurs as euhedral/subhedral grains and contains quartz, zircon, rutile and ilmenite inclusions typically concentrated in the core. We can define in this rock two types of garnets: the smaller garnet (< 400 μm) crystals are homogeneous in composition and similar to the rim of the larger ones, and the larger crystals (> 500 μm) which usually show a weak compositional zonation (Fig. 2g, h). X-ray mapping for Mg, Al, Fe, Ca, Si, and Mn shows an increase of Mn and decrease of Mg from the rim to the core. Zoning of the other elements could not be resolved by X-ray mapping. However, spot analyses reveal systematically somewhat higher grossular, lower pyrope contents and higher $X_{Fe}{}^{g}$ ($X_{Fe}{}^{g} = Fe^{2+}/(Fe^{2+} + Mg)$), in the core of garnet crystal (Table 1). X_{Mg} values increase often with temperature; this compositional zoning suggests a prograde metamorphic growth of the garnet crystal as mentioned by Thöni et al. (2008). Thus, the wide rims of the larger garnets and the homogeneous composition of the smaller ones form presumably part of the peak and will be discussed further below. A similar compositional zoning of garnet (associated with evidence of prograde inclusions) in a MORB-eclogite is interpreted as the consequence of growth by Stipska and Powell (2005).

Omphacite crystals have an average composition of: Q= 0.55–0.58, Jd=0.39–0.42, Ae=0.00–0.05 (where Q, Jd and Ae are explained in Table 1) and show occasionally a weak zoning in Fe. Amphibole crystals present no compositional zoning and are in equilibrium with the surrounding omphacite, quartz and garnet. Thus the studied sample has only one amphibole generation which is interpreted as part of the peak paragenesis.

The amphibole of this sample shows no poikilitic texture and microstructural evidence for later growth as often described for the Pohorje-Koralpe-Saualpe region eclogites, where amphibole is interpreted as early evidence of retrogression (e.g. Miller et al. 2005a). Chemically, amphiboles classify as pargasite (according to Leake et al. 1997). The small amount of clinozoisite has an $X_{Fe}{}^{cz}$ around 0.05 ($X_{Fe}{}^{cz} = Fe^{3+}/(Fe^{3+}+Al)$). In summary, we infer a (Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2) peak assemblage of omphacite - garnet - amphibole - clinozoisite - quartz - rutile.

Table 1 Representative mineral analyses of omphacite, garnet, amphibole, clinozoisite and indicative composition for clinopyroxene/plagioclase symplectites for the low-Mg eclogite sample from Hohl (K19)

Omphacite					Garnet						Amphibole		Clinozoisite			Plagioclase s.	
Analysis	o3	o4	o5	di6 s.		Rim g6r	g52r	Core g21c	g51c		a12	a13		cz1	cz2		pl 15
SiO2	55.19	55.31	54.93	54.43		39.49	38.81	38.68	38.54		44.39	44.89		39.39	38.25		64.58
TiO2	0.17	0.16	0.13	0.12		0.08	0.04	0.07	0.00		0.56	0.69		0.10	0.11		0.00
Al2O3	11.09	10.86	10.51	2.01		22.37	21.56	21.21	21.69		16.66	15.63		32.26	31.37		22.01
FeO	3.85	3.79	4.62	5.82		22.58	23.12	24.09	24.40		10.03	10.20		2.27	2.24		0.26
MnO	0.04	0.02	0.02	0.12		0.54	0.47	1.10	0.91		0.03	0.10		0.15	0.00		0.00
MgO	9.04	9.05	9.21	13.93		7.55	6.83	5.17	4.60		12.27	12.63		0.47	0.40		0.26
CaO	14.14	14.31	14.07	21.10		8.30	8.34	9.13	9.28		9.36	9.01		23.25	23.31		3.29
Na2O	6.20	6.05	6.01	1.41		0.00	0.00	0.00	0.00		4.17	4.08		0.00	0.02		10.14
K2O	0.01	0.01	0.00	0.01		0.00	0.00	0.00	0.00		0.38	0.50		0.00	0.00		0.02
Cr2O3	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		0.00	0.00		0.00	0.00		0.05
Total	99.72	99.55	99.50	98.95		100.90	99.17	99.45	99.42		97.86	97.73		97.90	95.70		100.61
per 6 oxygens					*per 12 oxygens*					*per 23 oxygens*			*per 12.5 oxygens*			*per 32 oxygens*	
Si	1.97	1.98	1.97	2.01		3.00	3.01	3.02	3.01		6.33	6.39		3.01	3.00		11.38
Al iv	0.03	0.02	0.03	0.00		0.00	0.00	0.00	0.00		1.67	1.61		0.00	0.00		4.57
Al vi	0.44	0.43	0.42	0.09		2.00	1.97	1.95	2.00		1.12	1.01		2.90	2.89		
Ti	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		0.06	0.07		0.01	0.01		0.00
Cr	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		0.01	0.00		0.00	0.00		0.00
Fe + 3	0.00	0.00	0.00	0.00		0.00	0.01	0.02	0.00		0.34	0.47		0.14	0.15		0.00
Fe + 2	0.11	0.11	0.14	0.18		1.44	1.49	1.55	1.61		0.86	0.74		–	–		0.04
Mn	0.00	0.00	0.00	0.00		0.03	0.03	0.07	0.06		0.00	0.01		0.01	0.00		0.00
Mg	0.48	0.48	0.49	0.77		0.85	0.79	0.60	0.54		2.61	2.68		0.05	0.05		0.00
Ca	0.54	0.55	0.54	0.84		0.67	0.69	0.76	0.78		1.43	1.37		1.90	1.96		0.62
Na	0.43	0.42	0.42	0.10		0.00	0.00	0.00	0.00		1.15	1.13		0.00	0.00		3.46
K	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		0.07	0.09		0.00	0.00		0.01
OH	–	–	–	–		–	–	–	–		2.00	2.00		1.00	1.00		–
Total	4.00	3.99	4.01	3.99		8.00	8.00	7.99	7.99		17.65	17.59		9.03	9.05		20.07
XJd	0.44	0.43	0.44	0.11													
Wo-En-Fs-triangle (Quad; Morimoto 1988)					$Fe^{2+}/(Fe^{2+} + Mg)$	0.63	0.65	0.72	0.75				$XFe^{cz} = Fe^{3+}/(Fe^{3+}+Al)$	0.05	0.05	an	0.15
wo (Ca)	0.48	0.48	0.46	0.47	$Mg/(Fe^{2+}+Mg)$	0.37	0.35	0.28	0.25							ab	0.85
en (Mg)	0.42	0.42	0.42	0.43	$Ca/(Fe^{2+} + Mg + Ca)$	0.23	0.23	0.26	0.27							or	0.00
fs (Fe)	0.10	0.10	0.12	0.10	almandine	47.85	49.17	51.35	53.96								
Quad-Jd-Ae-triangle (Morimoto 1988)					andradite	0.00	0.73	0.95	0.00								
Q (Ca + Mg + Fe tot)	0.56	0.58	0.58	0.90	grossular	22.52	22.52	24.89	26.04								
Jd (Na)	0.41	0.42	0.39	0.10	pyrope	28.49	26.53	20.36	17.97								
Ae (Fe^{3+})	0.02	0.00	0.03	0.00	spessartine	1.15	1.05	2.46	2.03								

The abbreviations r, c and s correspond to rim, core and symplectites, respectively.

Thermobarometry and pseudosection modelling

Previous thermobarometry

In the 90´s of the last century, a series of *PT* estimates for the Koralpe eclogites have been published, all resulting in estimates of 591–622°C and 18.3–20.8 kbar. Miller (1990) and Miller and Thöni (1997) arrived at these conditions using conventional thermobarometry such as garnet-clinopyroxene thermometry, thermobarometry of Massone et al. (1993) and a garnet-phengite thermometer (Green and Hellmann 1982). More recently, Miller et al. (2007) obtained 22–24 kbar and 670–760°C and even 24–28 kbar at 700–785°C (using Brandelik and Massone (2004) and Krogh-Ravna and Terry (2004) respectively) for a number of locations from the Saualpe, Koralpe and Pohorje regions. The same authors also used two different rutile thermometers to constrain temperatures. They concluded that — within the uncertainties — the eclogites experienced similar conditions in all three regions (see also Thöni et al. 2008).

In contrast, Janak et al. (2004, 2006) give estimates for the Pohorje eclogites around 30 kbar and 800°C and use the observations of radial cracks around quartz inclusions in garnet as evidence for the stability of coesite in these rocks. Interestingly, the Pohorje metapelites (at least in the north of the massif) reached significantly lower pressure (Tenczer and Stüwe 2003) implying that the Pohorje eclogites could be exotic to their hosts. However, there is some debate about the existence of ultra high pressure rocks in the Pohorje massif (e.g. Miller and Konzett 2005) and the observation of radial cracks as evidence for former coesite has long been refuted in the Koralpe (Neubauer 1991). In summary, pressure estimates since the 90´s for the eclogites from the Koralpe region vary widely between 18 and 28 kbar, but none of these estimates was performed with an estimate of the uncertainties or tested for its compatibility with predictions by pseudosections. As the lower and the higher end of the published estimates have widely different implications for the interpretation of the field gradient across the region it is important to constrain them better.

Conventional thermobarometric calculations

In order to illustrate the shortcomings associated with conventional barometry when error bars are considered, we have performed thermobarometry for the sample discussed here. For this thermobarometry we use a maximum set of independent end member reactions of the peak assemblage o – g rim – q – cz – hb – ru – H_2O in THERMOCALC (Powell et al. 1998) and the activity models listed in the next chapter. Figure 3a, b show these 8 independent reactions with their single standard deviations. Allocating 1 sigma errors to the *Kd* measurements as well as the formation enthalpy of the involved end members and assuming the entropy and volume changes are experimentally known, it may be seen that only the temperature sensitive equilibria have narrow error bars (Fig. 3b). Pressure sensitive equilibria have up to 10 kbar standard deviations. A weighted average of the reactions gives a *PT* result around 22.9 kbar and 628°C with the corresponding large uncertainties (Fig. 3a). Looking at the standard deviations for each of these equilibria, the average *PT* result from above is better quoted as: 628±55°C and 22.9± 3 kbar.

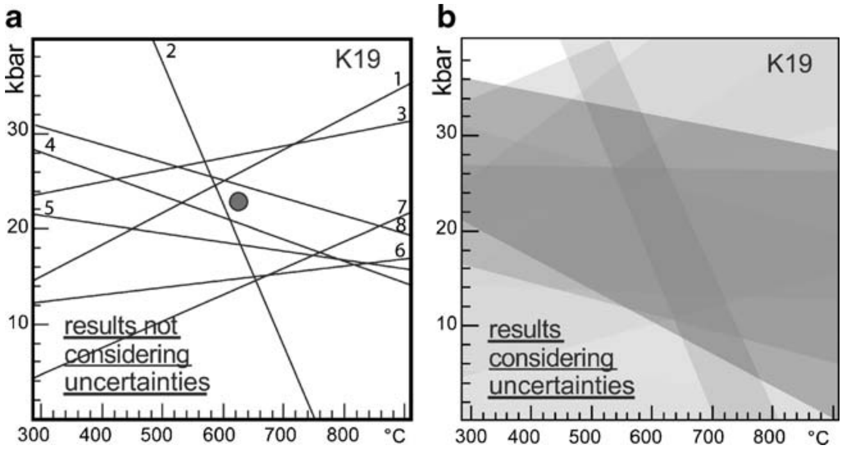


Fig. 3 Average *PT* results for the sample K19 from Hohl with peak assemblage composed of o – g rim – q – cz – hb – ru – H_2O. **a** The eight independent reactions : (1) 12di + 3ts = 2py + 4gr + 3tr; (2) gr + 2tr = 7di + py + 2q + $2H_2O$; (3) gr + 3ts = 3di + 3py + 4cz + $2H_2O$; (4) 15hed + 12cz = 13gr + 5alm + 12q + $6H_2O$; (5) 5fact + 3ts = 9di + 7hed + 6alm + 8q + $8H_2O$; (6) 60di + 3parg + 18cz = 3jd + 4py + 26gr + 12tr; (7) 2py + 4gr + 3gl = 6di + 6jd + 3ts; (8) 15hed + 12jd + 12ep = 12acm + 13gr + 5alm + 12q + $6H_2O$. Endmember abbreviations are those used by THERMOCALC. They give an average *PT* of: 628 ± 55°C; 22.9 ± 3 kbar (dot). The dot is not at the intuitive crossing of the reactions as the average is weighted. **b** the same as in **(a)** but with considering 2 sigma errors for each of these reactions

Pseudosection modelling

In order to refine the varying *PT* estimates from the literature and the conventional estimates discussed above, a series of thermodynamic pseudosections were constructed. Several pseudosections were calculated for a Gressenberg high-Mg eclogite (Bruand et al. unpublished data) because they allowed a comparison of predicted equilibrium with measured disequilibrium compositions. However, they did not allow a well constrained *PT* estimate because the observed mineral compositions and zoning patterns could not even approximately be predicted by the pseudosection approach and for these reasons are not presented in this contribution. We therefore concentrate here on the well-equilibrated Hohl eclogite (low-Mg: K19) discussed above. An anhydrous bulk composition for this sample was obtained by XRF analyses giving weight percent of the major oxides of: SiO_2=49.64; Al_2O_3= 14.33; FeO=12.13; MgO=7.87; CaO=11.37; Na_2O=2.84; TiO_2=1.80. The total of MnO+P_2O_5+K_2O is only about 0.35% and the loss on ignition is: LOI=0.18. In order to be able to use the new activity model for amphibole of Diener et al. (2007) in our calculations, we need to evaluate the Fe_2O_3/FeO ratio of the sample. To constrain this Fe_2O_3/FeO ratio, the Fe_2O_3 concentration in each of the phases was calculated (using "REEnorm" and AX of Holland and Powell 1998, which gave the same results). The calculated Fe_2O_3/FeO ratios for each phase were then averaged according to the observed mode of each phases present in the sample. This results in: p=Fe_2O_3/FeO=0.12 for the Hohl sample. Interestingly, this is also the value suggested by Diener et al. (2007) for a typical MORB composition.

In summary, we calculate pseudosections for sample K19 in the NCFMASHTO system using normalised oxide mole proportions of SiO_2=51.83; Al_2O_3=8.82; FeO=9.52; MgO= 12.25; CaO=12.72; Na_2O=2.88; TiO_2=1.41 and O=0.57 to reflect p=0.12. THERMOCALC 3.30 (Powell et al. 1998; recent upgrade) and the internally consistent thermodynamic dataset 5.5 (Holland and Powell 1998; November 2003 upgrade) were used for the calculations. For the activity models we used those of Holland and Powell (1998) and Holland et al. (1998) for chlorite and epidote, White et al. (2000) for ilmenite-hematite, Holland and Powell (2003) for plagioclase, White et al. (2007) for garnet, Green et al. (2007) for clinopyroxene and Diener et al. (2007) for amphibole.

Eclogite parageneses are very sensitive to the water content of the rock (Stipska and Powell 2005) which therefore has to be constrained. Indeed, in the Koralpe, Tenczer et al. (2006) showed that the metapelites have experienced a very dry Eo-alpine metamorphic evolution and Riesco et al. (2005) showed that there are complex interactions between mafic rocks and metapelites with respect to the water content. Here, we constrain the water content using a P-M_{H2O} pseudosection (Fig. 4) for the bulk composition cited above and for a *P* range of interest between 10 and 25 kbar. The pseudosection was calculated for a peak temperature of 700°C (Miller et al. 2007). Other than the phases seen on Fig. 4, the pseudosection was also tested for stability of lawsonite and talc, which were found to be metastable across the tested range.

The pseudosection can be divided into a H_2O-saturated and a H_2O-undersaturated part. In the saturated field, the observed peak assemblage o-g-q-cz-hb-ru plots in the pressure range between 15 and 17 kbar (outlined field in Fig. 4). Towards higher pressures kyanite appears and plagioclase appears below 15 kbar. In most of the H_2O-undersaturated part, kyanite appears already above 14 kbar whereas plagioclase disappears at about 15 kbar. Both phases are not present in the studied sample. The assemblage of the Hohl sample is present in both the H_2O-undersaturated and saturated fields. However, in the undersaturated range this field is small and close to the saturation line (Fig. 4). Consequently, the P-M_{H2O} pseudosection suggests a water content above 1.5 mole %. As the H_2O-undersaturated peak assemblage is close to the saturation line, we have chosen to calculate a *PT* pseudosection for water saturated conditions (Fig. 5) and discuss the robustness of our results towards somewhat lower H_2O contents in the discussion section.

The H_2O-saturated *PT* pseudosection of the K19 sample shows the appearance of kyanite at higher pressure and temperature, the presence of clinozoisite below about 720°C and the stability of garnet above about 550°C (Fig. 5). This pseudosection permits to localise the peak paragenesis (o-g-q-hb-cz-ru-H_2O) in a relatively large field between 12 and 20 kbar and 550–720°C. However, this field is composed of two parts with different clinopyroxene compositions: the upper part has an omphacitic composition whereas the lower part has a diopsidic composition. Thus, the metamorphic peak can be constrained to the upper part of this field. Using isopleths for composition of omphacite and garnet, the peak conditions can be further constrained. Omphacites are more or less homogeneous in composition (X_{Jd}=0.42 +/− 0.02, Table 1). The garnet cores have $X_{Fe}{}^{g}$ values between 0.67 and 0.76 and the garnet rims (inferred to be part of the peak assemblage, see below) between 0.63 and 0.69. X_{Ca} isopleths (X_{Ca} = Ca/(Fe^{2+}+Mg + Ca)) for garnet in view of the weak difference of the X_{Ca} garnet values between the core and the rim (0.23 and 0.26–0.27 see Table 1), can not be interpreted and are not represented in this pseudosection. Using these compositional constraints for garnet and omphacite, the metamorphic peak is constrained between 16.5 and 20.5 kbar and 620°C and 720°C (Fig. 5). Assuming that the peak temperature is 650–700°C (average from the literature on eclogites), similar to the peak temperature on the metapelites (i.e. Stüwe and Powell 1995; Thöni and Miller

1996) the pressure would be quite tightly constrained to be 17–19 kbar.

Some constraints on the pro- and retrograde evolution prior and after the metamorphic peak are provided by garnet cores and late stage symplectites, respectively: Garnet cores are slightly more Fe - rich than their rims. In the pseudosection Fig. 5, X_{Fe}^{g} isopleths reveal that X_{Fe}^{g} composition of the garnet from the core (>0.70) to the rim (<0.70) can only be reached by an increase of grade as already suggested by the increase of Mg (wt. %) in garnet (see Hohl sample description). Therefore, the pseudosection calculations confirm that the zoning of the bigger garnet is due to growth zoning. Curiously, the core compositions of the garnets do not correspond to the garnet-field boundary (Fig. 5). However, compositionally different garnet cores are small and patchy (Fig. 2g, h), so that we suggest that the garnets have not preserved the initial growth composition. The absence of zoning in the smaller homogeneous garnets, (which have the same chemical composition as the rims of the larger zoned garnets >500 µ), is interpreted in terms of a growth of the small crystals near the metamorphic peak (this corresponds to the interpretation of Biermeier and Stüwe 2003).

Evidence for the retrograde evolution is given by the q - di - pl symplectites within omphacite (Fig. 2e, f). Similar di - q - pl symplectite textures associated with omphacite were interpreted by Will and Schmädicke (2001) or Yang (2004) as evidence for decompression. However, as this is a very localized reaction with a different and rather uncertain effective bulk composition proceeding at disequilibrium conditions, it is not possible to ascertain the post-peak *PT* evolution.

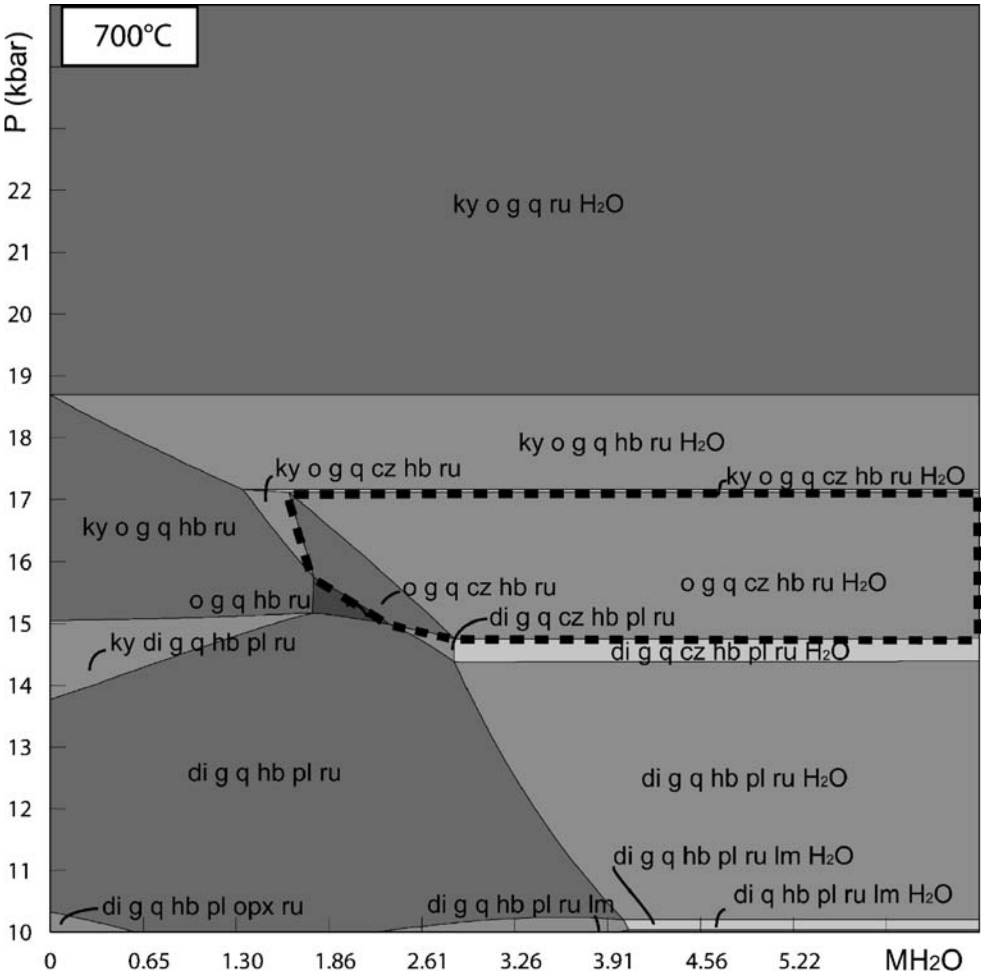


Fig. 4 *P*-MH_2O (MH_2O in mol.%) pseudosection calculated at 700°C for a low-Mg eclogite from Hohl (K19). This pseudosection is calculated in the NCFMASHTO (SiO_2=51.83; Al_2O_3=8.82; FeO=9.52; MgO=12.25; CaO=12.72; Na_2O=2.88; TiO_2=1.41; O=0.57) system and therefore the lighter grey fields have a variance of 3 (8 phases) and the darkest grey have a variance of 6 (5 phases). The peak paragenesis observed in this sample is located in the fields outlined with a thick dashed line. The two fields represent the assemblage o - g - q - cz - hb - ru with and without H_2O

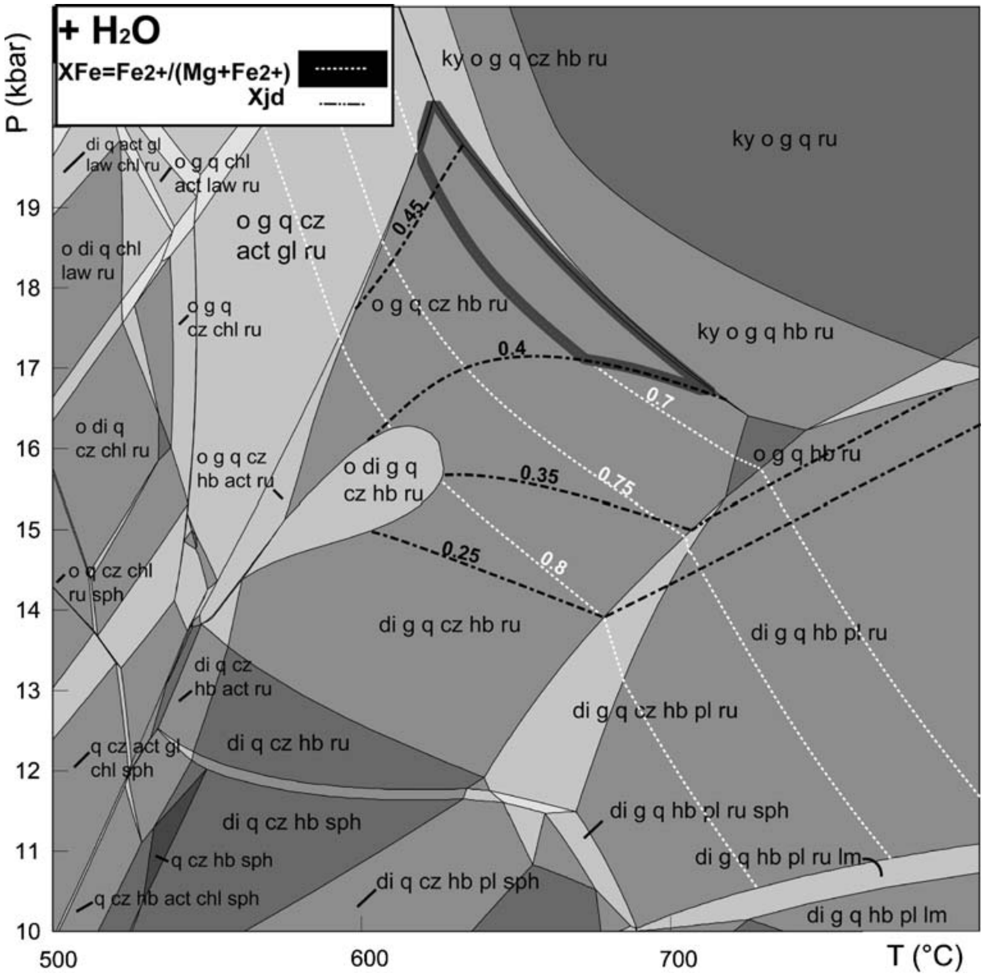


Fig. 5 *PT* pseudosection calculated for H_2O-saturated low-Mg eclogite (K19). Same bulk as for Fig. 4 is used. The pseudosection is calculated in the NCFMASHTO chemical system and shows field variances between 2 for the lightest fields (9 phases) and 6 for the darkest grey fields (5 phases). The paragenesis observed in this sample is located in the o -g - q - cz - hb - ru - H_2O field. The diagram shows isopleths for garnet ($X_{Fe}{}^{g} = Fe^{2+}/(Fe^{2+}+Mg)$, white dotted line) and omphacite (X_{Jd}=Na/(Na+Ca), black dash-dotted line) which help to constrain the *PT* range for the metamorphic peak (black bold contour)

Discussion

Robustness towards oxidation state and water content

Peak conditions and post-peak evolution were inferred assuming H_2O-saturated conditions for the entire evolution of the eclogite studied here. This is consistent with the suggestion of Miller et al (2007) that some of the Koralpe eclogite precursor experienced seawater alteration in the Permian. In fact, Riesco et al. (2005) showed that mafic rocks in the nearby Saualpe complex were H_2O-saturated during the Eo-alpine evolution thereby causing fluid flow from the mafics towards some of the H_2O-undersaturated metapelites. We therefore suggest that an interpretation of the eclogites in terms of a H_2O-saturated evolution is justified. Moreover, H_2O undersaturated conditions would cause a shift of the peak field towards lower *PT*. In view of our key result — namely that the metamorphic conditions of the eclogites are comparable to those of the metapelites which equilibrated around 20 kbar/685°C (Thöni and Miller 1996), 18 kbar/700°C (Faryad and Hoinkes 2003) and 700°C for temperature peak for Plattengneiss (Tenczer et al. 2006) — this would strengthen our conclusion. Of the other chemical components, the largest uncertainty is in the oxidation state of the rocks as described by the oxygen content of the bulk composition. We have tested the pseudosection of Fig. 5 for p=0.12 and $p = 0.2$ and there is negligible change of the relevant bounding equilibria around the peak field.

Comparison with previous thermobarometry

Our conclusion for the metamorphic peak conditions may now be compared to the previously published results. Most of these results indicated somewhat higher *P-T* conditions. In the most recent studies Miller et al. (2007) concluded that the metamorphic conditions of the mafic rocks lie in the range between 22 and 28 kbar (using barometry of Brandelik and Massone 2004 and Krogh-Ravna and Terry 2004) and 19–21 kbar using Waters and Martin (1993). Our result of Fig. 5 is more concordant with the latter but also with earlier studies of Miller (1990) and Miller and Thöni (1997), who suggested 18–20 kbar. Moreover a recent experimental study on the Bärofen eclogite (Tropper et al. 2008) suggest such lower pressure (~20 kbar).These lower pressure conditions are important for the interpretation of the metamorphic field gradient across the Saualpe-Koralpe-Pohorje region as Miller et al. (2007) have argued (based on conventional thermobarometry) that there is no distinguishable difference between the eclogites of the Pohorje, Saualpe and Koralpe regions.

Our results have important implications to the discussion of the metamorphic field gradient: Miller and Konzett (2005) argued that the Pohorje eclogites discussed by Janak et al. (2004) not necessarily did experience ultra high pressure conditions in the coesite stability field. They suggested that the Pohorje peak conditions may be as low as those of the Koralpe and that the uncertainties of calibrated barometers do not allow a conclusive interpretation. While we agree with the interpretation of Miller and Konzett (2005), the lower pressure of the Eo-alpine event obtained in this study would suggest that a gradient from Koralpe to Pohorje is more likely. Nevertheless, the debate cannot be resolved until pseudosections have been constructed for a series of eclogites along the transect.

Tectonic interpretation

Our data confirm that the peak metamorphic pressures of the eclogites are concordant with those of the metapelites (Thöni and Miller 1996; Faryad and Hoinkes 2003) and overlap with them within error. The possible pressure difference of 2–5 kbar when compared with the Tenczer et al. (2006) study on the Plattengneiss can possibly be ascribed to the fact that eclogites and metapelites equilibrated as slightly different times along a common *PT* path. This is supported by the fact that the peak conditions of the eclogites appear to reflect both the *P* and the *T* peak, while those of the metapelites in Tenczer et al. (2006), only reflect the *T* peak, which appears to have been reached from higher pressures (e.g. Stüwe and Powell 1995).

The conclusion that the peak metamorphic conditions of the Koralpe eclogites are comparable to those of the metapelites makes much of the tectonic interpretation of the region easier. In particular, it does not require any tectonic processes that inserted the eclogites into the metapelites during or after the metamorphic peak and it allows a continuous Eo-alpine metamorphic cycle for both rock types. The orogen-wide distribution of Permian metamorphism and that of the Eo-alpine metamorphic grade are similar (Schuster and Stüwe 2008) which also suggests that metamorphism affected the sequence as a whole without substantial mixing of rock types of different grade.

In terms of a tectonic evolution, it is important to note that the Hohl eclogite studied here (and several others with similar parageneses) are located structurally above the Plattengneiss shear zone (Putz et al. 2006, Fig. 1). Within the model of Kurz et al. (2002) this shear zone was responsible for the partial exhumation of the eclogites. However, this is only possible if the eclogites would occur exclusively in the footwall of the shear zone. Thus, our data also allow other models for the interpretation of the Plattengneiss shear zone. For example, Roffeis et al. (2008) suggested that the Plattengneiss shear zone may be a suture zone of a crustal wedge that was extracted downwards and southwards during a south directed Eo-Alpine subduction in the style suggested by Froitzheim et al. (2003). Within this model, eclogites in both the hanging and the footwall of the shear zone should be part of a continuous sequence with those in the footwall possibly being about 1–2 kbar higher in pressure. Careful relative *PT* studies on the eclogites may reveal such a difference in future studies.

Conclusion

With modelling calculation of a low-Mg eclogite (sample K19) using the new amphibole model (Diener et al. 2007) we are able to reproduce the phase stabilities of this sample and constrain *PT* peak conditions considering certain isopleths of composition for omphacite and garnet. In summary, it can be said that the Hohl eclogite may be interpreted in terms of a H_2O-saturated evolution involving pressure and temperature increase to a metamorphic pressure and temperature peak around 18.5 kbar–670°C. Therefore these results suggest that a metamorphic gradient from Koralpe to Pohorje is more likely. Moreover the *PT* concordance between previous metapelite data of the Saualpe-Koralpe region and our result on a metabasite suggest a common metamorphic history for the two lithologies.

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References

Biermeier C, Stüwe K (2003) Strain rates from snowball garnets? J Met Geol 21:253–268

Brandelik A, Massone 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

Chemenda A, Mattauer M, Bokun AN (1996) Continental subduction and a mechanism for exhumation of high-pressure metamorphic rocks: new modelling and field data from Oman. Earth Planet Sci Lett 143:173–182

Dale J, Powell R, White RW, Elmer FL, Holland TJB (2005) A thermodynamic model for Ca-Na clinoamphibole in Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2–H_2O-O for petrological calculations. J Met Geol 23:771–791

Diener JFA, Powell R, White RW, Holland TJB (2007) A new thermodynamic model for clino- and orthoamphiboles in the system Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2–H_2O-O. J Met Geol 25:631–656

England PC, Holland TJB (1979) Archimedes and the Tauern eclogites: the role of buoyancy in the preservation of exotic tectonic blocks. Earth Planet Sci Lett 44:287–294

Faryad SW, Hoinkes G (2003) P-T gradient of Eo-Alpine metamorphism within the Austroalpine basement units east of the Tauer Window (Austria). Mineral Petrol 77:129–159

Froitzheim N, Pleuger J, Roller S, Nagel T (2003) Exhumation of high- and ultrahigh-pressure metamorphic rocks by slab extraction. Geology 31:925–928. doi:10.1130/G19748.1

Green TH, Hellmann PL (1982) Fe-Mg partitioning between coexisting garnet and phengite at high pressure, and comments on a garnet-phengite geothermometer. Lithos 15:253–266

Green ECR, Holland TJB, Powell R (2007) An order-disorder model for omphacitic pyroxenes in the system jadeite-diopside-hedenbergite-acmite, with applications to eclogite rocks. Am Mineral 92:1181–1189

Haüy M (1822) Traité de Minéralogie, 2nd edn. Deuxième tome, Bachelier et Huzard, Paris

Hejl E (1997) Cold spots during the Cenozoic evolution of the Eastern alps: thermochronological interpretation of apatite fission-track data. Tectonophys 272:159–173

Holland TJB, Baker JM, Powell R (1998) Mixing properties and activity-composition relationships of chlorites in the system MgO-FeO-Al_2O_3-SiO_2–H_2O. Eur J Mineral 10:395–406

Holland TJB, Powell R (1998) An internally consistent thermodynamic data set for phases of petrological interest. J Met Geol 16:309–343

Holland TJB, Powell R (2003) Activity-composition relations for phases in petrological calculations: an asymmetric multicomponent formulation. Contrib Mineral Petrol 145:492–501

Janak 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 Eastern Alps. Tectonics 23 TC5014, doi:10.1029/2004TC001641

Janak M, Froitzheim N, Vrabec M, Krogh-Ravna K, Hoog EJ, Hoog JCM (2006) Ultrahigh-pressure metamorphism and exhumation of garnet peridotite in Pohorje, Eastern Alps. J Met Geol 24:19–31

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 Met Geol 22:579–592

Kurz W, Fritz H, Tenczer V, Unzog W (2002) Tectonometamorphic evolution of the Koralm Complex (Eastern Alps): constraints from microstructures and textures of the “Plattengneiss” shear zone. J Struct Geol 24:1957–1970

Lapen TJ, Johnson CM, Baumgartner LP, Dal Piaz GV, Skora S, Beard BL (2006) Coupling of oceanic and continental crust during Eocene eclogite-facies metamorphism: evidence from the Monte Rosa nappe, Western Alps. Contrib Mineral Petrol 153:139–157. doi:10.1007/s00410-006-0144-x

Leake BE, Woolley AR, Arps CES, Birch WD, Gilbert MC, Grice JD, Hawthorne FC, Kato A, Kisch HJ, Krivovichev VG, Linthout K, Laird J, Mandarino JA, Maresch WV, Nickel EH, Rock NMS, Schumacher JC, Smith DC, Stephenson NCN, Ungaretti L, Whittaker EJW, Youshi G (1997) Nomenclature of amphiboles: Report of the subcommittee on amphiboles of the International Mineralogical Association, commission on new minerals and mineral names. Am Mineral 82:1019–1037

Massone HUJ, Grosch U, Willner A (1993) Geothermometrie mittels Ti-Gehalten an Kalihellglimmern. Ber Dt Mineral Ges, Beih Eur J Mineral 5:85

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 by Janak et al. Tectonics 24:TC6010. doi:10.1029/2004TC001765

Miller C, Mundil R, Thöni M, Konzett J (2005a) Refining the timing of eclogite metamorphism: a geochemical, petrological, Sm-Nd and U-Pb case study from the Pohorje Mountains, Slovenia (Eastern Alps). Contrib Mineral Petrol 150:70–84

Miller C, Thöni M (1997) Eo-Alpine eclogitisation of Permian MORB-type gabbros in the Koralpe (Eastern Alps, Austria): new geochronological, geochemical and petrological data. Chem Geol 137:283–310

Miller C, Thöni M, Konzett J, Kurz W, Schuster R (2005b) Eclogites from the Koralpe and Saualpe type-localities, Eastern Alps, Austria. Mitt Österr Mineral 150:227–263

Miller C, Zanetti A, Thöni M, Konzett J (2007) Eclogitisation of gabbroic rocks: redistribution of trace elements and Zr in rutile thermometry in an Eo-alpine subduction zone (Eastern Alps). Chem Geol 239:96–123

Moore DE, Blake MC (1989) New evidence for polyphase metamorphism of glaucophane schist and eclogite exotic blocks in the Franciscan complex, California and Oregon. J Met Geol 7:211–228

Morimoto M (1988) Nomenclature of pyroxenes. Mineral Mag 52:535–550

Neubauer F (1991) Kinematic indicators in the Koralm and Saualm eclogites (Eastern Alps). Zbl Geol Paläont Teil 1:139–155

Neubauer F, Fritz H, Genser J, Kurz W, Nemes F, Wallbrecher E, Wang X, Willingshofer E (2000) Structural evolution within an extruding block; model and application to the Alpine-Pannonian system. In: Lehner FK, Urai JL (eds) Aspects of tectonics faulting. Springer, New York, pp 141–153

Philpotts AR (1989) Petrography of igneous and metamorphic rocks. Prentice Hall, Upper Saddle River, p 178

Platt JP (1993) Exhumation of high-pressure rocks: a review of concepts and processes. Terra Nova 5:19–133

Powell R, Holland TJB, Worley B (1998) Calculating phase diagrams involving solid solution via non-linear equations, with examples using THERMOCALC. J Met Geol 16:577–588

Putz M, Stüwe K, Jessell M, Calcagno P (2006) Three-dimensional model and late stage warping of the Plattengneiss Shear Zone in the Eastern Alps. Tectonophysi 412:87–103

Riesco M, Stüwe K, Reche J (2005) Formation of corundum in metapelites around ultramafic bodies. An example from the Saualpe region, Eastern Alps. Mineral Petrol 83:1–25

Ring U, Brandon TM, Willett SD, Lister GS (1999) Exhumation processes. In: Ring U, Brandon TM, Willett SD and Lister GS (eds) Exhumation processes: normal faulting, ductile flow and erosion. Geol Soc Am Spec Publ 154:1–28

Roffeis C, Stüwe K, Powell R (2008) pressure gradients across the Plattengneiss Shear Zone. EGU General Assembly, Geophys Res Abs 10:EGU2008-A-09637

Schuster R, Kurz W (2005) Eclogites in the Eastern Alps: High-pressure metamorphism in the context of the Alpine orogeny. Mitt Österr Mineral Ges 150:183–198

Schuster R, Stüwe K (2008) Permian metamorphic event in the Alps. Geology 36:603–606. doi:10.1130/G24703A.1

Stipska P, Pitra P, Powell R (2006) Separate or shared metamorphic histories of eclogites and surrounding rocks? An example from the Bohemian Massif. J Met Geol 24:219–240

Stipska P, Powell R (2005) Constraining the P-T path of a MORB-type eclogite using pseudosections, garnet zoning and garnet-clinopyroxene thermometry: an example from Bohemian massif. J Met Geol 23:725–743

Stüwe K, Powell R (1995) Geothermobarometry from modal proportions. Application to a PT path of the Koralm complex, Eastern Alps. Contrib Mineral Petrol 119:83–93

Tenczer V, Stüwe K (2003) The metamorphic field gradient in the eclogite type locality Koralpe region, Eastern Alps. J Met Geol 21:377–393

Tenczer V, Stüwe K, Powell R, Dale J (2006) Evolution of H_2O content in a polymetamorphic terrain: The Plattengneiss Shear Zone (Koralpe, Austria). J Met Geol 24:281–295

Thöni M (2006) Dating eclogite-facies metamorphism in the Eastern Alps - approaches, results, interpretations: a review. Mineral Petrol 88:123–148

Thöni M, Jagoutz E (1993) Isotopic constraints for Eo-Alpine high-P metamorphism in the Austroalpine nappes of the Eastern Alps: bearing on Alpine orogenesis. Schweiz Mineral Petrogr Mitt 73:177–189

Thöni M, Miller C (1996) Garnet Sm-Nd data from the Saualpe and Koralpe (Eastern Alps, Austria): chronolohical and PT constraints on the thermal and tectonic history. J Met Geol 14:453–466

Thöni M, Miller C, Blichert-Toft J, Whitehouse MJ, Konzett J, Zanetti A (2008) Timing of high-pressure metamorphism and exhumation of eclogite type-locality (Kupplerbrunn-Prickler Halt, Saualpe, south-eastern Austria): constraints from correlations of the Sm-Nd, Lu-Hf, U-Pb and Rb-Sr isotopic systems. J Met Geol 26:561–581

Tropper P, Kunze R, Manning C (2008) Experimental constraints on the role of brines in the transformationof gabbros to eclogites: a case study from the Bärofen metagabbros (Koralpe, Styria). Pangeo Austria Meeting

Waters DJ, Martin HN (1993) Geobarometry in phengite-bearing eclogites. Terra Abs 5:410–411

White RW, Powell R, Holland TJB (2007) Progress relating to calculation of partial melting equilibria for metapelites. J Met Geol 25:511–527

White RW, Powell R, Holland TJB, Worley BA (2000) The effect of TiO_2 and Fe_2O_3 on metapelitic assemblages at greenschist and amphibolite facies conditions: mineral equilibria calculations in the system K_2O-FeO-MgO-Al_2O_3-SiO_2–H_2O-TiO_2-Fe_2O_3. J Met Geol 18:497–511

Will TM, Schmädicke E (2001) A first find of retrogressed eclogites in the Odenwald crystalline complex, mid-German crystalline rise, Germany: evidence for a so far unrecognised high-pressure metamorphism in the Central Variscides. Lithos 59:109–125

Yang TN (2004) Retrograded textures and associated mass transfer: evidence for aqueous fluid action during exhumation of the Qinglongshan eclogite, Southern Sulu ultrahigh pressure metamorphic terrane, eastern China. J Met Geol 22:653–669