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Autor(en): **Dachs, E.**

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High-pressure mineral assemblages and their breakdown-products in metasediments South of the Grossvenediger, Tauern Window, Austria

by *E. Dachs*[1]

Abstract

Permomesozoic metasediments of Penninic series south of the Grossvenediger, Austria, have been studied along a cross-section.

Textures, mineral chemistry and metamorphic evolution of high-pressure relics and their breakdown-products in polymetamorphic metasediments closely associated with eclogitic rocks in the northern part of this cross-section ("Eclogite Zone") document a common metamorphic history of this area.

High-pressure mineral assemblages and their breakdown-products are:

in marbles: omphacite (jadeite$_{31-33}$) → diopside → tremolite
omphacite → barroisite → actinolite + albite,

in garnet mica schists: omphacite (jadeite $_{42-54}$) → symplectite
omphacite + kyanite → paragonite + zoisite/margarite ± symplectite
talc + phengite-I → biotite + chlorite + quartz
garnet + phengite-I → biotite + plagioclase
→ biotite + phengite-II + chlorite + calcite
kyanite + zoisite → margarite + quartz.

Lawsonite pseudomorphs (consisting of paragonite + zoisite + quartz), included in garnets of metasediments, were presumably formed at a metamorphic stage prior to the eclogite-facies metamorphism.

A minimum-pressure of 12.5 ± 0.5 kb can be inferred from the coexistence of omphacite + quartz (temperature range 550–600 °C). For the assemblage omphacite + kyanite + paragonite + zoisite/margarite ± symplectite and assuming $a_{H_2O} \sim 1$, the pressure estimate is 20 kb, a similar value as derived for intercalated eclogites, by applying the equilibrium paragonite = jadeite + kyanite + H_2O.

This high-pressure event was followed by a strong uplift and reequilibration at 550 °C / 6–7 kb (Tertiary metamorphism). A compilation of all available PT-estimates documents the present knowledge of the PT-path of the high-pressure zone.

Keywords: Penninic metasediments, eclogites, metamorphic evolution, high-pressure metamorphism, Tauern window.

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[1] Institut für Mineralogie und Petrographie, Universität, Wilhelmstrasse 56, D-7400 Tübingen.

Zusammenfassung

Permomesozoische Metasedimente Penninischer Serien südlich des Grossvenediger, Österreich, wurden entlang eines Querschnittes untersucht.

Texturen, Mineralchemismus und die metamorphe Evolution von Hochdruck-Relikten und ihren Abbauprodukten aus polymetamorphen Metasedimenten, die eng assoziiert mit eklogitischen Gesteinen im Nordteil dieses Profils auftreten («Eklogit-Zone»), belegen eine gemeinsame metamorphe Geschichte dieses Gebietes.

Hochdruck-Paragenesen und ihre Abbauprodukte sind folgende:

in Marmoren: Omphacit (Jadeit$_{31-33}$) → Diopsid → Tremolit
Omphacit → Barroisit → Aktinolith + Albit,
in Granatglimmerschiefern: Omphacit (Jadeit$_{42-54}$) → Symplektit
Omphacit + Disthen → Paragonit + Zoisit/Margarit ± Symplektit
Talk + Phengit-I → Biotit + Chlorit + Quarz
Granat + Phengit-I → Biotit + Plagioklas
→ Biotit + Phengit-II + Chlorit + Calcit
Disthen + Zoisit → Margarit + Quarz.

Lawsonitpseudomorphosen in Granaten von Metasedimenten (bestehend aus Paragonit + Zoisit + Quarz) wurden wahrscheinlich vor der Eklogitfazies-Metamorphose gebildet.

Ein Minimaldruck von 12.5 ± 0.5 kb lässt sich aus der Koexistenz von Omphacit + Quarz für dieses Ereignis ableiten (Temperaturbereich 550–600 °C). Für die Paragenese Omphacit + Disthen + Paragonit + Zoisit/Margarit ± Symplektit und unter der Annahme $a_{H_2O} \sim 1$, ergibt sich bei der Anwendung des Gleichgewichts Paragonit = Jadeit + Disthen + H_2O eine Druckabschätzung von 20 kb und damit ein ähnlicher Wert, wie er aus benachbarten Eklogiten abgeleitet wurde.

Diesem Hochdruckereignis folgte eine starke Heraushebung und eine weitgehende, neuerliche Gleichgewichtseinstellung bei 550 °C/6–7 kb (Tertiäre Metamorphose). Eine Zusammenstellung aller verfügbaren PT-Abschätzungen dokumentiert den gegenwärtigen Kenntnisstand über den PT-Pfad der Hochdruckzone.

Introduction

Permomesozoic metasediments of the Tauern Window (TW) were involved in Alpine regional metamorphism. In the Penninic terrain exposed south of the Grossvenediger, a Cretaceous high-pressure event is well documented by the occurrence of eclogites, blueschists and high-pressure assemblages in metasediments of the "Eclogite Zone" (EZ, see Miller, 1977, Holland, 1979a, Franz & Spear, 1983, Spear et al., 1985, Dachs, 1985, Frank et al., 1986). Estimates of peak-metamorphic conditions are about 20 kb, 550–600 °C, $a_{H_2O} \sim 1$ (eclogites).

After the overthrusting of the Austroalpine nappe pile, all units of the TW were affected by a Tertiary metamorphism, which largely obliterated the evidence of the earlier eclogite/blueschist-events. Various geothermometers and -barometers, as well as phase equilibria in Penninic rock suites along a cross-section south of the Grossvenediger, indicate an increasing grade for this younger metamorphic overprint, from 450–480 °C at the TW-margin in the south to 550 °C / 6–7 kb in the central part near the base of the "Upper Schieferhülle" (USH, see HOERNES & FRIEDRICHSEN, 1974, HOSCHEK, 1982, DACHS, 1985).

The present paper concentrates on the high-pressure assemblages in metasediments, which occur in the EZ in the northern part of this cross-section (Dorfertal, Timmeltal).

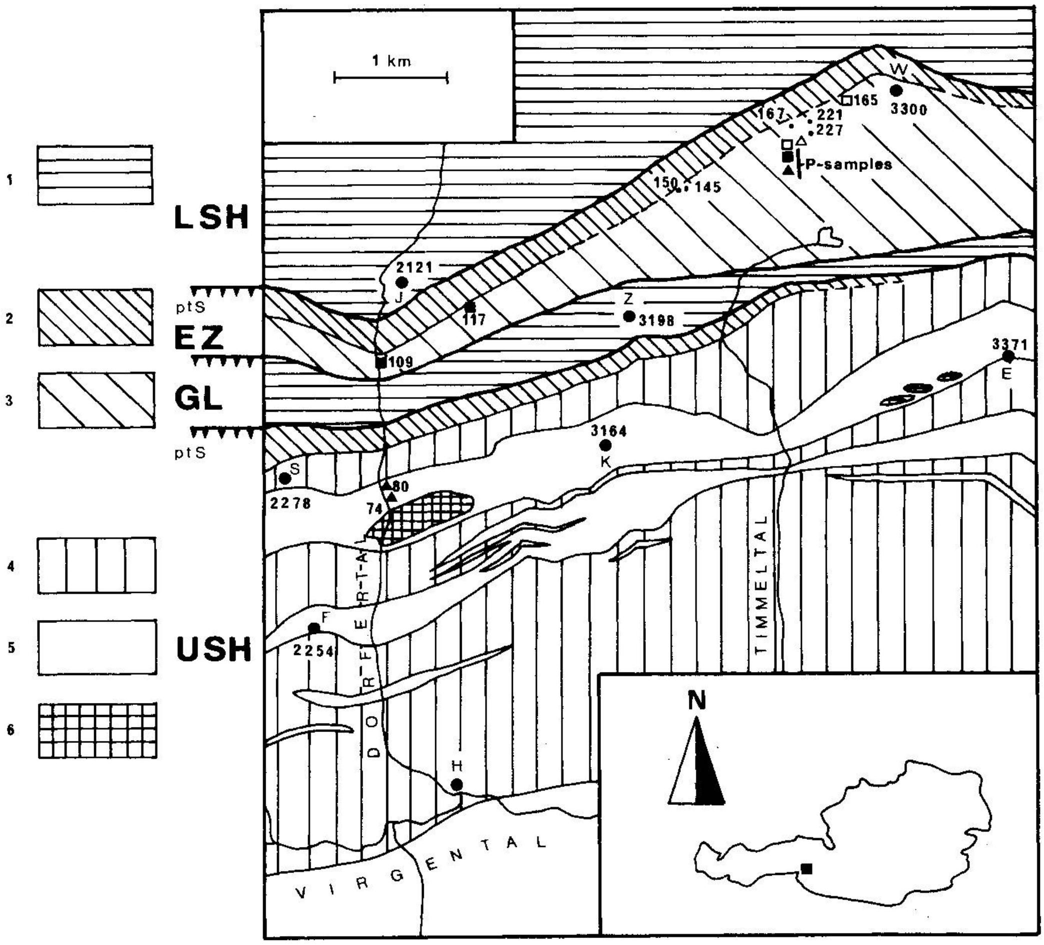


Fig. 1 Geological map of the southern Grossvenediger area (simplified after RAITH et al., 1980, and own results). Numbers give sample localities.
1: mainly paragneisses and mica schists of the LSH / paleozoic?
2: quartzites, garnet mica schists (± graphitic), marbles / permotriassic?
3: high pressure rocks of the EZ / jurassic-cretaceous?
4: greenschists ("prasinites") of the USH; ± garnet in the north / jurassic-cretaceous?
5: calc(carbonate-)mica schists (± garnet) of the USH ("Bündner schists") / jurassic-cretaceous?
6: serpentinite of the USH / jurassic-cretaceous?
▼▼▼ thrust plane
▲ lawsonite pseudomorphs included in garnets of metasediments
■ omphacite-relics in marbles
□ omphacite relics in garnet mica schists
△ talc-phengite in metasediments
W = Weissspitze, Z = Zoppetspitze, J = Johannes-Hütte
K = Kreutzspitze, E = Eichham, S = Schlüsselspitze, F = Finsterwitz, H = Hinterbichl.

Geological setting

The area of study lies in the central part of the TW, south of the Grossvenediger. A geological map of the generally south dipping rocks, simplified after Raith et al. (1980) and own results, is given in Fig. 1.

In the north rock series of the "Lower Schieferhülle" (LSH), or "Venediger nappe" (Frisch, 1976), form the lowest tectonic unit. The Hercynian metamorphic rocks of the LSH are intruded by granodiorites and granites of Permian age ("Zentralgneis-cores"). A series of probably Permotriassic sediments (ptS) was deposited onto this basement complex. White marbles of this rocks unit are a striking feature beneath brown-coloured clastic metasediments in the northridge of the Weissspitze (3300 m).

Going further south we enter the EZ. It forms a narrow zone of high-pressure metamorphic rocks with its greatest thickness in the upper Timmeltal, then thinning out to the west and to the east. Metabasic eclogites and their retrograde derivatives (Miller, 1977, Holland, 1979a) occur in association with high-pressure metasediments, mainly calcareous rocks with gradations to garnet mica schists and quartzites (Franz & Spear, 1983, Spear et al., 1985, Dachs, 1985). Near the boundary of the underlying LSH, the eclogites outcrop as boudinaged, lenticular bodies of various extent, with sheared contacts to the enclosing metasediments (mainly calc mica schists). This basal horizon of the EZ could be a tectonic melange (Miller, 1977, Franz & Spear, 1983).

Intact geological layering of eclogites and metasediments over considerable distances has on the other hand been preserved in the central EZ of the upper Timmeltal (Raith et al., 1980, Dachs, 1985). The thickness of the eclogite-layers there (metabasalts and -tuffs) ranges from some 10 m down to a few cm and less. Small omphacite-symplectite layers and omphacite in marbles and garnet mica schists could represent tuffitic material transformed during the Eoalpine high-pressure event.

Due to lithological and geochemical affinities to the rocks of the USH (Abraham et al., 1974, Raith et al., 1977) or "Glockner-nappe" (Frisch, 1976), the EZ is regarded as tectonically separated part of the USH.

To the south the EZ is in part overlain by a series of micaschists, metaarcoses, gneisses and subordinate garnet amphibolites. This "Glimmerschiefer-Lamelle" (GL), which separates the EZ in the north from the main body of the USH in the south, has been interpreted as a sheet of the LSH by Raith et al. (1980). The GL is overlain by the clastic, Permotriassic, basal sequence of the USH, followed by a thick unit of Jurassic/Cretaceous age ("Bündner-schist series"), consisting of carbonate-rich schists, intercalated with prasinites, chlorite schists, amphibolitic metabasites and serpentinites.

High-pressure assemblages and their breakdown-products in metasediments

The observed high-pressure relics in metasediments and their breakdown-products are listed in Table 1. Sample localities are indicated in Figure 1. Selected mineral analyses of assemblages from Table 1 are compiled in Table 2.

Tab. 1 High-pressure assemblages and their breakdown-products in metasediments of the EZ. Numbers in parenthesis refer to analyses of these phases given in Table 2.

rock type	sample	high pressure relics (assemblages)	breakdown products
marble	P12	omph(1) 1)	dio(2), tre(3), dol, qz
	109 117	omph-inclusion in zoned act (4)	barr(5), act(6), ab(7), cal
garnet mica schist ± quartzitic	P7,P8	omph (zoned in P8) rim(8) - core(9)	sy (diopsidic pyroxen + ab-rich pl ± actinolitic amph)
	165,167	omph - ky(10)	pa(11), ma, ± sy
	217	omph - ky	pa, zoi, sy
	P7	tc(12) - phe-I(13)	bio, chl
	P7,P14	ky - zoi(14)	ma(15), qz
	165,167	ga - phe-I(16)	bio(17), pl(18)
	145	ga - phe-I	phe-II(19), bio(20), chl, cal

[1] Mineral abbreviations: act = actinolite, ab = albite, amph = amphibole, ap = apatite, barr = barroisite, bio = biotite, cal = calcite, chl = chlorite, dio = diopside, dol = dolomite, ep = epidote, fes = Fe-sulfide, ga = garnet, gr = graphite, il = ilmenite, jd = jadeite, ky = kyanite, law = lawsonite, ma = margarite, omph = omphacite, pa = paragonite, phe = phengite, pl = plagioclase, qz = quartz, ru = rutile, sy = symplectite, tc = talc, tit = sphene, tur = turmaline, zoi = zoisite.

MARBLES

The marbles are medium to coarse grained rocks, with calcite as the dominant carbonate mineral. Dolomite is often completely lacking. Phyllosilicates (phengite-I with Si-values ranging from 6.63–6.94 per formula unit (pfu), related to 22 oxygen, phengite-II, a texturally younger mica phase with Si = 6.20–6.22 pfu, chlorite and/or phlogopite), quartz, tremolite, talc, albite, paragonite and a Fe-sulfide may be additional phases. In phlogopite-bearing marbles phengite-I shows the highest Si-contents (Si = 6.84–6.94 pfu).

Omphacite (30.5–32.5 mol% jadeite-component, acmite component < 5.5 mol%) forms

a) isolated clusters within the carbonate-matrix together with diopside, tremolite, dolomite, quartz. In this case a breakdown

(1) omphacite → diopside → tremolite,

involving Na-loss from the marble seems to have been operative.

b) Omphacite also occurs in a special marble type ("albite-tremolite-marble") with the paragenesis

actinolite–albite (anorthite-component < 1.3 mol%) ± calcite.

Tab. 2a Selected microprobe analyses of phases listed in Table 1. Mineralchemical data were obtained on an ARL-SEMQ electron microprobe at the Department of Mineralogy and Petrography, University of Innsbruck. Analysed natural minerals were used as standards and the data were corrected with the empirical Bence-Albee method. An attached energy dispersive system (KeVex) was used only for fast qualitative analyses. Mineral formulae of the amphiboles were calculated with a program of Mogessie & Tessadri (1982), formulae of pyroxenes with total cations = 4.000 according to Dietrich & Petrakakis (1984).

Nb. [a]	1	2	3	4	5	6	7	8	9	10
mineral	omph	dio	tre	omph	barr	act	ab	omph rim	omph core	ky
SiO_2	55.75	55.10	56.81	56.29	52.98	55.79	67.84	57.54	55.42	36.28
TiO_2	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.05	0.00
Al_2O_3	8.71	3.29	1.49	7.95	5.52	0.59	19.00	12.14	11.37	63.40
FeO [b]	0.56	0.86	0.45	3.01	4.21	5.13	0.12	1.89	7.02	0.09
MnO	0.06	0.06	0.00	0.07	0.02	0.25	0.00	0.00	0.31	0.04
MgO	13.17	16.96	25.69	12.03	21.16	22.47	0.07	9.77	6.52	0.00
CaO	15.62	20.16	10.99	15.17	9.03	12.32	0.22	11.97	10.22	0.00
Na_2O	5.27	2.11	1.29	5.33	3.09	0.05	11.79	7.10	8.66	0.00
K_2O	0.00	0.00	0.12	0.02	0.02	0.02	0.05	0.01	0.00	0.00
F			-		1.22	0.81				
total [c]	99.15	98.54	96.84	99.87	98.31	98.84	99.09	100.44	99.57	99.81
Si	1.980	1.990	7.777	1.996	7.452	7.830	2.995	2.003	1.971	0.982
Al^{IV}	0.020	0.009	0.223	0.004	0.548	0.098	0.989	0.000	0.029	0.018
Al^{VI}	0.345	0.131	0.017	0.329	0.368	0.000	0.000	0.501	0.448	2.003
Ti	0.003	0.000	0.000	0.000	0.002	0.000	0.000	0.001	0.001	0.000
Fe^{2+}	0.000	0.000	0.052	0.047	0.496	0.602	0.004	0.055	0.034	
Fe^{3+}	0.038	0.027		0.042					0.175	0.002
Mn	0.002	0.002	0.000	0.002	0.002	0.030	0.000	0.000	0.009	0.001
Mg	0.697	0.913	5.241	0.636	4.437	4.701	0.005	0.507	0.346	0.000
Ca	0.594	0.780	1.662	0.576	1.361	1.853	0.010	0.445	0.390	0.000
Na	0.363	0.148	0.342	0.367	0.843	0.014	1.009	0.479	0.597	0.000
K	0.000	0.000	0.021	0.001	0.004	0.004	0.003	0.000	0.000	0.000
F			-		0.543	0.360				
OH			-		1.457	1.640				
tot.cat.	4.019	4.000	15.335	4.000	15.513	15.130	5.015	3.991	4.000	3.007
jd/X_F/an	30.00	12.10		32.50	0.271	0.180	1.000	50.70	42.20	
ac	3.50	2.70		4.20				0.00	17.50	

[a] numbers refer to assemblages of Table 1 (numbers set there in parenthesis)
[b] total iron as FeO, except Fe_2O_3 in zoisite and plagioclase
[c] total corrected for O = F
tot. cat. = total cations; - not determined
jd = mol% jadeite-component in pyroxenes
X_F = F/(F + OH) in analyses with fluorine
an = mol% anorthite-component in plagioclase
ac = mol% acmite-component in pyroxenes

The *actinolite* is discontinously zoned in some cases with an amphibole of barroisitic composition in the core, which may contain omphacite as inclusion. In this case omphacite was decomposed according to a simplified reaction

Tab. 2b

Nb. [a]	11	12	13	14	15	16	17	18	19	20
mineral	pa	tc	phe-I	zoi	ma	phe-I	bio	pl	phe-II	bio
SiO_2	45.89	60.72	50.67	39.12	29.74	52.37	38.15	63.17	46.40	36.22
TiO_2	0.09	0.00	0.17	0.02	0.00	0.25	1.36	0.00	0.10	0.09
Al_2O_3	40.28	0.67	28.10	32.97	50.76	25.79	19.12	22.47	32.72	19.54
FeO [b]	0.10	3.35	0.90	0.77	0.37	1.56	12.60	0.30	2.49	16.47
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.11
MgO	0.23	30.87	4.13	0.13	0.70	4.77	14.43	0.48	1.78	12.81
CaO	0.41	0.05	0.01	25.16	10.66	0.00	0.18	3.00	0.01	0.03
Na_2O	7.33	0.13	0.65	0.02	1.56	0.30	0.15	9.31	0.55	0.12
K_2O	0.56	0.01	9.47	0.01	0.02	10.56	8.82	0.21	9.95	8.82
F	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-	-
total [c]	94.89	95.80	94.10	98.20	93.81	95.60	94.88	98.94	94.00	94.21
Si	5.887	7.784	6.762	2.969	4.002	6.934	5.587	2.817	6.285	5.462
Al^{IV}	2.113	0.101	1.238	0.031	3.998	1.066	2.413	1.181	1.715	2.538
Al^{VI}	3.976		3.181	2.918	4.050	2.959	0.887		3.506	0.935
Ti	0.009	0.000	0.017	0.001	0.000	0.025	0.151	0.000	0.010	0.010
Fe^{2+}	0.011	0.359	0.100		0.042	0.173	1.543	0.011	0.282	2.078
Fe^{3+}				0.049						
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.000	0.014
Mg	0.044	5.838	0.821	0.015	0.140	0.941	3.149	0.032	0.359	2.880
Ca	0.056	0.007	0.001	2.046	1.537	0.000	0.028	0.143	0.002	0.005
Na	1.823	0.032	0.168	0.003	0.407	0.077	0.043	0.805	0.144	0.035
K	0.096	0.002	1.612	0.001	0.003	1.784	1.648	0.012	1.719	1.697
F	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-
OH	4.000	4.000	4.000	1.000	4.000	4.000	-	-	-	-
tot.cat.	14.02	14.18	13.90	8.03	14.18	13.96	15.46	5.00	14.02	15.65
an								15.00		

(2a) omphacite + H_2O + CO_2 → barroisite + albite + calcite
and in a second step
(2b) barroisite ± calcite → actinolite + albite,

with the paragenesis actinolite + albite as final product.

GARNET MICA SCHISTS

Common rock constituents are phengite-I (Si = 6.50–6.93 pfu), garnet and quartz. Varying amounts of paragonite, zoisite, kyanite, plagioclase and talc may be present as additional phases. Accessories are rutile, sphene, apatite, Fe-sulfide and graphite.

Textural evidence suggests that phengite-II (Si = 6.12.–6.29 pfu), margarite, chlorite, biotite and plagioclase (anorthite component < 26 mol%) are breakdown-products.

Dispersed grains of omphacite may occur in these rocks. Omphacite also forms clusters, or distinct mm- to cm-size layers, aligned with the foliation. In the garnet mica schists omphacite and kyanite are always mantled by symplectitic breakdown-products.

Omphacite is generally homogeneous. The jadeite-content varies between 42.2 and 54 mol%. The acmit-component is less than 2 mol% (in one sample a discontinuously zoned omphacite was detected, with 17.5 mol% acmite-component in the core).

In the fine grained *symplectites* sodic plagioclase forms intergrowths with diopsidic pyroxene and/or actinolitic amphibole.

Maximum Fe_2O_3 in *kyanite* is 0.6 wt%.

The following simplified breakdown-reactions can be deduced from the observed phase relations in the omphacite-bearing portions of the garnet mica schists:

(3) omphacite + H_2O → symplectite (diopsidic pyroxene + albite-rich
plagioclase ± actinolitic amphibole),
(4) omphacite + kyanite + H_2O → paragonite + zoisite/margarite
± symplectite.

Other assemblages indicative for high-pressure metamorphism of the metapelites are (Table 1):

talc-phengite (Si = 6.76 pfu)
kyanite-zoisite (CHATTERJEE, 1976, CHATTERJEE et al., 1984,
STORRE & NITSCH, 1974).

Coexisting talc + phengite are typical for high-pressure metapelites in the Gran Paradiso area (CHOPIN, 1981).

South of the Grossvenediger this assemblage has only been found in the phengite-paragonite-quartz matrix of sample P7, where rims of biotite + chlorite suggest the following breakdown-reaction:

(5) talc + phengite-I → biotite + chlorite + quartz.

Kyanite and zoisite have been observed to break down according to

(6) kyanite + zoisite → margarite + quartz.

Margarite contains little muscovite-component (< 0.43 mol%), but up to 29.9 mol% paragonite-component in solid solution and an average of 0.6 wt% MgO and 0.57 wt% FeO.

Paragonite contains 2.5–13.7 mol% muscovite-component and 0.5–3.8 mol% margarite component in solid solution. Only minor amounts of Fe and Mg (0.13–1.14 wt% FeO, 0.15–0.45 wt% MgO) were detected.

Textural relations indicate that *zoisite/clinozoisite-epidote* minerals formed at several stages of the PT-evolution and as a result different generations of these minerals can be observed in some samples.

At peak-metamorphic conditions zoisite/clinozoisite-epidote phases coexisted with kyanite, garnet, phengite-I, quartz (± omphacite) in garnet mica schists and with calcite, dolomite, quartz, phengite-I (± omphacite) in marbles. As retrograde phases clinozoisite/epidote minerals formed as breakdown-products of omphacite + kyanite and of garnet.

In marbles Fe-poor (< 1.2 wt% Fe_2O_3) homogeneous zoisite/clinozoisite minerals are present. In other types of metasediments a compositional zoning is generally developed with increasing Fe-content towards the rim. A similar type of zoning, observed in adjacent metabasites, was correlated by RAITH (1976) with decreasing metamorphic conditions.

Phengitic micas occur in two texturally and chemically different generations: phengite-I and phengite-II. Depending on bulk rock composition phengite-I has Si-values of 6.50–6.93 pfu. Phengite-II has low Si-contents of 6.12–6.29 pfu. The paragonite-component is variable, nevertheless a general trend of increasing paragonite-component with decreasing phengite-contents is indicated (2.2.–10.1. mol% paragonite-component in phengite-I, 7.7.–19.7 mol% paragonite-component in phengite-II). TiO_2 is present averaging 0.25 wt%.

According to HEINRICH (1982) uplift of high-pressure garnet mica schists should induce dehydration-reactions involving garnet and phengite-I, such as:

(7) garnet + phengite-I → phengite-II + biotite + plagioclase + H_2O,
eclogite-facies amphibolite-facies

where phengite-II is less phengitic than phengite-I.

Tab. 3 Mineral constituents (listed in order of decreasing amounts) and type of garnet zoning, as discussed in the text, from metasediments of the studied area. Minerals in parenthesis are inclusions.

sample		mineral constituents	zoning type
74	USH	phe-I, pa; qz, ga(ctd, ap, pa, zoi, qz),dol, cal, bio, zoi/ep, chl, pl	2
80	USH	qz, phe-I, cal, dol, ga(pa, zoi, qz , ru, chl,phe, ap, tit), pa, zoi, chl	3
145	EZ	phe-I, qz, ga(qz, phe, ru, chl), bio, chl, zoi, cal, tur, ru, fes	3
150	EZ	phe-I, qz, ga(qz, ctd, ru), bio, chl, pa, pl, il, ru, fes	1
165	EZ	phe-I, qz, ga(qz, chl, ru), bio, zoi, pl, chl, omph, sy, ru, ap	2
167	EZ	ga(qz, pl, chl), phe-I, qz, pl, pa, chl, bio, ab, act, tc, ru, ti	1
221	EZ	ga(ctd, pa, zoi, qz, chl, ru, ap), phe-I, qz, pa, ky, chl, ma, zoi, ru, il, fes	2
227	EZ	phe-I, qz, ga(qz, phe, bio, gr), bio, tit, zoi, ru, gr	2
P3	EZ	ga(qz, phe, ru, il, chl), phe-I/II, qz, chl, pa ,zoi, cal, dol, ap, ru, tit, gr	3
P4	EZ	ga(qz, phe, ru), phe-I, zoi, qz, bio, ru, tit, ap, gr	3
P7	EZ	ga(zoi, pa, qz, ru, fes), phe-I/II, tc, pa, zoi, ky, qz, chl, pl, bio, omph, sy, ma, cal fes, ru, tit, ap, gr	3
P8	EZ	phe-I, ga(qz, ru, zoi, omph), zoi(omph), qz, bio, omph-I/II, sy, chl, pl, ru, fes	2
P14	EZ	ga(ctd, qz, phe, ru), phe-I, zoi, qz, ky, pa, ma, bio, ru, ap	3
P16	EZ	phe-I, ga(qz, ctd, pa, chl, gr, ru, fes), qz, pa, zoi, chl, bio, ru, gr, fes, cal, dol	2

In the studied samples garnet + phengite-I very rarely show any signs of reaction. Narrow rims of biotite + plagioclase surrounding phengite-I and garnet indicate a similar type of reaction. A fine grained reaction-zone of phengite-II, biotite, chlorite and calcite between garnet and phengite-I points to another breakdown-reaction.

Garnet chemistry and zoning was analysed in 14 samples (various types of garnet mica schists) from the EZ and the USH (mineral constituents of these samples and the observed garnet zoning type, as discussed in the text, are listed in Table 3, whereas the variation of garnet core- and -rim-composition is given in Table 4).

All garnets are continuously zoned and three types of zoning may be distinguished (Figure 2a, b, c).

Tab. 4 Variation of garnet composition expressed in terms of the almandine-, pyrope-, grossular- and spessartine component (mol%), analysed in carbonate-poor and in carbonate-rich garnet mica schists and in garnet mica schists containing omphacite-relics. r = rim; c = core.

rock type		garnet mica schist carbonate-poor	garnet mica schist carbonate-rich	garnet mica schist with omph-relics
almandine	r	48.8 - 75.7	58.4 - 65.0	47.7 - 56.1
	c	51.2 - 74.7	70.0 - 76.7	51.2 - 66.9
pyrope	r	6.4 - 34.7	5.3 - 8.8	20.5 - 35.2
	c	3.0 - 18.0	4.4 - 4.9	4.7 - 19.4
grossular	r	8.9 - 27.2	26.6 - 31.0	14.3 - 22.1
	c	8.7 - 22.2	16.4 - 24.0	14.5 - 19.5
spessartine	r	0.3 - 3.7	0.9 - 2.2	0.2 - 0.6
	c	1.9 - 18.6	1.4 - 5.9	5.8 - 20.6
zoning type		1, 2, 3	2,3	2,3
observed in samples		145, 150, 167, 221 227, P4, P14, P16	74, 80, P3	165, P7, P8

Type 1 is restricted to samples without carbonate- or zoisite-minerals and is similar to the zoning of eclogite-garnets (MILLER, 1977). Examples of this type are shown in Figure 2a in the diagrams of sample P5 (retrograde altered eclogite) and sample 150 (garnet mica schist, EZ).

(Mn + Ca) are enriched in the core with simultaneous Mg-minimum. Towards the rim (Mn + Ca) decrease in a bell-shaped curve, whereas Mg increases continously. Fe behaves antipathetic to Mn: an increase from core to rim, compensating the (Mn + Ca)-depletion is followed by two maxima, as soon as Mn has reached low concentrations. Near the rim Fe decreases.

Due to inclusions in garnets with a zoning similar to type 1 (chlorite, epidote, amphibole, albite in the core, omphacite, kyanite near the rim) increasing PT-

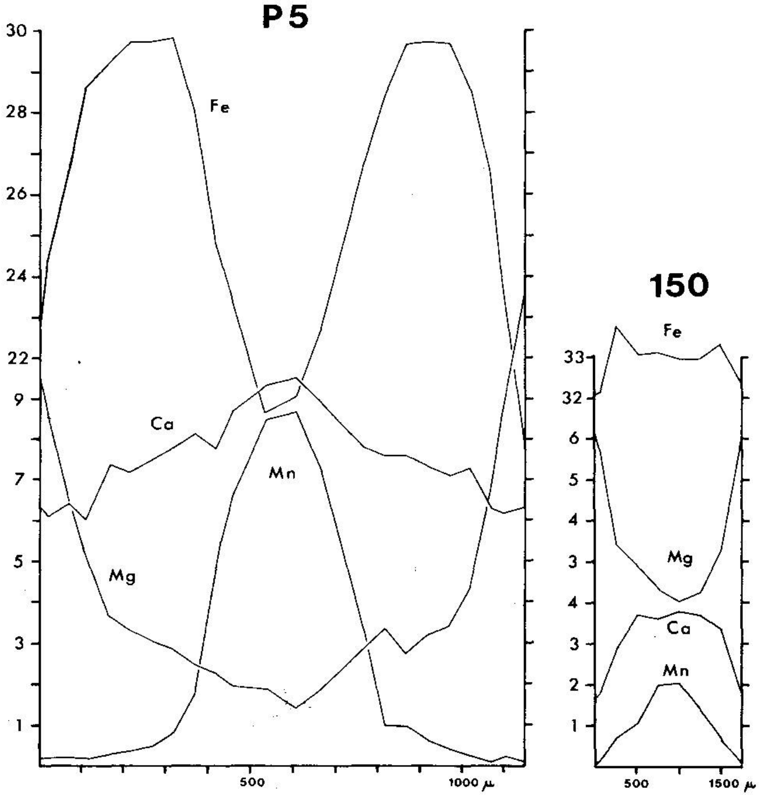
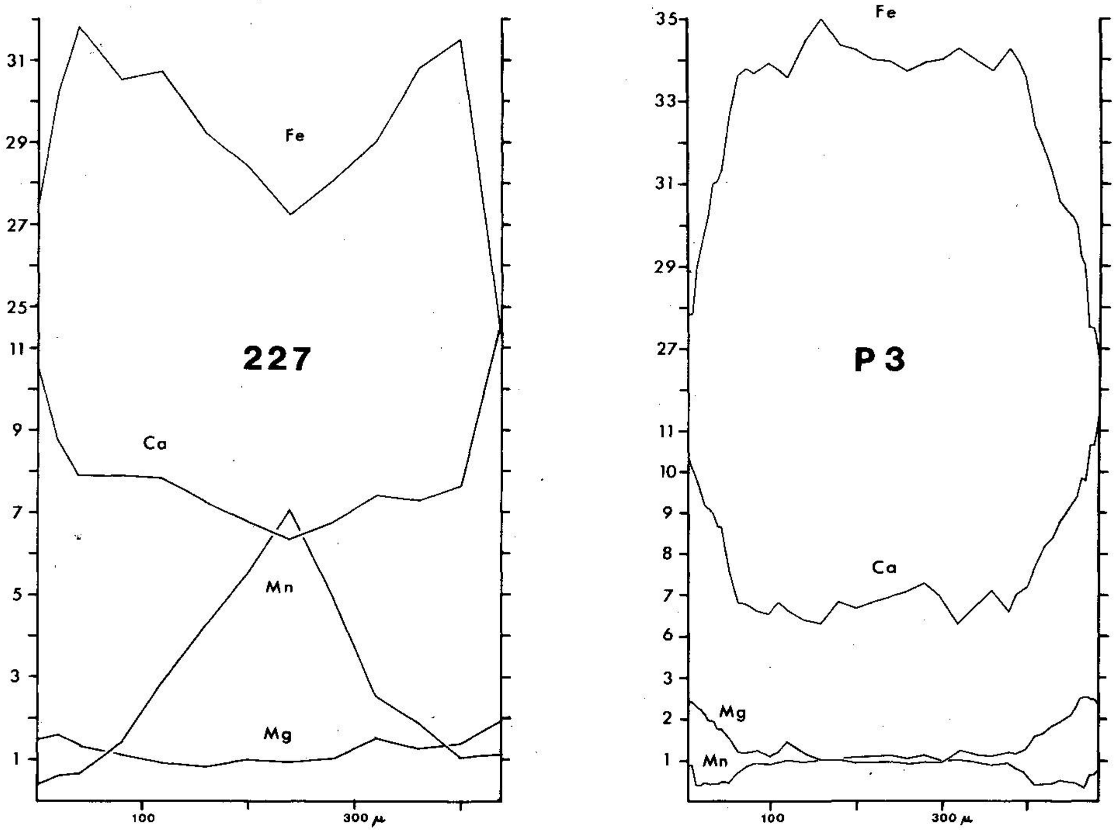


Fig. 2a, b, c Representative compositional profiles (wt%) of garnets from high-pressure rocks with a) zoning type 1 (retrograde eclogite, sample P5, EZ; garnet mica schist, sample 150, EZ), b) zoning type 2 (garnet mica schist, sample 227, EZ) and c) zoning type 3 (graphitic garnet mica schist, sample P3, EZ).



conditions during garnet growth have been documented by MILLER (1977). The same may be valid for garnets of high-pressure metasediments with zoning type 1.

Other inclusions (listed in order of abundance) are: Fe-rich chlorite, chloritoid, zoisite, paragonite, quartz, phengite (Si = 6.21–6.42 pfu), rutile, graphite, ilmenite, apatite, Fe-sulfide, calcite, omphacite, kyanite, plagioclase.

Type 2 (Figure 2b) is characterized by the same development of Mn and Fe as in type 1, but (Mg + Ca) show a minimum in the core and an increase towards the rim.

Type 3 (Figure 2c) exhibits the similar concentration trend for Ca and Mg as in type 2, but there is only little Mn-enrichment in the core. This is compensated for Fe by a concentration-plateau in the core region with a sharp decrease of Fe towards the rim.

The same genetic interpretation, as suggested for garnets with zoning type 1, may also be valid for types 2 and 3, which probably are the result of different bulk rock composition. It is confirmed by the fact that omphacite may occur in these samples (as inclusion near the rim, or outside of garnet), indicating that they experienced a high-pressure event.

An additional indication for a high-pressure evolution of the metasediments are *lawsonite pseudomorphs*. They occur as rectangular or rhombic form-relics within garnet. The minerals now present are paragonite + zoisite + quartz, suggesting the reaction (FRANZ & ALTHAUS, 1977)

(8) lawsonite + albite → paragonite + zoisite + quartz.

Lawsonite pseudomorphs also occur in metabasites and -sediments of the USH outside the EZ (FRY, 1973, MILLER, 1977, RAITH et al., 1977, 1980, DACHS, 1985).

Metamorphic evolution

Textures and phase relations clearly indicate that several metamorphic episodes are recorded in the eclogites and in the surrounding metasediments. Relevant phase equilibria and geothermo- und -barometers have been applied to provide constraints on the path of these rocks in PT-space (HOERNES & FRIEDRICHSEN, 1974, MILLER, 1977, HOLLAND, 1979a, RAITH et al., 1980, HOSCHECK, 1981, 1982, FRANZ & SPEAR, 1983, SPEAR et al., 1985, DACHS, 1985, FRANK et al., 1986). The results are summarized in Table 5. The common PT-path for metabasites and -sediments of the EZ is shown in Figure 3. It will perhaps be modified, if more reliable PT-estimates are available in future.

Lawsonite pseudomorphs preserved as form-relics in garnets of metasediments, as well as the inclusion mineral of garnet, probably represent fragmen-

Tab. 5 Compilation of all available PT-estimates from rocks of the EZ and the USH in the Grossvenediger area.

nb.	rock type		geothermometer, -barometer/phase equilibrium applied	PT-estimate	references
1	metasediment EZ/USH	high pressure event	$\text{law} + \text{ab} \longrightarrow \underbrace{\text{pa} + \text{zoi} + \text{qz}}_{\text{law-pseudomorphs in garnet}}$?		DACHS (1985) this paper
2	eclogite EZ		garnet-clinopyroxene-thermometry: $K_{D\,ga-omph}^{Fe-Mg}$ at 10 kb omph coexisting with qz	500 - 550°C P > 10 kb	MILLER (1977)
3	eclogite EZ		garnet-clinopyroxene-thermometry: $K_{D\,ga-omph}^{Fe-Mg}$ at 20 kb clinopyroxene + magnesite = dolomite + orthopyroxene pa = omph(jd_{50}) + ky + H_2O	620 ± 30° C P = 19.5 ± 2.5 kb $a_{H2O} \sim 1$	HOLLAND (1979a)
4	eclogite EZ		garnet-clinopyroxene-thermometry: $K_{D\,ga-omph}^{Fe-Mg}$ at 10 kb corrected for Ca-contents oxygen isotope fractionation between qz/ru and qz/omph ab = omph(jd_{50}) + qz chl + ky = Mg-ctd + tc pa = omph(jd_{50}) + ky + H_2O equilibria applied to coexisting omph, ky, pa, tc, Mg-ctd of eclogite T-527 from Weißspitze	550 - 570° C 540 - 580° C P > 12.5 ± 0.5 kb T ~ 570°C P ~ 19.6 kb $a_{H2O} \sim 1$	FRANK et al. (1986)
5	marble EZ		coexisting dio-tre-dol-cal-qz ± zoi phase equilibria of the system $CaO\text{-}MgO\text{-}SiO_2\text{-}H_2O\text{-}CO_2$	T = 600°C assumed from 3, P = 18-25 kb a_{H2O} close to 1	FRANZ & SPEAR (1983)
6	omph-relics in metasediments EZ		omph coexisting with qz (inclusion in omph) ab = omph(jd_{50}) + qz pa = omph(jd_{50}) + ky + H_2O, applied to coexisting omph-ky-pa(-zoi/ma-sy) in metasediments	T = 550 - 600°C assumed from 3 and 4 P > 12.5 ± 0.5 kb assuming a_{H2O}= 1, then P ~ 20 kb	DACHS (1985) this paper
7	metasediment		phase equilibria not more eludicated in abstract	T = 590°C, P = 19 kb	SPEAR et al. (1985)
8	metabasites and -sediments EZ/USH	Tertiary regional metamorphism	oxygen isotope - thermometry	T ~ 550°C in the EZ decreasing to the south	HOERNES & FRIEDRICHSEN (1974)
9	metasediment		garnet - biotite geothermometer plagioclase-biotite-garnet-muscovite geothermobarometer	T = 500 - 550°C P = 6-7 kb	HOSCHEK (1982)
10	metasediments of th EZ, USH and the "Matreier Zone"		calcite - dolomite geothermometer garnet - biotite geothermometer plagioclase-biotite-garnet-muscovite geothermobarometer phase relations between tre-zoi-cal-dol-qz at 550°C	T max.550° C in the EZ, decreasing to 450-480°C at the TW- margin in the south P = 6-7 kb in the EZ	DACHS (1985)
11	marble USH		fluid inclusion data	T = 460-525°C P = 2.3-4.5 kb	HOSCHEK (1981)
12	metasediments EZ		data-source not explained in abstract	T < 350°C P < 2.5 kb	SPEAR et al.(1985)

tary assemblages of the earliest metamorphic stage recorded in the metasediments. A reaction that might be responsible for the breakdown of lawsonite is

(8) lawsonite + albite → paragonite + zoisite + quartz,

which is traced in Figure 3 (labled 1) according to FRANZ & ALTHAUS (1977), valid for $a_{H_2O} = 1$. Garnet growth probably started somewhere in this area.

The peak?-metamorphic conditions of the high-pressure event are best recorded by mineral parageneses of eclogitic rocks, with values of 550-600 °C, pressures around 20 kb and $a_{H_2O} \sim 1$ (estimates 2, 3 and 4). Estimate 5 is based

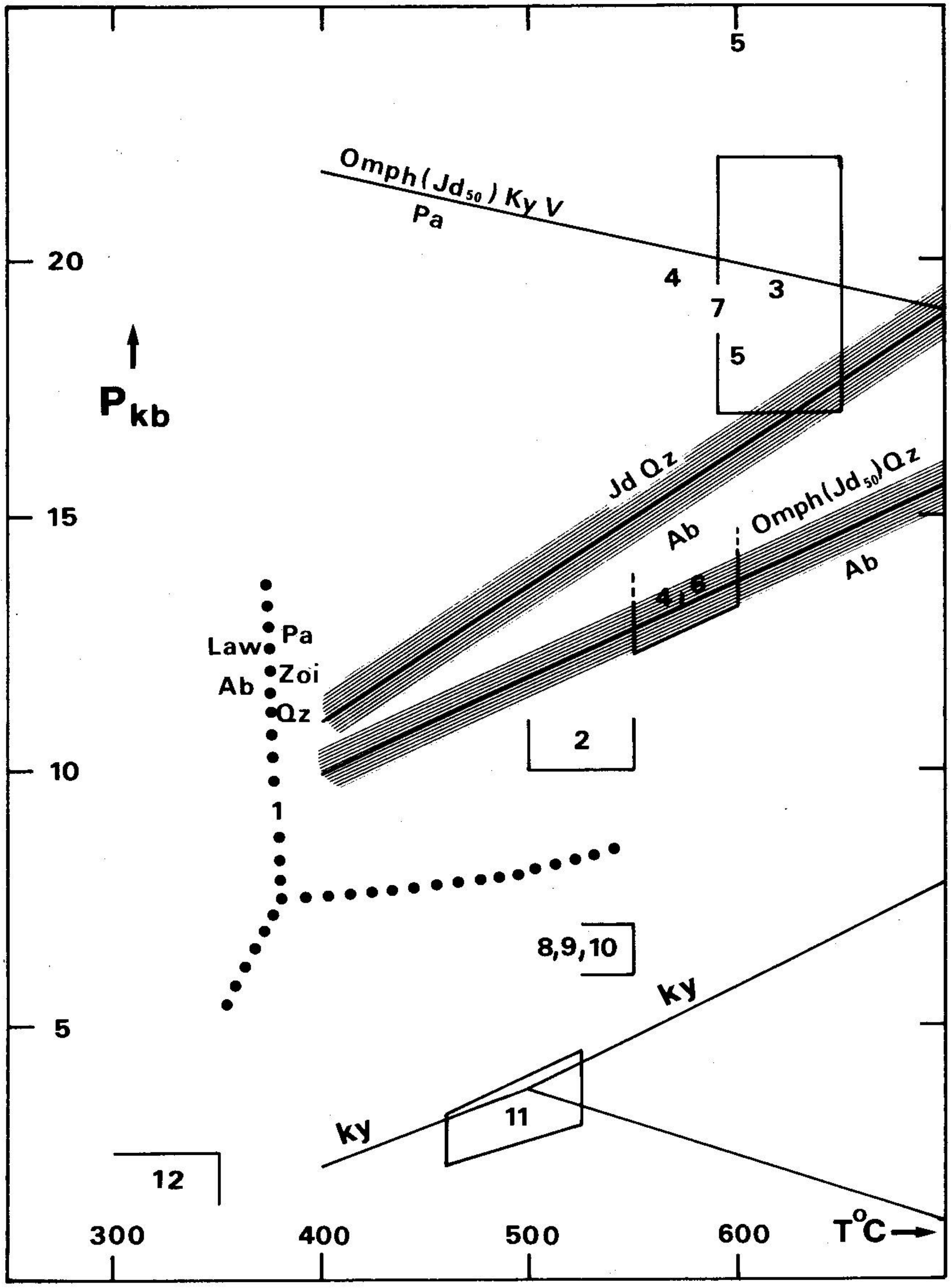


Fig. 3 Plot of PT-estimates (listed in Table 5), for high-pressure rocks of the EZ.

Data source of the traced equilibria:

paragonite = omphacite (jadeite$_{50}$) + kyanite + vapor	HOLLAND (1979b)
albite = omphacite (jadeite$_{50}$) + quartz	HOLLAND (1980)
lawsonite + albite = paragonite + zoisite + quartz	FRANZ & ALTHAUS (1977)
phase-diagram of the Al_2SiO_5-modifications	HOLDAWAY (1971)

on calculated phase relations of the marble-assemblage diopside–tremolite–dolomite–calcite–quartz ± zoisite. It beares considerable uncertainties, as it is questionable, if the MRK-equation used in the calculations yields correct H_2O–CO_2-activities at high pressures. Nevertheless relatively high pressures and a water-activity close to 1 are qualitatively indicated for this assemblage.

Assuming a temperature range of 550–600 °C during eclogite-facies metamorphism (estimates 3 and 4), a minimum-pressure of 12.5 ± 0.5 kb can be estimated from omphacite-relics in metasediments, based on the equilibrium

albite = omphacite (jadeite$_{50}$) + quartz.

In Figure 3 a trace for the endmember-reaction and for omphacite (jadeite$_{50}$) is given, calculated according to HOLLAND (1980), also showing experimental uncertainty. If also $a_{H_2O} \sim 1$ as in eclogites (estimates 3 and 4), pressures of about 20 kb are indicated by the paragenesis

omphacite–kyanite–paragonite–zoisite/margarite ± symplectite

and the equilibrium

paragonite = omphacite (jadeite$_{50}$) + kyanite + H_2O,

which is contoured in Figure 3 according to HOLLAND (1979b).

The subsequent metamorphic history is characterized by a strong uplift, which initiated the breakdown-reactions described. At 550 °C / 6–7 kb extensive reequilibration, post-dating the main tectonical displacements, took place, as indicated by consistent results of various geothermo- and -barometers (estimates 8, 9, 10). Deduced from calcite–dolomite geothermometry (DACHS, 1985), this Tertiary metamorphism shows an increasing grade from 450–480 °C at the southern TW-margin to ~550 °C in the central part near the base of the USH.

Still later metamorphic stages are reflected by fluid inclusion data and by late mineral formations (estimates 11 and 12).

Conclusions

The investigation of Penninic metasediments occurring together with eclogites in a narrow zone south of the Grossvenediger, clearly revealed that these experienced a common metamorphic history. The main arguments confirming this interpretation are as follows:

Field evidence: gradations from eclogites and their derivatives to metasediments without intervening shear zones suggest intact geological layering over considerable distances in the central EZ.

Petrological evidence: high-pressure assemblages as relics in metasediments. A minimum-pressure of 12.5 ± 0.5 kb in the temperature range 550–600 °C is confirmed by omphacite (jadeit$_{50}$)-relics coexisting with quartz. Assuming $a_{H_2O} \sim 1$ a pressure near 20 kb results from the assemblage

omphacite-kyanite-paragonite-zoisite/margarite ± symplectite.

Lawsonite pseudomorphs in garnets of EZ-metasediments, which probably were formed at a metamorphic stage prior to the eclogite-facies metamorphism, indicate a prograde metamorphic evolution.

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