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Relics of high-pressure metamorphism from the Großglockner region, Hohe Tauern, Austria: Textures and mineral chemistry of retrogressed eclogites.

ALEXANDER PROYER[1], EDGAR DACHS[1], WALTER KURZ[2]

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Relikte der Hochdruckmetamorphose des Großglocknergebietes, Hohe Tauern, Österreich: Texturen und Mineralchemie retrograder Eklogite

Zusammenfassung

Stark retrograde Eklogite treten im Großglocknergebiet (Tauernfenster, Österreich), östlich der „Eklogitzone" auf. Diese Glaukophan- und Paragonit-führenden Eklogite wurden teilweise bereits während der frühen Hebung, noch innerhalb der Eklogitfazies, hydriert, was zum Wachstum von grobkörnigem Amphibol (ohne Plagioklas), hauptsächlich aus Omphazit führte. Die endgültige Platznahme und gemeinsame Metamorphose mit den heutigen Nebengesteinen fand unter Bedingungen der Grünschiefer- bis unteren Amphibolitfazies statt und erzeugte aufgrund unterschiedlicher Hydrierungsgrade eine große Vielfalt von Gesteinstypen und Texturen. Die mineralogische und texturelle Entwicklung und die besonderen Merkmale des Symplektitstadiums werden detailliert beschrieben.

Abstract

Strongly retrogressed eclogites have been investigated from the Grossglockner area, situated east of the "Eclogite Zone" of the Tauern Window in Austria. These glaucophane- and paragonite-bearing eclogites were partly rehydrated during early exhumation, still within the eclogite facies, resulting in the growth of coarse grained amphibole (without plagioclase), mainly from omphacite. The final emplacement in and co-metamorphism with their present country rocks under conditions of upper greenschist to amphibolite facies, produced a great variety of rock types and textures caused by different degrees of retrograde hydration. The mineralogic and textural evolution and symplectite stage features are described in detail.

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1. Introduction

Eclogite facies rocks of the Penninic "Tauern Window" of the Eastern Alps have been reported and described in the more recent literature, up till now mainly from the so-called "Eclogite-Zone" (e.g. MILLER 1977, HOLLAND 1979), which is intercalated between the tectonically lower Venediger nappe and the tectonically higher Rote Wand – Modereck nappe and Glockner nappe (KURZ et al. 1998; Fig. 1a, b). As early as the 1930's, strongly retrogressed eclogites have been recognized in other equivalent or higher tectonic units of the Penninic nappe pile. The map of CORNELIUS & CLAR (1939) shows several locations in the Glockner area, east of the Eclogite Zone, where a special type of "garnet-bearing, partly eclogitic prasinite" was encountered. They interpreted this as being derived from eclogites, because of the symplectitic amphibole-plagioclase-textures, which they called "Diablastik", observed in thin sections. Five of these locations have been sampled and investigated in order to find well preserved eclogites and to document the nature of high-pressure metamorphism in the Hohe Tauern, east of the actual "Eclogite Zone" (STURM et al. 1996).

The purpose of this paper is to provide information on the textures and mineral chemistry of these retrogressed eclogites, which have not been further investigated since the 1930's, and to give a preliminary interpretation of their metamorphic evolution. Further details of the mineral chemistry and results of geothermobarometry will be given in a subsequent publication (DACHS & PROYER, submitted).

2. Geological setting and sample locations

Retrogressed eclogites from the following five locations have been investigated:

1+2: Locations Hochtor and Margrötzenkopf are situated in the Rote-Wand-Modereck-nappe (Fig. 1b; regarding nomenclature and correlation with earlier terms see KURZ et al. 1996). They comprise some eclogitic blocks from the pass immediately above the Hochtor-tunnel of the Grossglockner Hochalpenstraße and a larger area of garnet-bearing amphibolites, embedded in micaschists, in the summit region of the Grosser Margrötzenkopf, a few hundred meters west of Hochtor.

3: Location Zodererkaser is an outcrop area of several hundred square meters found about 1500 meters to the south of the Hochtor. This location is steep mountain pasture on the slope north of the Grossglockner Hochalpenstraße and is ca. 2200 m above sea level. It is also a part of the Rote-Wand-Modereck-nappe.

4: Location Gamsgrube is a band of eclogitic amphibolite, with an average thickness of about 20 meters, running from the footpath north of the Pasterzenboden near Hofmannshütte straight north towards the Fuscherkarkopf (from 2400 m to above 3000 m altitude). This moderately to steeply southeast-dipping band is underlain by graphitic garnet-micaschists and overlain by carbonaceous garnet-micaschists and greenschists of the Bündner Schist country rocks (Glockner nappe).

5: Location Dorfertal is a folded eclogitic amphibolite band that is a few meters thick. It dips moderately to steeply to the south, cutting across the Kalser Dorfertal in the area of Schöneben, cropping out only in the almost inaccessible eastern and western slopes of the valley. Country rocks are graphitic micaschists and greenish gneisses. The host rock series are in a tectonic position equivalent to that of the Eclogite Zone, between the Grossvenediger and the Rote Wand-Modereck nappe.

3. Petrography and mineral chemistry

3.1 Margrötzenkopf

The samples from this location are the most strongly retrogressed ones. Garnet is present as relic grains, corroded or pseudomorphed by chlorite + epidote ± biotite, but occasionally still preserving inclusions of glaucophane, paragonite, epidote and rutile as remnants of an earlier high-pressure stage (omphacite has not been discovered yet). Garnets are slightly zoned grossular-rich almandines with a typical core-rim variation of $Alm_{57}Pyr_{6}Gro_{23}Spe_{14}$ to $Alm_{63}Pyr_{12}Gro_{21}Spe_{4}$ (for abbreviations see appendix). A coarse grained variety of

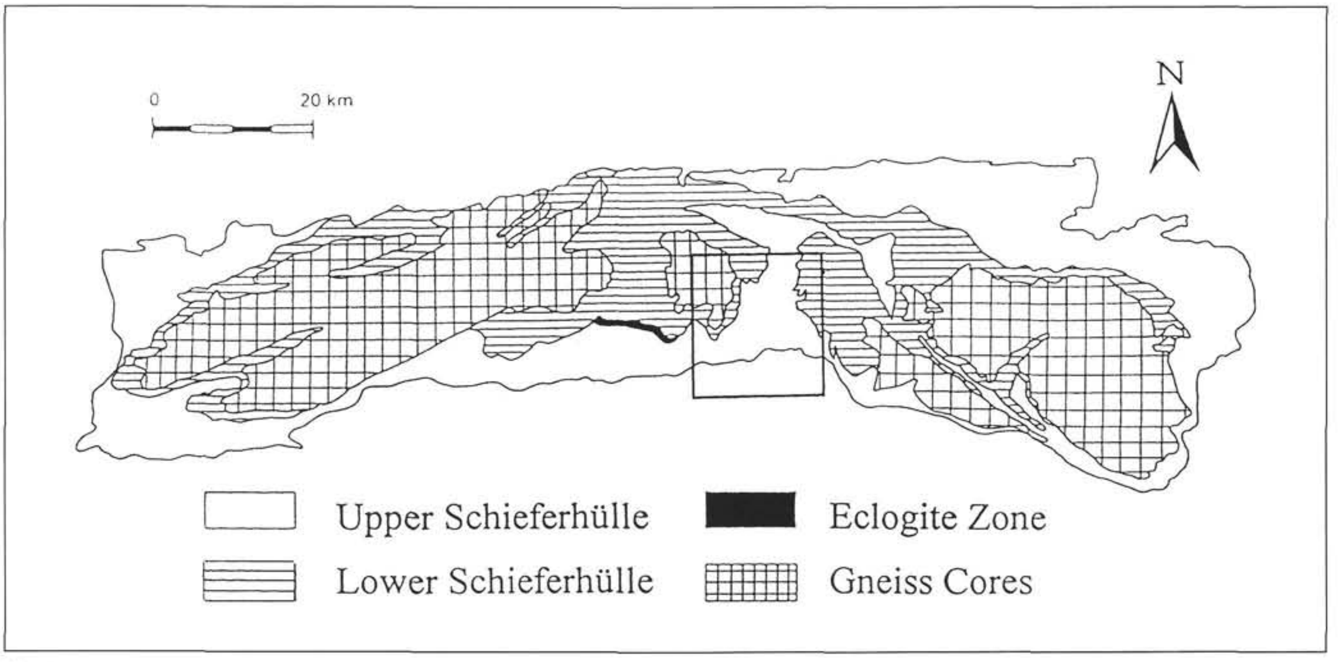


Fig. 1a
Geologic sketch map of the Tauern Window with the four major tectonic units and the sampling area outlined in the central part.

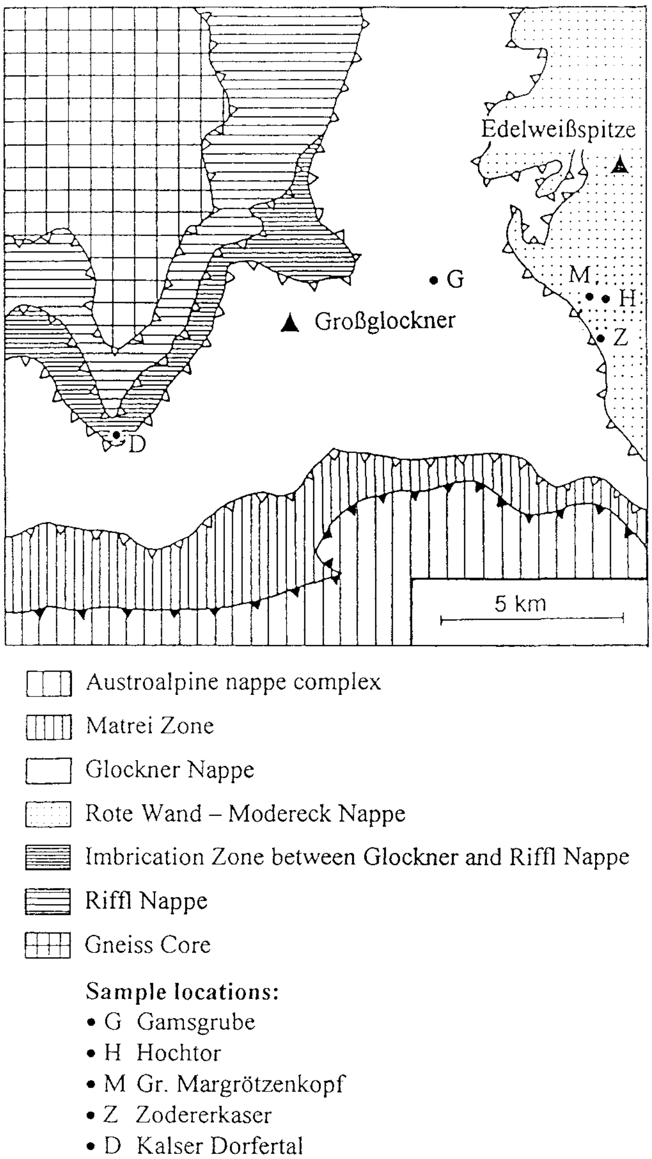


Fig. 1b
More detailed geologic map of the central Tauern Window with nappe units according to KURZ et al. (1996), showing the five sampling localities as described in legend and text.

amphibole has rarely formed in pressure shadows of (earlier) garnet. Generally, however, amphibole (actinolite to magnesiohornblende) forms fine grained symplectitic intergrowths with plagioclase (albite to oligoclase), and is further replaced by chlorite + coarser grained plagioclase. Sometimes amphibole-rich and chlorite+plagioclase-rich domains evolve parallel to schistosity. The most hydrated rock types have almost no amphibole left, or only as fine grained inclusions in eye-shaped plagioclase porphyroblasts. Paragonite is sometimes preserved in the matrix as well, where it is replaced by chlorite. Epidote is present in at least two textural varieties: Old, coarse grained clinozoisite with rutile inclusions is being replaced by chlorite. Texturally younger, more ferric clinozoisite forms fine grained idiomorphic laths. Coarse grained young epidote is found in garnet-pseudomorphs, having grown from former epidote inclusions. Additional phases are calcite and sphene. Sphene overgrows and replaces matrix rutile. Titanohematite may be present as well, especially near garnet or garnet pseudomorphs, either alone or growing from rutile and/or transforming into sphene.

3.2 Hochtor

Eclogites from Hochtor are massive dark green rocks with macroscopically visible garnet and carbonate of up to 1mm in size. The high-pressure minerals are relatively well preserved.

Garnet displays considerable continuous zoning from core ($Alm_{36}Pyr_4Gro_{31}Spe_{29}$) to rim ($Alm_{60}Pyr_{18}Gro_{21}Spe_1$), with a sharp increase of Mg at the outermost rim, inversely correlated to Ca and Fe (Fig. 2). It contains inclusions of epidote, paragonite, glaucophane, omphacite and rutile, as well as ilmenite near its core. Epidote and paragonite often form rhomb-shaped pseudomorphs after lawsonite.

Omphacite (composition around $Jd_{40}Ae_{10}Q_{50}$) is found as inclusions in garnet and in the matrix, forming ovoid grains surrounded by fine grained symplectite. It contains inclusions of rutile, quartz, paragonite, fine grained talc and rare glaucophane.

Glaucophane is also found as inclusions in garnet and in the matrix as cores of pale bluish green amphibole which constitutes relatively coarse grained more or less coherent patchworks intergrown with or partly replacing garnet and omphacite. This amphibole variety is texturally and compositionally very characteristic and significant, also for localities Zodererkaser and Dorfertal (see below). It contains around 0.5 Na pfu in the B-site and around 7.5 Si pfu, thus plotting into the composition fields actinolite, hornblende, winchite, and barroisite (Fig. 3). The term "coarse grained amphiboles" was adopted, therefore, to describe this amphibole variety throughout this paper. They show slight color zoning at their rims and are replaced to a minor degree by symplectitic amphibole (actinolite, magnesiohornblende) + plagioclase (albite) or by even younger chlorite + plagioclase (oligoclase).

Zoisite (X_{Ep}= 0.08-0.16) is present as single grains or more frequently as grain aggregates in the matrix, together with paragonite and quartz, sometimes also enclosing relic glaucophane. Replacement of matrix **rutile** by hematite and sphene is common.

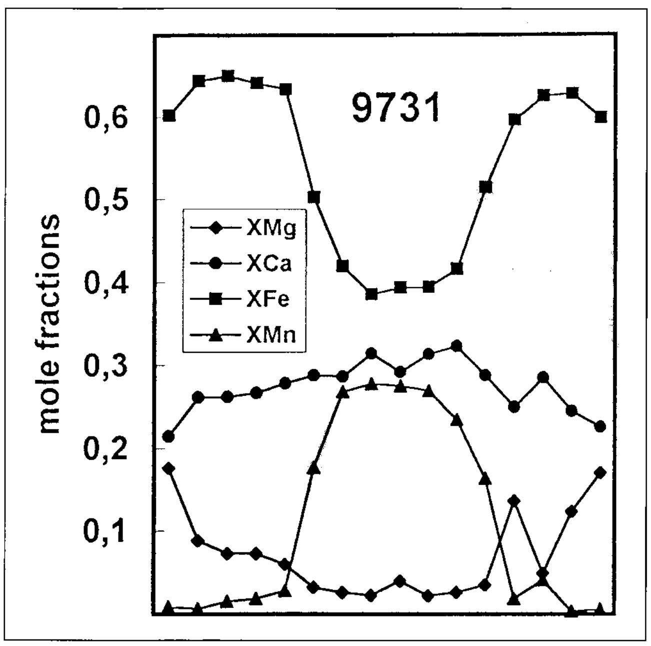


Fig. 2
Garnet rim-core-rim zoning profile from the well preserved eclogite sample 9731 (Hochtor), showing the inverse relationship of Mn and Fe characteristic for the majority of samples. The analyses are equally spaced across the whole grain diameter of about 600 microns.

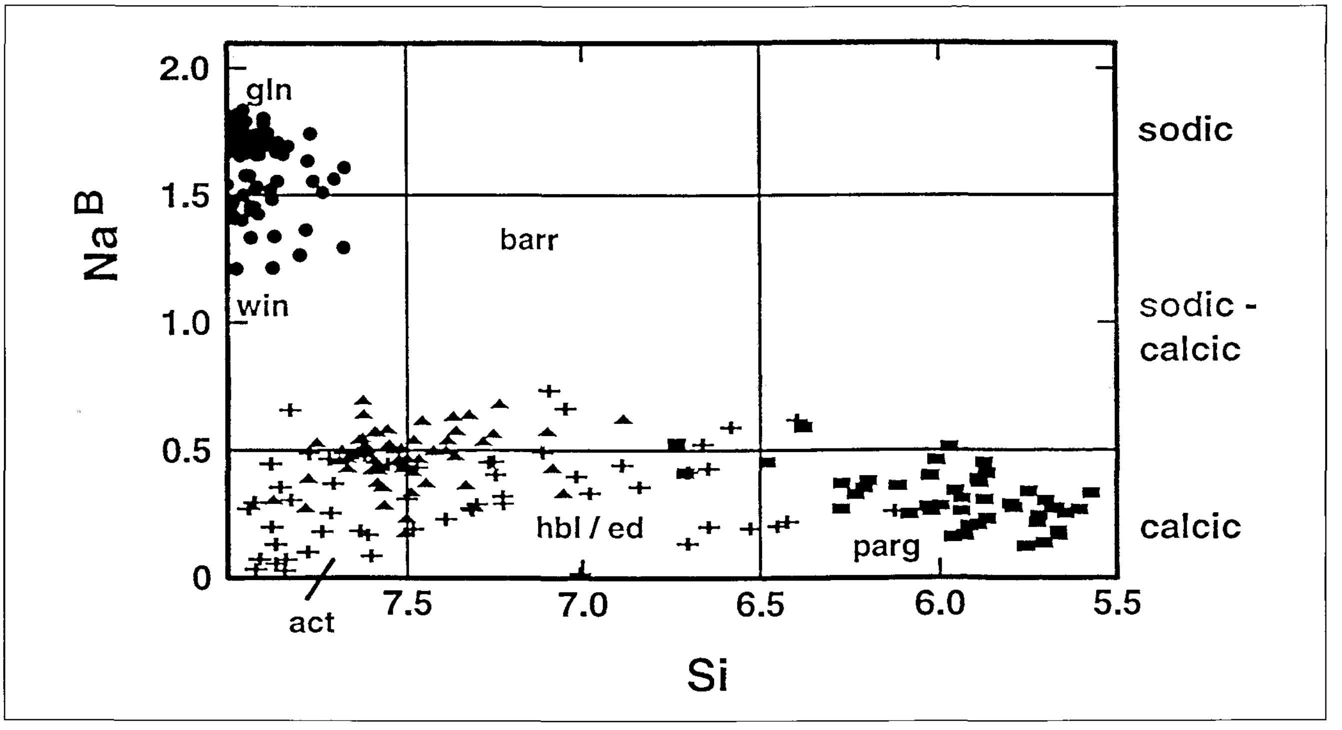


Fig. 3
Compositions of amphiboles from different metamorphic stages, plotted in formula units of Si versus formula units of Na in the B-position (Na^B): stage-II glaucophane and winchite (dots); stage-III coarse grained amphibole (triangles); stage-IV amphiboles in symplectite (crosses) and rims around garnet (rectangles). Amphiboles with Si > 7.0 per formula unit (pfu) have $(Na + K)_A < 0.5$ and $X_{Mg} > 0.5$ and are thus actinolites (act), magnesio-hornblendes (hbl) , barroisites (barr), winchites (win) and glaucophanes (gln). Amphiboles with Si < 7.0 pfu have $(Na + K)_A > 0.5$ and $X_{Mg} < 0.5$ and are thus edenites (ed) and ferropargasites (parg). Nomenclature according to LEAKE et al. (1997).

3.3 Zodererkaser

Retrogressed eclogites are usually medium grained greenish-grey rocks with garnet, amphibole, chlorite, plagioclase, zoisite and calcite. Garnet is almost unzoned, with rim composition $Alm_{66}Pyr_9Gro_{24}Spe_1$. Common inclusion phases are epidote, paragonite, quartz, rutile, ilmenite, sodic-calcic amphiboles (barroisite, winchite) and omphacite. Some garnets contain relics of a magmatic clinopyroxene (augite), overgrown by omphacitic clinopyroxene. High-pressure phases like omphacite and winchite are almost only preserved within garnet. Coarse grained matrix amphibole is preserved mainly in pressure shadows of garnet (Plate 1d). It shows retrograde zoning from bluish green cores to green rims and is replaced by a fibrous type of symplectite (actinolite / magnesiohornblende + albite), sometimes followed by chlorite + albite/oligoclase. The replacement textures, grain shapes and inclusions of garnet, epidote, paragonite and also the transformation sequence of rutile via hematite to sphene are similar to those observed in the Hochtor samples.

3.4 Gamsgrube

The retrogressed eclogite band consists of inconspicious dark green massive to slightly banded and very fine grained rocks. Garnets of less than 1mm size or pseudomorphs of these are sometimes macroscopically discernible, some rocks show color banding by amphibole and epidote rich layers. Small white specks of plagioclase blasts in peripheral samples and brown dots of weathered carbonate can also be recognized in the field. Relic omphacite is almost impossible to identify in the field and a large number of specimens, mostly garnet-bearing ones, were taken in order to find the relics of an earlier eclogite stage.

Most of the samples are retrogressed to a symplectitic amphibolite assemblage of amphibole + epidote + chlorite + plagioclase + quartz + garnet + paragonite + sphene, very often also containing calcite and biotite.

Well preserved eclogite parageneses however consist of garnet + omphacite + dolomite + epidote + paragonite + rutile with some quartz and glaucophane and rare phengite (Plate 1a).

Table 1 contains analyses of minerals from different metamorphic stages and textural positions in a representative sample from this location to illustrate the mineral chemical complexity of these rocks.

Garnet grains are up to 1mm in size, idiomorphic, with inclusion-rich cores and a relatively thin, inclusion-poor rim (Plate 1a). They show typical bell shaped zoning profiles with

Table 1 →
Selected microprobe analyses of phases from various metamorphic stages as preserved in a sample of a retrogressed eclogite from location Gamsgrube (stages: I: pre-eclogite, II: eclogite, III: coarse grained amphibole growth, IV: final hydration; for further details see text). The stage III analysis is a representative coarse grained amphibole from location Dorfertal. Formula units were calculated with the software PET (DACHS, 1998). Fe^{3+} recalculation (mean value) and nomenclature of amphiboles are according to Leake et al. (1997). Fe^{3+} recalculation of garnet, omphacite and Fe-Ti-oxides is according to DROOP (1987). All Fe in epidote, plagioclase and sphene calculated as Fe^{3+}. Abbreviations: grt: garnet; cpx: clinopyroxene, zo/ep: (clino)zoisite/epidote, amph: amphibole, plag: plagioclase, ilm: ilmenite, mag: magnetite, ti-ht: titanohematite, cal: calcite, dol: dolomite, chl: chlorite, omph: omphacite, ae-au: aegirine-augite, gln: glaucophane, tar: taramite, (f-)pg: (ferro-)pargasite, act: actinolite, ed: edenite, mg-ha: Mg-hastingsite, pa: paragonite, phe: phengite, ab: albite, bar: barroisite, i: inclusion, r: rim around, symp: symplectite

Table 1

Mineral	cpx	ilm	grt	grt	cpx	cpx	zo/ep	amph	amph	amph	dol	mica	mica	amph
Name	ae-au				omph	omph		gln	gln	gln		pa	phe	bar
Texture	i-omph	matrix	core	rim	I	II	core	i-grt	core	rim	matrix	matrix	matrix	matrix
Stage	I	I	I	II	II	II	II	II	II	II	II	II	II	III
SiO_2	54.22	0.04	37.07	37.48	55.81	56.40	38.12	55.90	56.90	56.40	0.00	47.51	51.42	49.35
Al_2O_3	4.11	0.02	20.14	20.59	10.17	11.33	27.04	10.60	10.89	10.19	0.00	38.63	26.90	9.76
FeO	22.90	48.58	27.28	29.62	9.88	6.44	7.23	14.90	12.26	14.24	10.91	0.55	3.09	14.84
MgO	2.26	0.41	0.78	1.76	5.18	6.38	0.09	8.00	9.16	8.24	15.6	0.36	3.33	11.93
CaO	4.52	0.65	8.77	8.89	9.36	10.8	23.36	0.91	0.72	0.76	29.91	0.14	0.10	8.46
MnO	0.13	0.88	5.49	1.12	0.03	0.00	0.06	0.16	0.02	0.08	0.39	0.00	0.00	0.16
TiO_2	0.08	48.53	0.13	0.08	0.00	0.18	0.21	0.04	0.05	0.15	0.00	0.04	0.14	0.04
Na_2O	10.88	0.00	0.00	0.00	8.74	8.06	0.00	6.50	6.60	6.42	0.00	7.21	0.71	2.91
K_2O	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.05	0.02	0.04	0.00	1.06	9.37	0.12
Total	99.1	99.11	99.66	99.54	99.19	99.60	96.91	97.06	96.62	96.52	56.81	95.48	95.06	97.57
O-basis	6	3	12	12	6	6	12.5	23	23	23	2	11	11	23
Si	2.01	0.00	3.00	3.01	2.02	2.01	3.00	7.89	7.96	7.98	0.00	3.04	3.43	7.10
Al	0.18	0.00	1.92	1.95	0.43	0.48	2.51	1.76	1.80	1.70	0.00	2.91	2.12	1.66
Fe^{2+}	0.14	0.87	1.78	1.96	0.15	0.15	0.00	1.63	1.40	1.65	0.28	0.03	0.17	1.35
Fe^{3+}	0.57	0.16	0.07	0.03	0.15	0.04	0.48	0.13	0.03	0.03	0.00	0.00	0.00	0.44
Mg	0.13	0.02	0.09	0.21	0.28	0.34	0.01	1.68	1.91	1.74	0.72	0.03	0.33	2.56
Ca	0.18	0.02	0.76	0.76	0.36	0.41	1.97	0.14	0.11	0.12	0.99	0.01	0.01	1.30
Mn	0.00	0.02	0.38	0.08	0.00	0.00	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.02
Ti	0.00	0.92	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.02	0.00	0.00	0.01	0.00
Na	0.78	0.00	0.00	0.00	0.61	0.56	0.00	1.78	1.79	1.76	0.00	0.89	0.09	0.81
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.09	0.80	0.02
Cations	4.00	2.00	8.00	8.00	4.00	4.00	7.99	15.05	15.01	15.02	2.00	7.00	6.95	15.26

Mineral	amph	cpx	zo/ep	zo/ep	amph	amph	amph	amph	plag	chl	cal	mag	ti-ht	sphen
Name	tar	ae-au			f-pg	act	ed	mg-ha	ab					
Texture	i-grt	symp	rim	r-grt	r-grt	symp	symp	symp	symp	symp	matrix	matrix	matrix	matrix
Stage	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	VI
SiO_2	39.95	53.58	37.68	37.23	37.31	52.24	47.42	42.38	68.42	26.71	0.00	0.12	0.07	30.29
Al_2O_3	16.33	3.67	24.17	20.81	18.10	4.3	7.26	11.04	19.32	22.72	0.00	0.36	0.05	1.95
FeO	24.80	14.08	10.53	14.76	19.48	13.05	15.64	19.88	0.19	13.23	1.22	87.53	73.13	0.77
MgO	3.64	7.82	0.06	0.04	6.99	14.65	12.84	9.65	0.03	23.81	0.95	0.13	0.05	0.00
CaO	7.58	14.76	23.05	23.08	10.21	9.61	9.34	10.07	0.22	0.12	55.79	0.44	0.13	28.68
MnO	0.89	0.00	0.17	0.24	0.32	0.15	0.27	0.21	0.00	0.23	0.54	0.05	0.10	0.00
TiO_2	0.72	0.00	0.10	0.06	0.10	0.23	0.30	0.22	0.00	0.00	0.01	0.06	16.17	37.55
Na_2O	4.23	5.46	0.00	0.00	3.74	2.66	3.41	3.41	11.50	0.06	0.00	0.02	0.00	0.08
K_2O	0.15	0.00	0.00	0.03	0.50	0.08	0.23	0.22	0.00	0.00	0.00	0.01	0.00	0.00
Total	98.29	99.37	96.93	97.89	96.75	96.97	96.71	97.08	99.7	86.88	58.51	88.72	89.7	99.41
O-basis	23	6	12.5	12.5	23	23	23	23	8	14	1	4	3	5
Si	6.10	1.99	3.01	3.01	5.69	7.55	7.02	6.42	3.00	2.66	0.00	0.01	0.00	1.00
Al	2.94	0.16	2.28	1.98	3.25	0.73	1.27	1.97	1.00	2.67	0.00	0.02	0.00	0.08
Fe^{2+}	2.68	0.18	0.00	0.00	1.78	1.34	1.52	1.99	0.00	1.10	0.02	0.97	1.49	0.00
Fe^{3+}	0.49	0.25	0.70	1.00	0.70	0.24	0.41	0.53	0.01	0.00	0.00	1.97	1.00	0.02
Mg	0.83	0.43	0.01	0.01	1.59	3.16	2.83	2.18	0.00	3.54	0.02	0.01	0.00	0.00
Ca	1.24	0.59	1.97	2.00	1.67	1.49	1.48	1.64	0.01	0.01	0.95	0.02	0.01	1.01
Mn	0.12	0.00	0.01	0.02	0.04	0.02	0.03	0.03	0.00	0.02	0.01	0.00	0.00	0.00
Ti	0.08	0.00	0.01	0.00	0.01	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.50	0.93
Na	1.25	0.39	0.00	0.00	1.11	0.75	0.98	1.00	0.98	0.01	0.00	0.00	0.00	0.01
K	0.03	0.00	0.00	0.00	0.10	0.02	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Cations	15.75	4.00	7.99	8.01	15.93	15.32	15.62	15.83	4.99	10.01	1.00	3.00	3.00	3.03

inverse Fe-Mn relationship (Fig. 2). Aegirine-augite has been found as cores of omphacite inclusions in garnet. Glaucophane, paragonite, epidote, quartz and calcite can be found in the inner, Mn-richer parts, whereas omphacite and dolomite dominate the outer, relatively inclusion-poor parts. During symplectitization garnet develops polymineralic reaction rims of amphibole + epidote + albite + magnetite (Plate 1b, also see below).

Omphacite-I lies compositionally around $Jd_{40}Ae_{18}Q_{42}$. It occurs as inclusions in garnet and constitutes the bulk of matrix omphacite (Plate 1a). It is very homogenous in BSE-imaging or slightly patchy, signalling incipient decomposition. Omphacite-II ($Jd_{50}Ae_5Q_{45}$) forms along the boundaries of omphacite-I against garnet, sometime before symplectite formation (Plate 2a). Diopside-rich clinopyroxene grows from omphacite, mostly near and around quartz grains, during symplectization (Plate 1b).

Amphiboles appear in a great variety of compositions (Fig. 3). Primary amphibole inclusions in garnet are winchite and mostly glaucophane ($X_{Mg} = 0.6$), often with taramite rims or completely replaced by taramite or pargasite. Matrix glaucophane is more Mg-rich ($X_{Mg} = 0.7$) and decomposes during decompression in the symplectite stage to more siliceous compositions (winchite – magnesiohornblende – actinolite) near quartz, and more aluminous compositions (magnesiohornblende – edenite – pargasite) next to epidote or paragonite (Plate 2d, Table 2b). Amphibole rims around garnet, evolving in the symplectite stage, are always deep bluish-green pargasite (Plate 1d), whereas symplectite amphibole varies again between actinolite, hornblende and edenite.

Epidotes are stable throughout the entire range of recorded metamorphic conditions and show a great variability in compositions within and among samples. Coarse grained zoisite and clinozoisite may be found coexisting/intergrown in the best preserved eclogite samples, whereas inclusions in garnet are zoned from epidote cores ($X_{Ep} = 0.7$-0.9) to clinozoisite rims ($X_{Ep} = 0.25$-0.45). Symplectite stage epidote in garnet rims is the most ferric one ($X_{Ep} = 0.85$-1.00), rims around paragonite are in the range of $X_{Ep} = 0.5$-0.6. Matrix clinozoisites develop rims of $X_{Ep} = 0.80$ to 1.00, or decompose to fine epidote grains. Chrome-rich epidote (up to 8 wt% Cr_2O_3) occurs around relics of chromite.

Phengite was rarely found as inclusion in garnet (3.27-3.30 Si pfu) or in the matrix (3.2-3.4 Si pfu).

Paragonite is a typical and abundant phase of the eclogite stage. Thin rims of clinozoisite develop around paragonite during the symplectite stage (Plate 1b). Paragonite breaks down to chlorite in the latest stage of metamorphism.

Calcite and ferrous dolomite are the only carbonate phases encountered. Calcite is sometimes preserved as inclusions in garnet cores. Dolomite is preserved as marginal inclusions in garnet and in larger amounts in the matrix of the least altered eclogite samples. Thin calcite rims around dolomite and sometimes marginal enrichment in Fe and Mn are characteristic for beginning hydration even before decomposition to calcite. Full conversion to calcite is observed in the most retrograde samples.

A considerable number of Fe-Ti-phases have been found in metastable coexistence in many of the samples: **rutile** is usually the first of the Fe-Ti-phases, preserved as inclusions in garnet, epidote or white mica, and is the main matrix Ti-phase in well preserved eclogites. Occasionally it is overgrowing or intergrown with earlier **ilmenite,** which is considered magmatic in origin. Such intergrowths can be found mainly as inclusions in garnet. **Titanohematite** is definitely a product of omphacite breakdown during late stage hydration. It may form overgrowths on rutile or separate grains and both types may be overgrown by later sphene, depending on the degree of retrogression. **Magnetite** occurs mainly in the symplectite stage. In some samples it is concentrated along the outer margins of polymineralic rims around garnet, in other cases it is more evenly distributed throughout the symplectite. **Sphene** is always the latest Ti-phase forming and stable in the most retrograde eclogites. Its Al-content is low, usually around 1-2 wt% Al_2O_3.

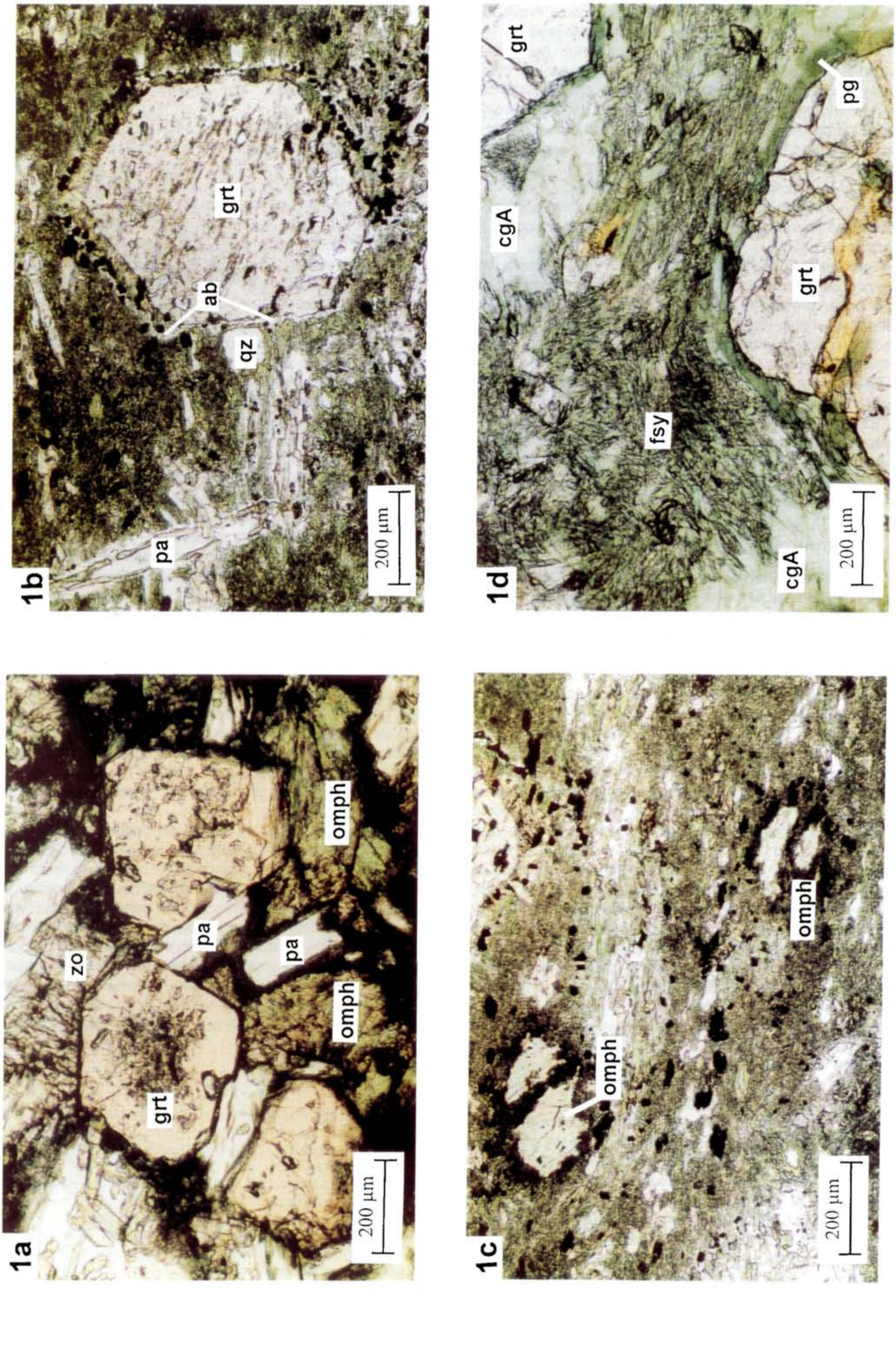
3.5 Dorfertal

Several samples of glaucophane-paragonite eclogite, comparable to those from Gamsgrube, have been found in the retrogressed eclogite band here. Others, however, can be labelled omphacite-bearing amphibolite, as they are composed of dominant coarse grained, mainly barroisitic amphibole, together with garnet (hypidiomorphic to xenomorphic), epidote, some paragonite, rutile and very little or no quartz. In the omphacite-bearing amphibolites, barroisite growth drastically reduces the amount of omphacite present, which remains as xenomorphic symplectized relics in the matrix or as rare inclusions in garnet and clinozoisite. Coarse grained amphibole also replaces and/or overgrows glaucophane and corrodes garnets marginally or even pervasively by invading the inclusion area. Clinozoisite starts to replace paragonite. Rutile is taken up as inclusions in the coarse grained amphiboles.

Garnet chemical zoning is rather smooth and bell-shaped. Similar to the other localities, garnet compositions range from an extreme of $Alm_{51}Pyr_5Gro_{34}Spe_{10}$ in the core to generally about $Alm_{64}Pyr_{11}Gro_{23}Spe_2$ in the rim, where a sudden drop in the outermost 10-30μm to about $Alm_{57}Pyr_{20}Gro_{22}Spe_1$ is often observed. Actinolite rimmed by barroisitic amphibole, and some diopside-rich clinopyroxene ($Jd_{18}Ae_{14}Q_{68}$) are regarded as pre-eclogite stage inclusions, possibly also some plagioclase, chlorite, calcite and sulfides. Inclusions are generally either very rare and fine grained in the highly deformed samples or abundant and large in the less deformed ones, where either primary inclusions of epidote, paragonite, quartz, glaucophane and omphacite, or secondary inclusions of coarse grained amphibole can be found.

Omphacite compositions and types are very similar to those from Gamsgrube: Type I (around $Jd_{38}Ae_9Q_{53}$) is dominant as inclusions or in the matrix, type II ($Jd_{43}Ae_3Q_{54}$) appears rarely along type I margins, close to garnet, quartz and sym-

Plate 1 →
Photomicrographs of retrogressed eclogites under plane-polarized light, bar is 200 μm in each case. a) Eclogite paragenesis from Gamsgrube: garnet (grt), omphacite (omph), paragonite (pa) and zoisite (zo). Additional dolomite, glaucophane, quartz and phengite are not within view. Dark areas show incipient breakdown to extremely fine grained symplectite. b) Gamsgrube: Replacement of idiomorphic garnet by polycrystalline rims of pargasitic amphibole + epidote (inner rim) and albite (ab) + magnetite (outer rim). Note the lack of corrosion of garnet along grain boundaries with matrix quartz (qz) and the light green rims of diopside around quartz grains. Paragonite (pa) is rimmed by clinozoisite and albite. c) Gamsgrube: Omphacite relics (omph) in symplectite matrix. Extremely fine grained symplectite near omphacite appears dark. Both hematite and magnetite can be found in the matrix. d) Zodererkaser: Coarse grained amphibole (cgA), grown or preserved mainly in garnet pressure shadows, but otherwise transforming to fibrous symplectite (fsy). Grain boundaries against garnet show transition in color and composition to ferropargasite.


1a
grt
zo
pa
pa
omph
omph
200 µm
1b
grt
ab
qz
pa
200 µm
1c
omph
omph
200 µm
1d
grt
cgA
pg
grt
fsy
cgA
200 µm

plectite. Diopside-rich clinopyroxene is a typical breakdown product of the symplectite stage around quartz grains.

Amphiboles range from pre-eclogite stage actinolite to winchite/glaucophane in inclusions and cores of coarse grained matrix amphiboles, and from the latter (mainly barroisites and magnesiohornblendes) to the various compositions (pargasite, actinolite, hornblende) of the final hydration stage. Glaucophane or highly sodic winchite are relics preserved either as inclusions in garnet or dolomite or in the cores of later amphiboles (Plate 2a, b). Glaucophane abundance is inversely related to that of dolomite, and sometimes only a few corroded grains included in dolomite are preserved outside garnet.

Epidotes from Dorfertal show great similarity to those from Gamsgrube. Some samples also have coexisting zoisite and clinozoisite preserved from the eclogite stage, whereas most others show core-rim zoning from around $X_{Ep} = 0.35 - 0.65$ or growth of small late stage epidote grains. Epidote in rims around garnet has about $X_{Ep} = 0.85$.

Phengite is again a rare mineral. 3.32 Si pfu were measured in a matrix phengite. Early **plagioclase** is always albite and evolves into a range of $X_{Ab} = 0.71 - 0.99$. **Carbonate,** if present, is dolomite, which is rimmed and replaced by calcite during retrogression. **Fe-Ti-phases** reaction sequences are the same as those described from Gamsgrube.

4. Metamorphic evolution

A considerable number of similarities exist in the mineralogic and textural evolution of rocks from the various localities, and a generalized scheme of metamorphic evolution seems justified. Major differences are pointed out where appropriate.

I. The **pre-eclogite stage** can be verified in only a few samples. Chromite and augitic clinopyroxene can be interpreted as relic magmatic phases. Ilmenite reacting to form rutile during high-pressure metamorphism is probably magmatic in origin as well, as sphene is considered the stable Ti-phase in low-temperature metabasites. Plagioclase, chlorite, calcite, actinolite and actinolite cores of barroisitic amphibole, all included in the cores of well preserved garnets, are considered remnants of a pre-eclogite stage, possibly of greenschist facies ocean floor metamorphism. Such pre-eclogite stage relics were found in samples from Zodererkaser, Gamsgrube and Dorfertal. The early high-pressure path through the blueschist facies may be deduced from the appearance of aegirine augite, from barroisite overgrowing earlier actinolite, from winchite/glaucophane and from rectangular or rhomb-shaped lawsonite pseudomorphs, all found as inclusions in garnet.

II. All of the best preserved **eclogite stage** samples fall into the field of paragonite-glaucophane eclogites. The modal amounts of glaucophane, however, are always low and may in some instances be only relic inclusions in garnet, epidote-aggregates and dolomite. Paragonite shows incipient replacement by coarse grained clinozoisite. Some large garnets that still contain pre-eclogite stage inclusions in their cores and show strong bell shaped zoning with inverse Fe-Mn relationship, incorporate omphacite, dolomite and rutile as inclusions in their outer parts during eclogite stage growth.

III. Coarse grained amphibole growth is reported from Dorfertal, Zodererkaser and also Hochtor, but not confirmed for Gamsgrube. It was caused by hydration during exhumation of the eclogites **(coarse-grained ampohibole stage; cgA-stage),** but it is difficult to establish whether this stage is confined to the eclogite facies or extends into the epidote-amphibolite facies: Plagioclase appears in some of the samples, but never coarse grained and always in very minor amounts, and is interpreted as a product of the last (final hydration) stage. Because plagioclase apparently does not form during the cgA-stage, the growth of coarse grained amphiboles is considered to have occurred still within the eclogite facies.

IV. The majority of samples from each locality display mineral parageneses and compositions of the **final hydration stage.** Some thin sections show a continuous transition from symplectized eclogite to amphibolite or from amphibolite to greenschist, pervasively along layers or radiating from cross-cutting fractures. Relic parageneses of earlier stages, including minerals like garnet, paragonite and barroisite, are replaced and pseudomorphed by more hydrated parageneses. The different parageneses and mineral compositions are therefore attributed to variable degrees of hydration rather than to variable PT-conditions, although the process of eclogite retrogression may have occurred over a certain PT-range.

Different degrees of hydration of eclogite produce the following sequence of features:

IVa. **Trace hydration stage:** Thin rims of pargasitic amphibole around garnet occur at contacts with omphacite or glaucophane, together with minor plagioclase further towards the matrix. Paragonite acquires a thin rim of amphibole as well along grain boundaries with omphacite. The trace hydration stage also produces marked compositional and color changes at the rims of coarse grained amphiboles, outlining all grain boundaries in the amphibole patchwork.

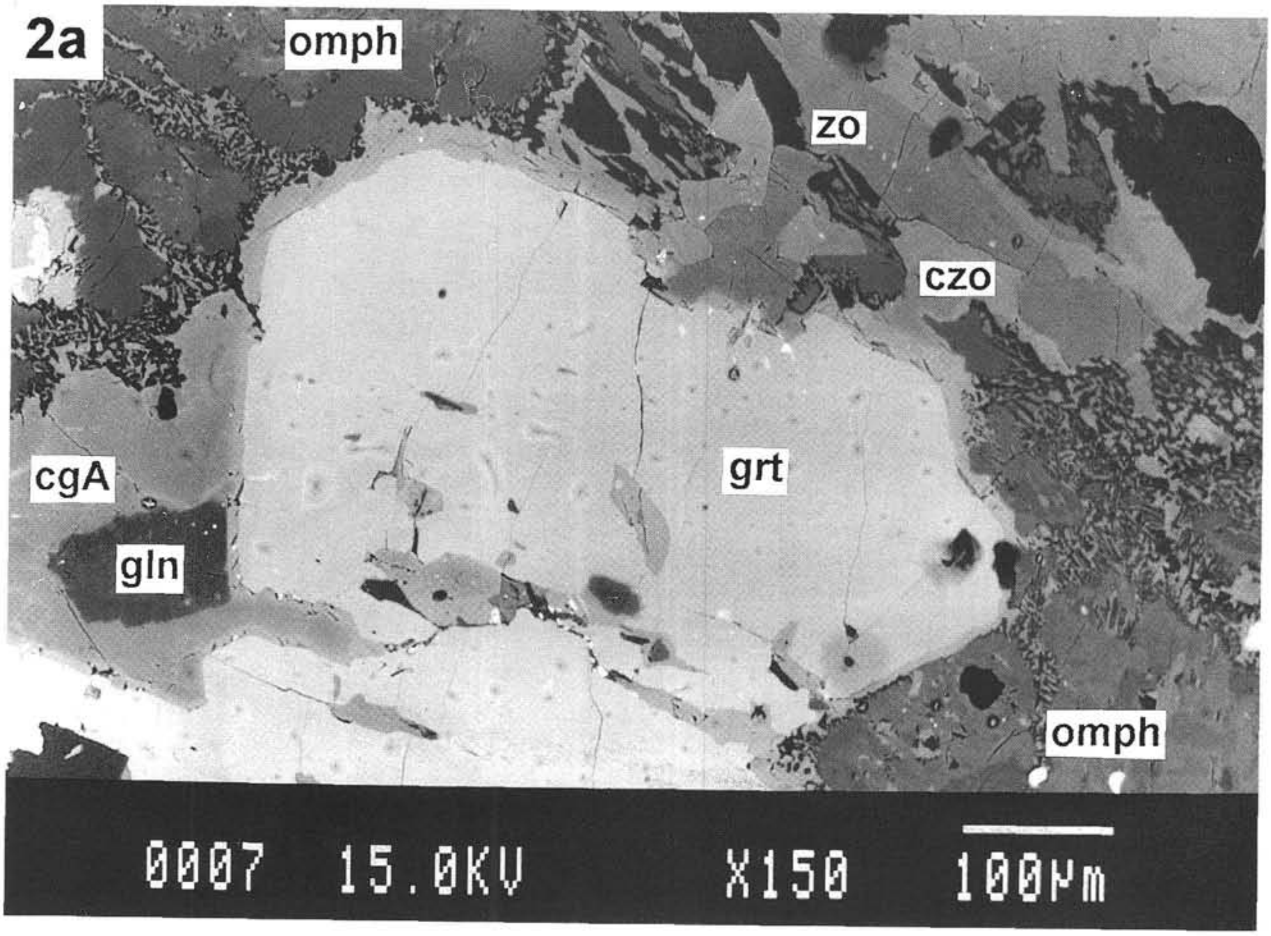
IVb. **Symplectite stage:** omphacite transforms into a very fine grained aggregate of plagioclase + amphibole and/or diopsidic clinopyroxene, which may contain dispersed minute grains of magnetite and/or hematite. Glaucophane becomes symplectized as well. Quartz is rimmed by diopside-rich clinopyroxene of a light green color. Garnet is fully rimmed by bluish-green pargasitic amphibole and Fe-rich epidote, with an additional outer rim of plagioclase ± magnetite. Inclusions within garnet are often affected by the transformations of this stage as well, especially glaucophane, which is partly or fully replaced by amphibole of variable composition. Paragonite gets an inner rim of epidote and an outer rim of plagioclase. Rutile is replaced by titanohematite. Ferrous dolomite is rimmed by calcite.

The symplectite stage in omphacite bearing amphibolites differs from that of normal eclogites in two respects. Symplectization may not be very abundant, as omphacite relics are rare and the coarse grained amphiboles have a tendency to recrystallize and develop compositional zoning instead of decomposing. In some instances however, a symplectitic breakdown of barroisite is observed, where symplectite-amphibole is fibrous rather than isometric in texture ("fibrous symplectite", Plate 1d). Thus one can observe "normal" and "fibrous" symplectite depending on the mineral precursor, and it becomes possible to deduce a prior cgA-stage from "pseudo-

Plate 2 a, b →

Back-scattered electron images of samples from Dorfertal (a,b) and Gamsgrube (c,d). Size is indicated by a bar of 100μm (a,b) and 10 μm (c,d) respectively. a) Eclogite with garnet (grt) surrounded by patchy omphacite (omph; dark grey), coarse grained amphibole (cgA) with a glaucophane core (gln; lower left) and coexisting zoisite (zo) and clinozoisite (czo). Clinozoisite and amphibole are corroding the garnet and develop rims during the symplectite stage.

b) Coarse grained amphibole (cgA) with a slightly inhomogenous glaucophane (gln) core in a matrix of symplectite, which preferrentially corrodes the glaucophane core.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omph
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czo
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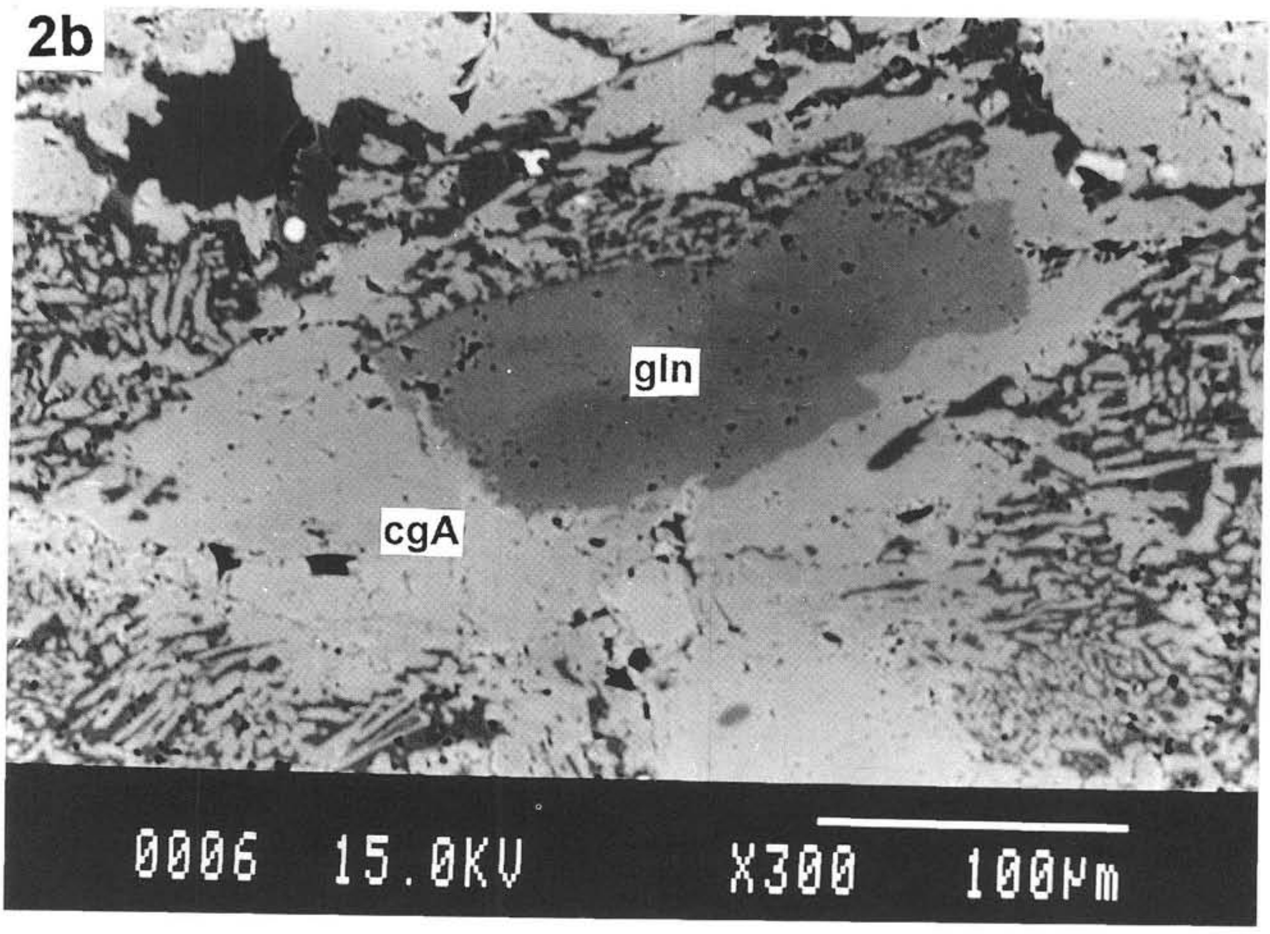

2b
gln
cgA
0006 15.0KV X300 100µm

morphs" of fibrous symplectite after coarse grained amphibole, even when no mineral relics are preserved. Omphacites and glaucophane inclusions in barroisite form the common type of symplectite instead.

IVc. **Recrystallized symplectite stage:** Plagioclase and amphibole of the symplectite become coarser grained and compositional differences to amphibole rims around garnet are smoothed out. Rims around quartz and paragonite disappear, dolomite has more or less fully converted to calcite and sphene starts to overgrow rutile or titanohematite of earlier stages. Omphacite and glaucophane have completely disappeared and xenomorphic garnet shows hardly any inclusions of these minerals any longer. First chlorite appears along cracks or around garnet and paragonite.

IVd. **Chlorite stage:** Chlorite grows from paragonite, garnet and sometimes epidote and the modal amounts of amphibole decrease. Plagioclase becomes modally abundant and shows different stages of recrystallization from amoeboid/inclusion rich towards eye-shaped/inclusion poor single crystals. It partly turns from albite to oligoclase. Garnet is replaced either by chlorite + epidote ± magnetite or by chlorite + biotite. The earlier amphibole rims have long disappeared. Different types of schists evolve, depending on which of the minerals amphibole, garnet and paragonite have already reacted off. The main rock type is greenschist, as usually some amphibole is preserved in a groundmass of chlorite, plagioclase, epidote, calcite, quartz and sphene ± hematite, magnetite. This paragenesis is equivalent to that found in metabasic country rocks.

Table 2a
Microprobe analyses of an omphacite inclusion in paragonite and its breakdown products, as shown in the BSE-image of Plate 2c. The outer rim towards paragonite is a pargasitic amphibole with a barroisite core (analyses 6 and 7), the inner zone is dominated by more SiO_2-rich amphiboles + albite. Abbreviations as in Table 1, wi: winchite

Point #	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Name	*omph*	*act*	*ed*	*wi*	*ab*	*pg*	*bar*
SiO_2	55.71	53.35	47.82	55.25	68.94	40.78	49.92
Al_2O_3	9.02	3.70	7.66	4.92	19.95	15.98	9.04
FeO	10.34	10.56	12.48	8.21	0.13	14.68	12.51
MgO	5.80	16.91	14.56	16.17	0.01	10.60	13.44
CaO	10.86	10.03	10.24	9.41	0.07	9.79	7.36
MnO	0.02	0.17	0.09	0.12	0.08	0.11	0.09
TiO_2	0.11	0.01	0.14	0.08	0.02	0.18	0.10
Na_2O	7.70	2.16	2.98	2.45	11.22	4.35	4.10
K_2O	0.00	0.11	0.16	0.04	0.00	0.40	0.25
Total	99.56	97.00	96.13	96.65	100.4	96.87	96.81
O-basis	6	23	23	23	8	23	23
Si	2.02	7.60	7.02	7.80	2.99	6.05	7.18
Al	0.39	0.62	1.33	0.82	1.02	2.80	1.53
Fe^{2+}	0.20	0.94	1.21	0.94	0.00	1.31	1.10
Fe^{3+}	0.11	0.32	0.32	0.03	0.01	0.51	0.40
Mg	0.31	3.59	3.19	3.40	0.00	2.35	2.88
Ca	0.42	1.53	1.61	1.42	0.00	1.56	1.13
Mn	0.00	0.02	0.01	0.01	0.00	0.01	0.01
Ti	0.00	0.00	0.02	0.01	0.00	0.02	0.01
Na	0.54	0.60	0.85	0.67	0.94	1.25	1.14
K	0.00	0.02	0.03	0.01	0.00	0.08	0.05
Cations	4.00	15.24	15.58	15.11	4.97	15.94	15.44
Na^B		0.38	0.30	0.57		0.39	0.75
$(Na+K)^A$		0.24	0.58	0.11		0.94	0.44

5. Discussion of some symplectite stage features

A detailed microprobe investigation of the minute reaction textures of the symplectite stage reveals some astonishing features, underlining the importance of very small scale equilibrium and kinetics in that stage.

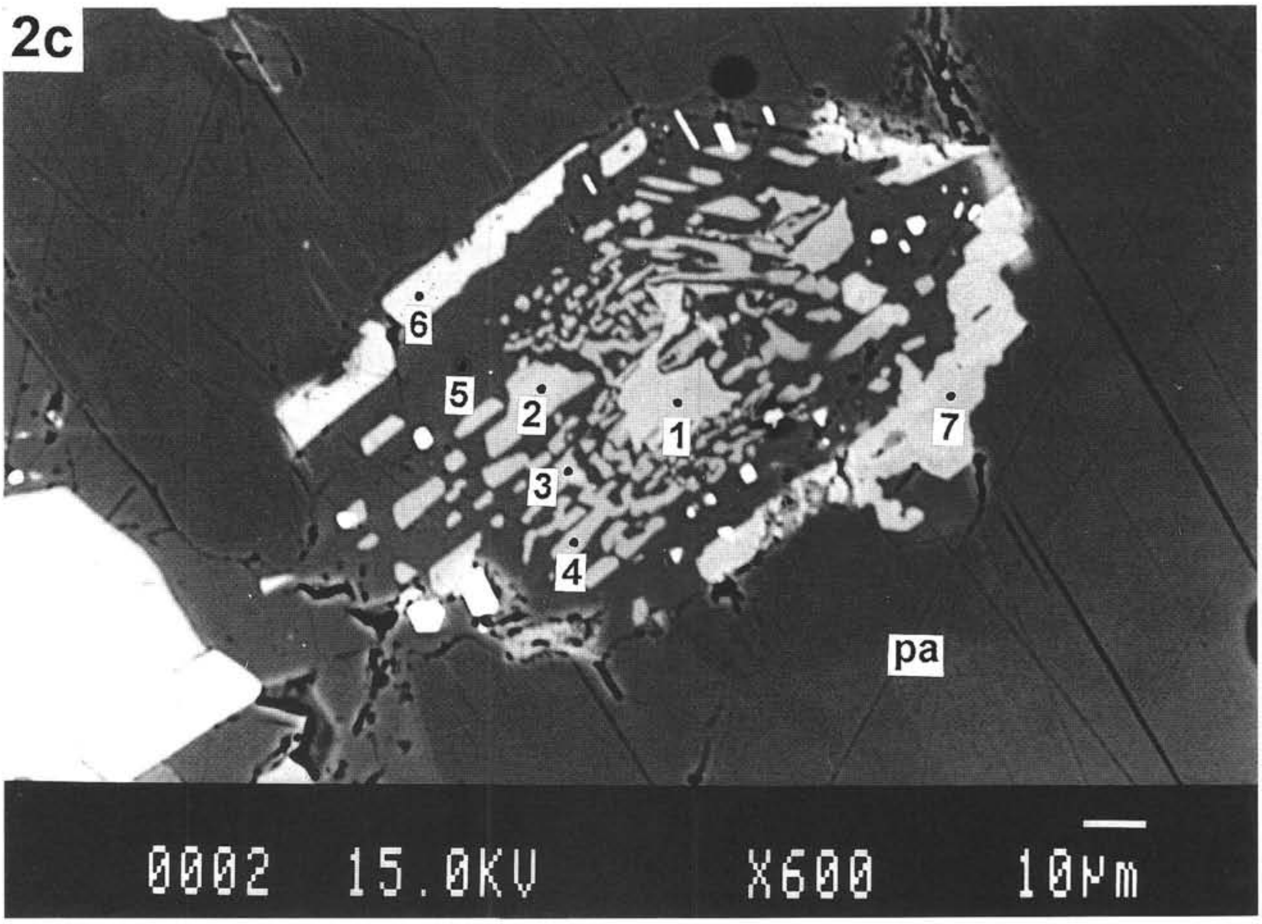
Omphacite is definitely the least stable mineral outside the eclogite facies and the one breaking down fastest. The first feature evolving mainly along grain boundaries, but sometimes throughout the grain of formerly very homogenous omphacites, is a decomposition into small irregularly shaped domains of slightly variable composition, which become apparent in back scattered electron imaging (Plate 2a). This happens immediately before the final lattice breakdown and the formation of albite and another phase, which can be diopside-rich clinopyroxene or an amphibole of hornblende to actinolite composition. The grain size of the breakdown products usually increases at a slight distance away from relic omphacite grains (Plate 1c). The presence of free silica favors diopside formation. This becomes evident from the rims around quartz grains, which are always diopside, and also from the reaction equation of the formation of albite from jadeite, which requires quartz. If silica is not supplied in sufficient quantity, an amphibole, which is always poorer in silica than diopside, forms instead. Diopside is structurally and thus kinetically favored over amphibole, however, which is the thermodynamically stable phase, in more hydrated eclogites.

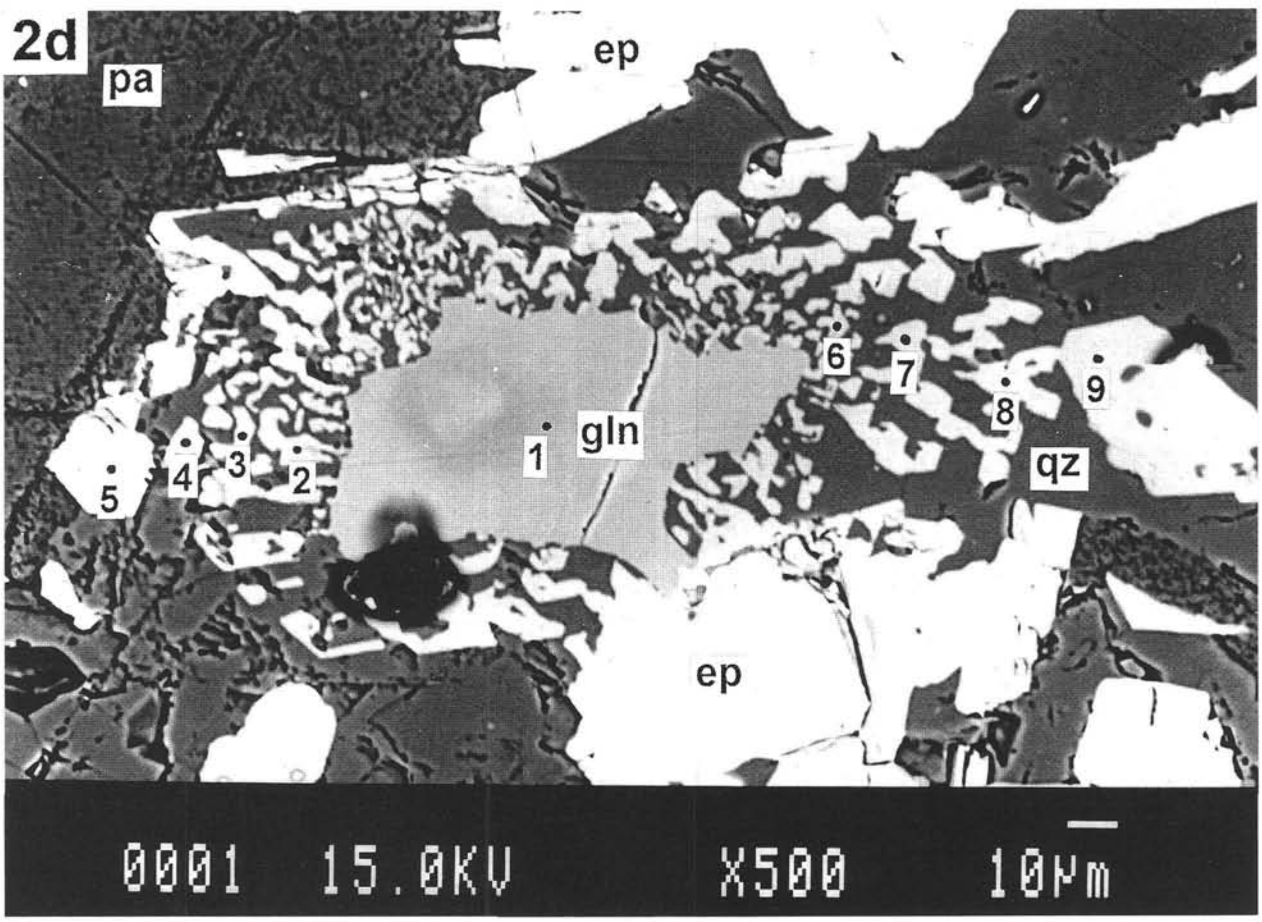
The compositions of amphiboles as well as those of plagioclases within a single symplectite area can vary, which is also indicative of the importance of chemical potential gradients over small distances in the symplectite stage. The symplectitic breakdown of an omphacite inclusion within paragonite for example shows Al-poor symplectite amphibole near the omphacite relic in the center and Al-rich pargasite along the paragonite grain boundary (Plate 2c, Table 2a). No diopside formed in this case.

Glaucophane breakdown occurs in a very similar fashion to that of omphacite, although diopside was never observed as a product. The contact relationships are again important for the composition of symplectite amphiboles forming: For example, one observes gradually decreasing Si-content of amphibole towards paragonite, while breakdown amphiboles near quartz are Si-rich (Plate 2d, Table 2b). In many instances, symplectite in the cores of coarse grained amphibole suggests the presence of former glaucophane.

The reactions of garnet in the symplectite stage are very revealing with regard to the general characteristics of hydration and element mobility of this stage. Textures indicate that garnet reacted gradually from its rim inwards, being replaced volumetrically by amphibole and epidote (Plates 1b, 2a). This rim-amphibole either nucleates and grows from decomposing omphacite or continues growing from glaucophane or barroisite already present in the matrix. Rim-epidote also often continues growing from matrix epidote. The thickness of the rim is independent of mineralogy, indicating dissolution-controlled reaction, and can always be recognized from the very different color of the new amphibole or epidote forming. Amphibole is deep bluish-green ferropargasite, i.e. very rich in Al

Plate 2 c,d) →
c) Symplectized former omphacite inclusion in paragonite (pa). Relic omphacite in the center, different types of amphibole evolving towards the paragonite host. Numbers refer to analyses in Table 2a.
d) Symplectized former glaucophane between paragonite (pa), epidote (ep) and quartz (qz). Relic glaucophane in the center, different types of amphibole evolving towards the neighbors. Numbers refer to analyses in Table 2b.


2c
6
5
2
1
7
3
4
pa
0002 15.0KV X600 10µm


2d
pa
ep
6
7
9
8
gln
1
5
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3
2
qz
ep
0001 15.0KV X500 10µm

Table 2b
Analyses of a glaucophane inclusion in paragonite and its breakdown amphiboles, as shown in the BSE-image of Plate 2d. Analyses 2 - 5 show gradually decreasing Si-contents of amphibole towards paragonite as adjacent mineral. If quartz is the neighbour, the breakdown amphiboles of glaucophane stay Si-rich (analyses 6 - 9). Abbreviations as in Table 1, mg-hbl: magnesio-hornblende, wi: winchite

Point #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Name	gln	mg-hbl	mg-hbl	ed	pg	wi	mg-hbl	act	act
SiO_2	56.87	51.32	49.57	45.80	43.17	53.51	50.43	52.15	54.52
Al_2O_3	10.57	5.39	6.49	9.29	13.77	7.23	4.65	3.75	1.71
FeO	13.39	11.93	13.01	15.23	16.25	12.25	13.71	12.91	13.39
MgO	8.58	15.01	14.22	12.72	9.97	12.59	14.28	15.46	15.62
CaO	0.88	10.09	9.78	9.99	8.79	7.64	10.11	9.78	9.24
MnO	0.01	0.18	0.22	0.13	0.16	0.15	0.21	0.18	0.17
TiO_2	0.05	0.07	0.10	0.06	0.20	0.01	0.18	0.09	0.00
Na_2O	6.46	2.43	2.93	3.25	4.07	3.62	2.42	2.15	1.88
K_2O	0.04	0.07	0.06	0.15	0.58	0.11	0.09	0.01	0.06
Total	96.85	96.49	96.38	96.62	96.96	97.11	96.08	96.48	96.59
O-basis	23	23	23	23	23	23	23	23	23
Si	7.99	7.43	7.24	6.78	6.42	7.64	7.41	7.55	7.86
Al	1.75	0.92	1.12	1.62	2.41	1.22	0.81	0.64	0.29
Fe^{2+}	1.56	1.21	1.29	1.46	1.63	1.38	1.41	1.17	1.31
Fe^{3+}	0.01	0.24	0.30	0.42	0.39	0.09	0.28	0.39	0.30
Mg	1.80	3.24	3.10	2.81	2.21	2.68	3.13	3.33	3.36
Ca	0.13	1.57	1.53	1.59	1.40	1.17	1.59	1.52	1.43
Mn	0.00	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.02
Ti	0.01	0.01	0.01	0.01	0.02	0.00	0.02	0.01	0.00
Na	1.76	0.68	0.83	0.93	1.17	1.00	0.69	0.60	0.52
K	0.01	0.01	0.01	0.03	0.11	0.02	0.02	0.00	0.01
Cations	15.01	15.33	15.46	15.67	15.80	15.22	15.38	15.23	15.11
Na^B	1.76	0.37	0.38	0.29	0.49	0.81	0.33	0.37	0.43
$(Na+K)^A$	0.01	0.33	0.46	0.67	0.80	0.22	0.38	0.23	0.11

and Fe^{2+}, the Si, Al and sometimes Ca content being almost equal to that of the garnet precursor. Epidote is distinctly richer in Fe^{3+}, displaying a strong yellow color. As epidote composition is also very similar to that of garnet, both phases are apparently the most adequate reaction products for the case of practically immobile Si and Al.

The reaction rims around garnet are continuous with only one exception: when quartz grains are next to garnet. In this case diopside formation around quartz is dominant and the albite of the outer rim around quartz is in touch with garnet, which does not corrode (Plate 1b).

Garnets in a completely symplectized former omphacite-rich domain often evolve an outer rim of albite plus magnetite. Magnetite and hematite can also be found further out in the symplectite, but magnetite is definitely concentrated in the rim (Plate 1b). This is obviously the place where Fe^{2+} is released from the reacting garnet to form magnetite, whereas hematite predominates in the matrix.

Magnetite rims are never preserved in the more hydrated samples, where magnetite either disappears or is equally distributed in minor amounts throughout the matrix, together with hematite.

6. Conclusions

The current state of knowledge on the retrogressed eclogites from the Glockner region allows the postulation of the following metamorphic evolutionary scenario on textural grounds: Metabasic rocks, partly carbonated and with igneous relics, were subjected to eclogite facies conditions in the stability field of glaucophane + paragonite (in a subduction zone). They were partially rehydrated after the peak of metamorphism, but still within the eclogite facies (cgA-stage).

The mineral assemblages and compositions produced during stage-IV in the most hydrated eclogites are equivalent to those observed and reported from metabasic country rocks (e.g. RAITH et al. 1977, FRANK et al. 1987, HOINKES et al. 1999), which is why we regard this stage coeval with the main metamorphic overprint of the Glockner and Rote Wand-Modereck nappe.

Co-facial metamorphism of eclogites and metasedimentary country rocks is confirmed only for the Eclogite Zone (MILLER 1977, HOLLAND 1979, FRANZ & SPEAR 1983, DACHS 1986, SPEAR & FRANZ 1986). The great majority of metabasites of the Glockner nappe show an early blueschist facies stage, but no signs of an eclogite stage prior to the medium grade regional metamorphism have hitherto been reported. This is why we favor tectonic emplacement of eclogites in the Bündner schists of the Glockner nappe over the alternative of a common high-pressure evolution of large parts of this tectonic unit. Metabasites are of subordinate abundance in the Rote-Wand-Modereck-nappe and no indications of eclogite facies metamorphism have been hitherto reported for this unit (FRASL, 1958, though mentioning eclogitic prasinite outcrops near the Modereck, did not regard these rocks as "true eclogites" formed under eclogite facies conditions). This also suggests tectonic emplacement of eclogite slices, rather than in situ high-pressure metamorphism.

Textural observations are of major importance in interpreting retrograde metamorphic stages and grades. New textural findings of this study are the dependence of the formation of symplectitic diopside on the presence of free quartz and the genetic interpretation of fibrous symplectite. Further details on reactions, mineral chemistry and the PT-history derived will be covered in a subsequent publication (DACHS & PROYER, submitted).

7. Acknowledgements

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Appendix

List of abbreviations:

Alm almandine
Pyr pyrope
Gro grossular
Spe spessartine
$Alm_{42}Pyr_{4}Gro_{38}Spe_{16}$ denotes mole fractions of each end member in garnet
Jd jadeite
Ae aegirine
Q quadrilateral clinopyroxene component (enstatite + ferrosilite + wollastonite)
$Jd_{50}Ae_{5}Q_{45}$ denotes mole fractions of each end member in omphacite
cgA coarse grained amphibole
pfu per formula unit
X_{Ep} mole fraction of component $Ca_2Al_2Fe[Si_3O_{12}/(OH)]$ in epidote
X_{Ab} mole fraction of albite in plagioclase
X_{Mg} Mg/(Mg + Fe)
m meters
μm microns
sqm square meters

Other abbreviations see Table 1 and figure captions.

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